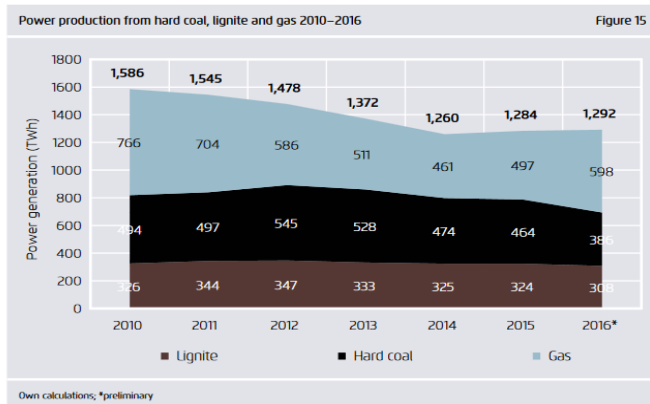
Trondheim Energy Transition
Natural Gas Workshop, Febr. 26, 2018



Research Outlook

Christian von Hirschhausen

based on joint research with several co-authors …

1. Modeling

2.1 Energy market competition analysis is complex …

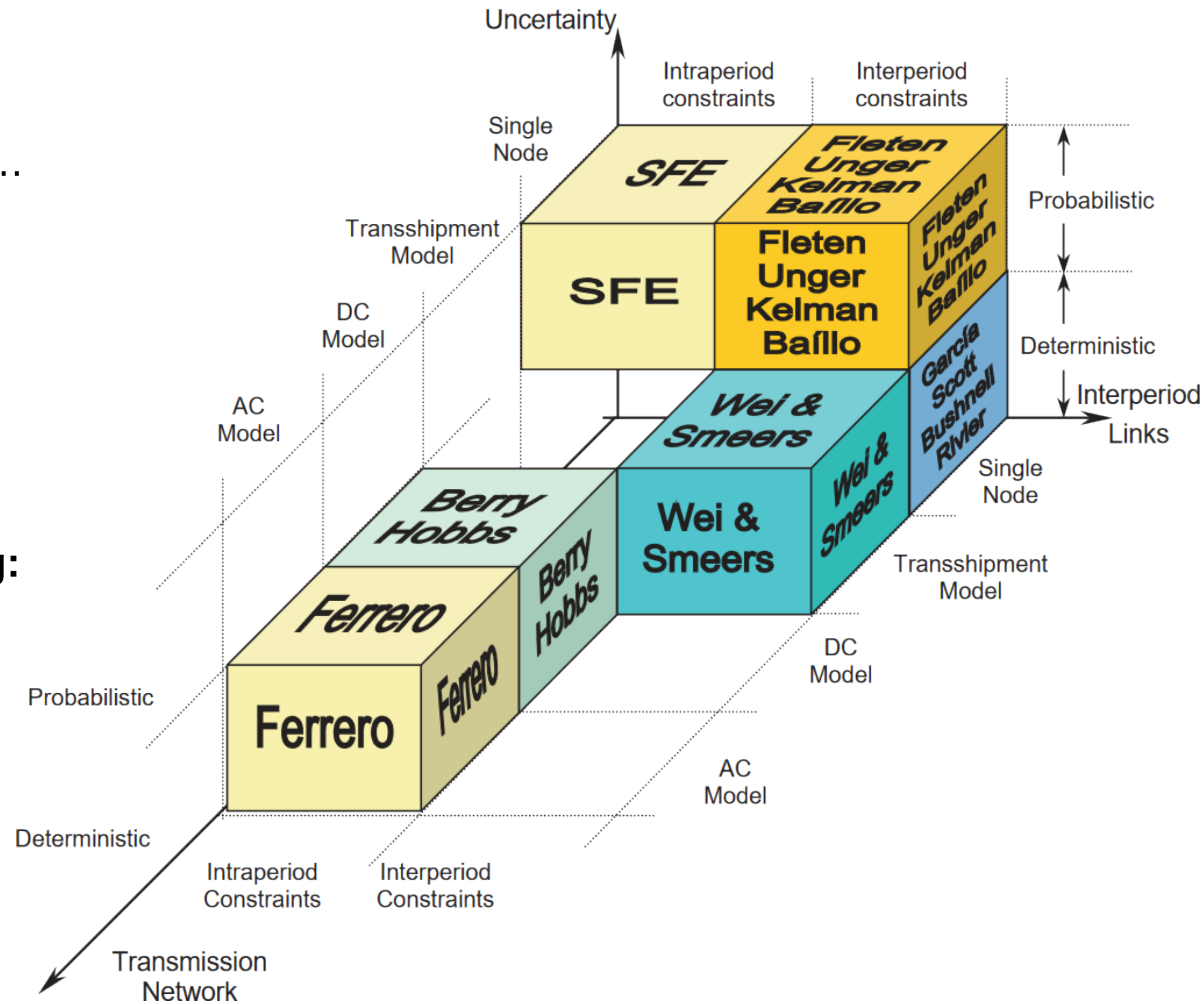
Assumptions on:

~ competition:
Cournot vs. perfect competition vs. …

~ trade:
perfect competition vs. national perspective

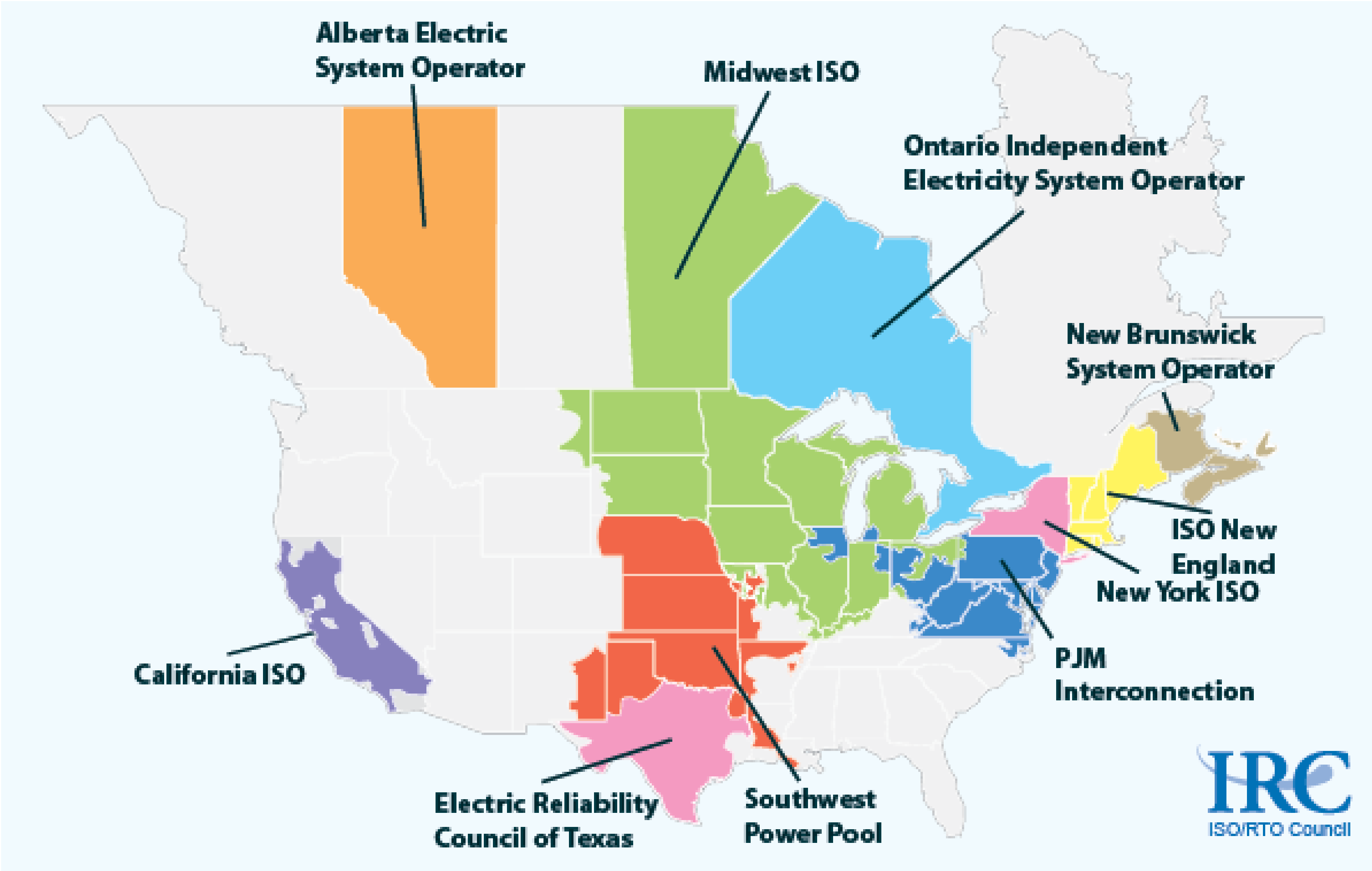
~ sector linkage:
partial vs. general equilibrium; macro-energy linkage

~ Different electricity sector modeling:
Methodologies:
~ optimization vs. simulation,
~ different objective functions,
~ different time perspectives, etc.



Source: Ventosa (2005)

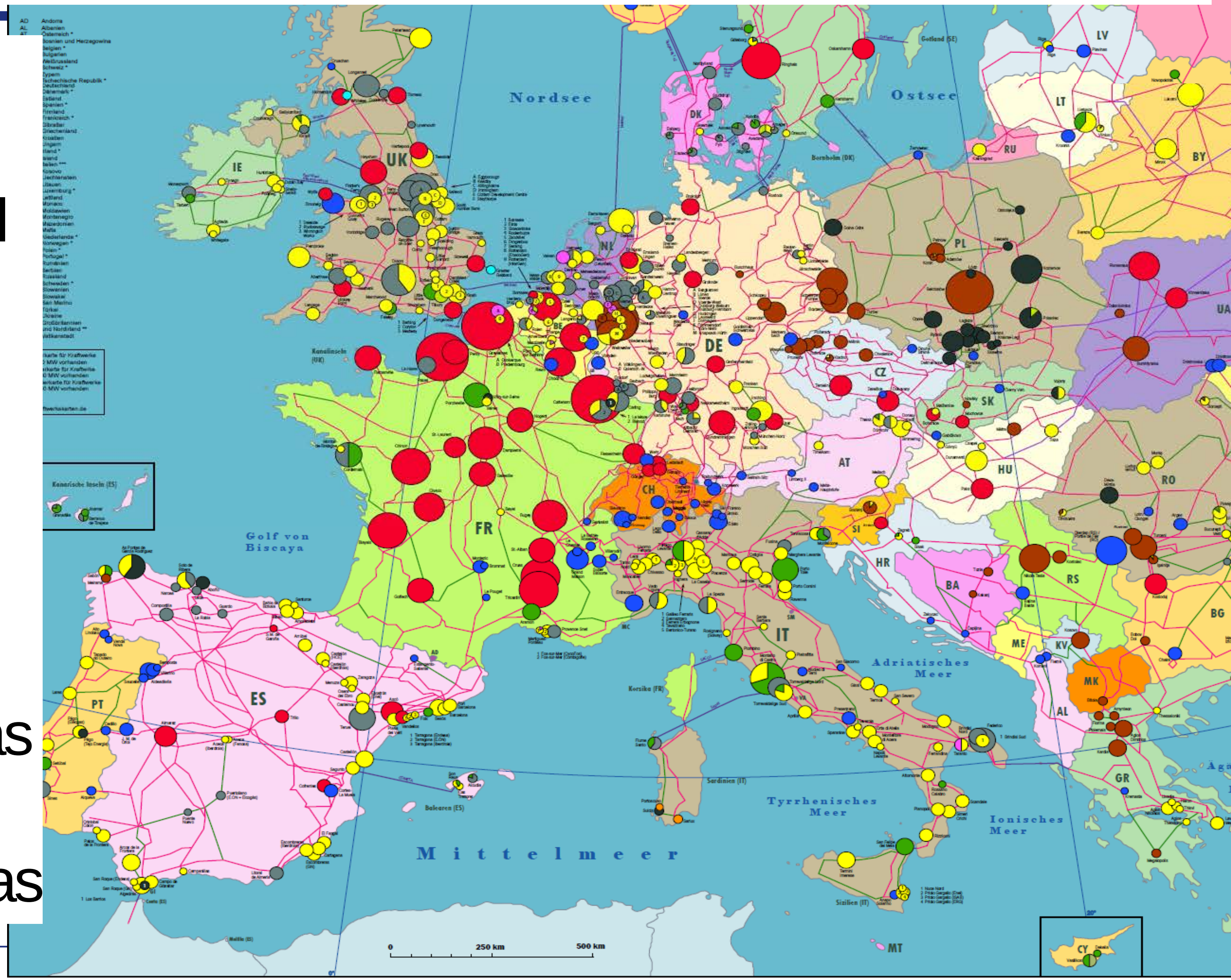
„Seams issues“ are complex: RTOs in restructured states



Energy Policies and Technologies are (largely) national: Generation Power Plants and Networks in Europe

- Water
- Biomass
- Hard coal
- Wind
- Lignite
- Diesel
- Fuel Oil
- Gas
- Nuclear
- Furnace gas
- Oil shale
- Synthetic gas

Source: Schneider, Kuhs (2013)



Bearbeitung: PD Dr.-Ing. habil. Jörg Schneider (Berlin) und Gunter Kuhs (Halle/S.)

2. Look at details

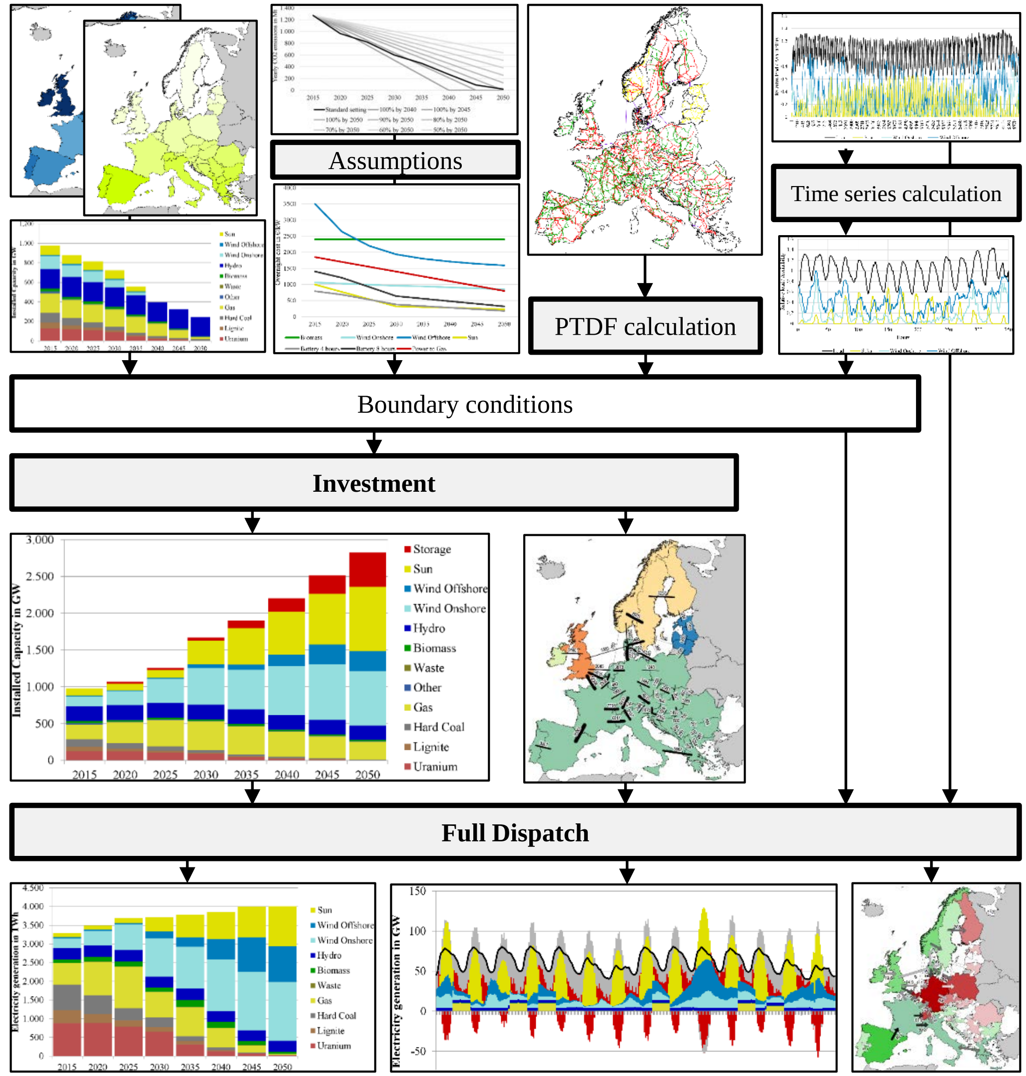
Model: dynELMOD
Determining cost-effective pathways in the electricity sector

dynELMOD (Gerbaulet and Lorenz, 2017):

Linear program to determine cost-effective development pathways in the European electricity sector

Model:
33 European countries
31 conventional or renewable generation and storage technologies
9 investment periods, five-year steps 2020 – 2050
Good storage representation (including reservoirs, DSM)
Approximation of loop-flows in the HVAC electricity grid
CCTS and CO2 storage constraints

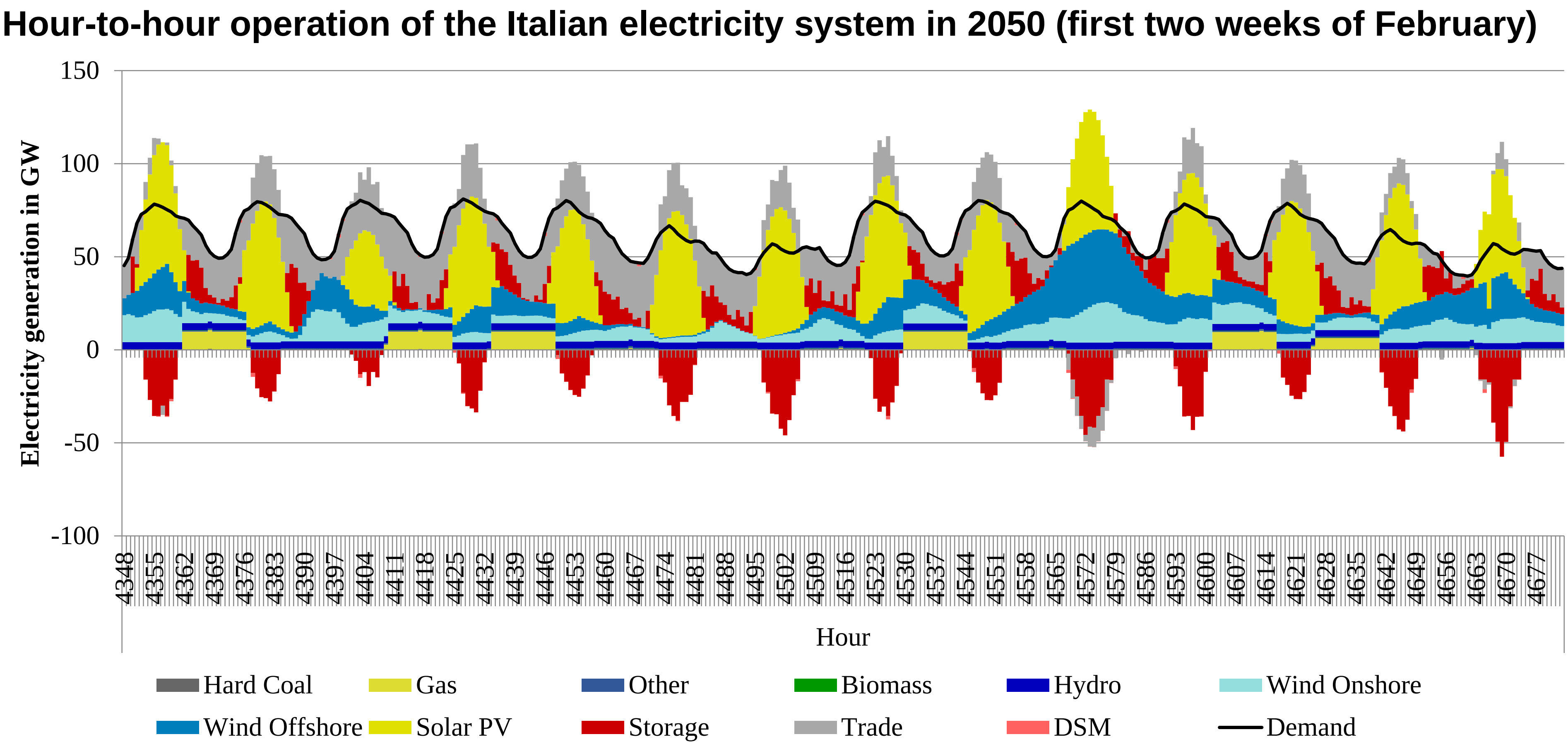
1. **Investment**
   – Investment into Conventional and renewable generation, cross-border capacities
   – Reduced time series used
2. **Dispatch**
   – Investment result from step 1 fixed
   – Time series with 8760 hours (validate result adequacy)



Outputs

- ➢ Investment into generation capacities, storage, transmission capacities
- ➢ Generation and storage dispatch
- ➢ Emissions by fuel
- ➢ Flows, imports, exports

Hour-to-hour operation of the Italian electricity system in 2050 (first two weeks of February)

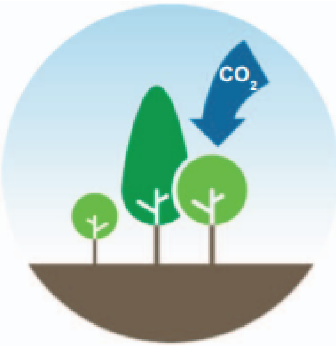


- In February 2050 Italy is also dependent on Storage and Imports
- Solar infeed is higher than in Germany

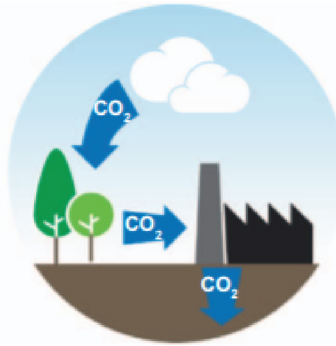
3. Broaden the Perspective

… creates attention in „The Economist“

6 potential „negative emission technologies“



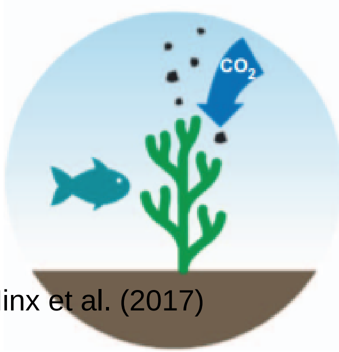
Afforestation and reforestation
Additional trees are planted, capturing CO_2 from the atmosphere as they grow. The CO_2 is then stored in living biomass.



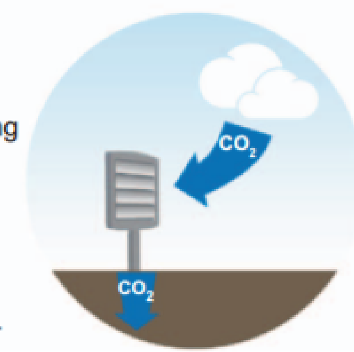
Bioenergy with carbon capture and sequestration (BECCS)
Plants turn CO_2 into biomass, which is then combusted in power plants, a process that is ideally CO_2 neutral. If CCS is applied in addition, CO_2 is removed from the atmosphere.

Biochar and soil carbon sequestration (SCS)
Biochar is created via the pyrolysis of biomass, making it resistant to decomposition; it is then added to soil to store the embedded CO_2. SCS enhances soil carbon by increasing inputs or reducing losses.

Enhanced weathering
Minerals that naturally absorb CO_2 are crushed and spread on fields or the ocean; this increases their surface area so that CO_2 is absorbed more rapidly.



Ocean fertilization
Iron or other nutrients are applied to the ocean, stimulating phytoplanton growth and increasing CO_2 absorbtion. When the plankton die, they sink to the deep ocean and permanently sequester carbon.



Direct air capture (DAC)
Chemicals are used to absorb CO_2 directly from the atmosphere, which is then stored in geological reservoirs.

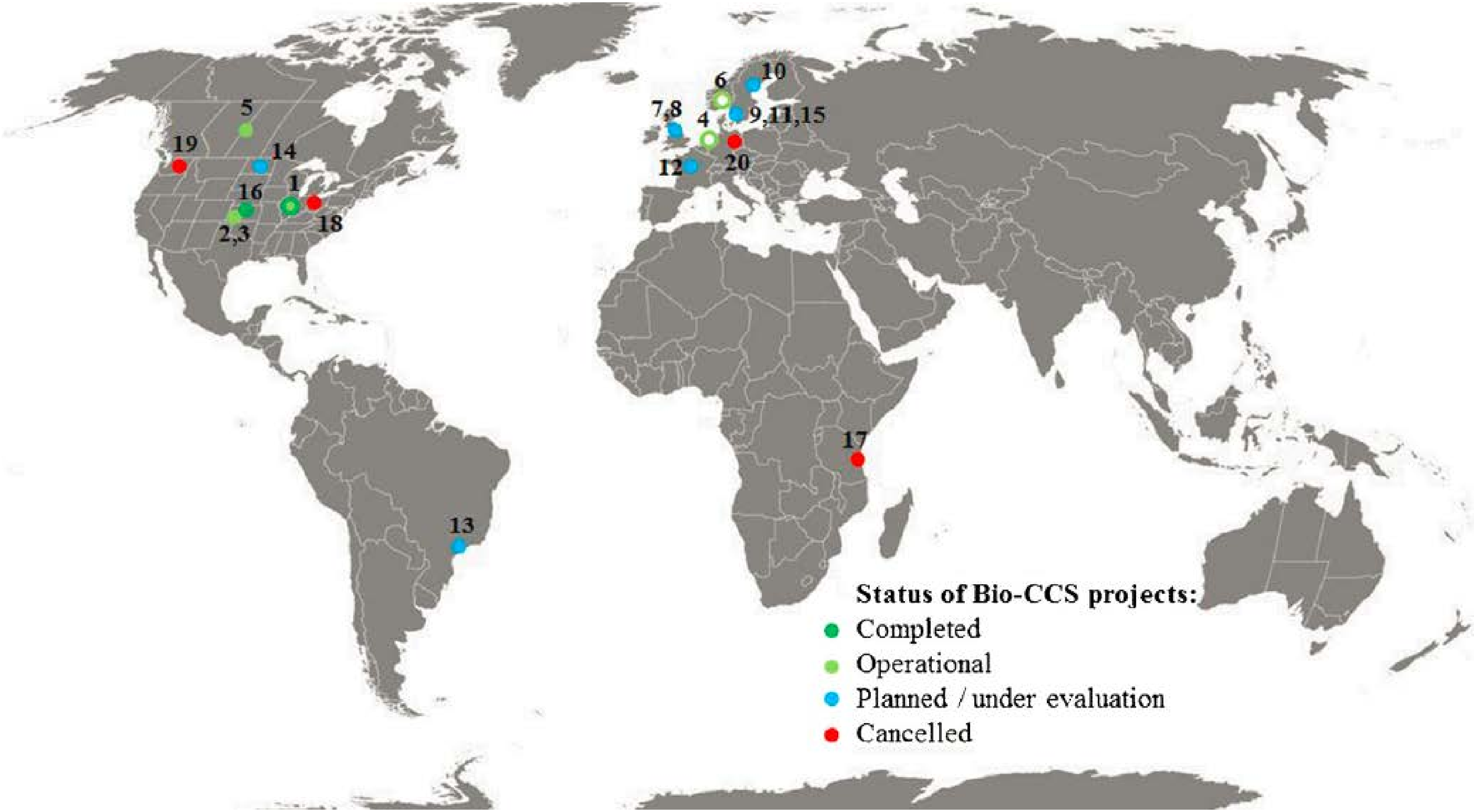
Source: Minx et al. (2017)

Large-scale CCTS Projects world-wide (IEA, 2017, Schiffer and Thielemann, 2017)

Tab.: Große laufende CCS-Projekte weltweit

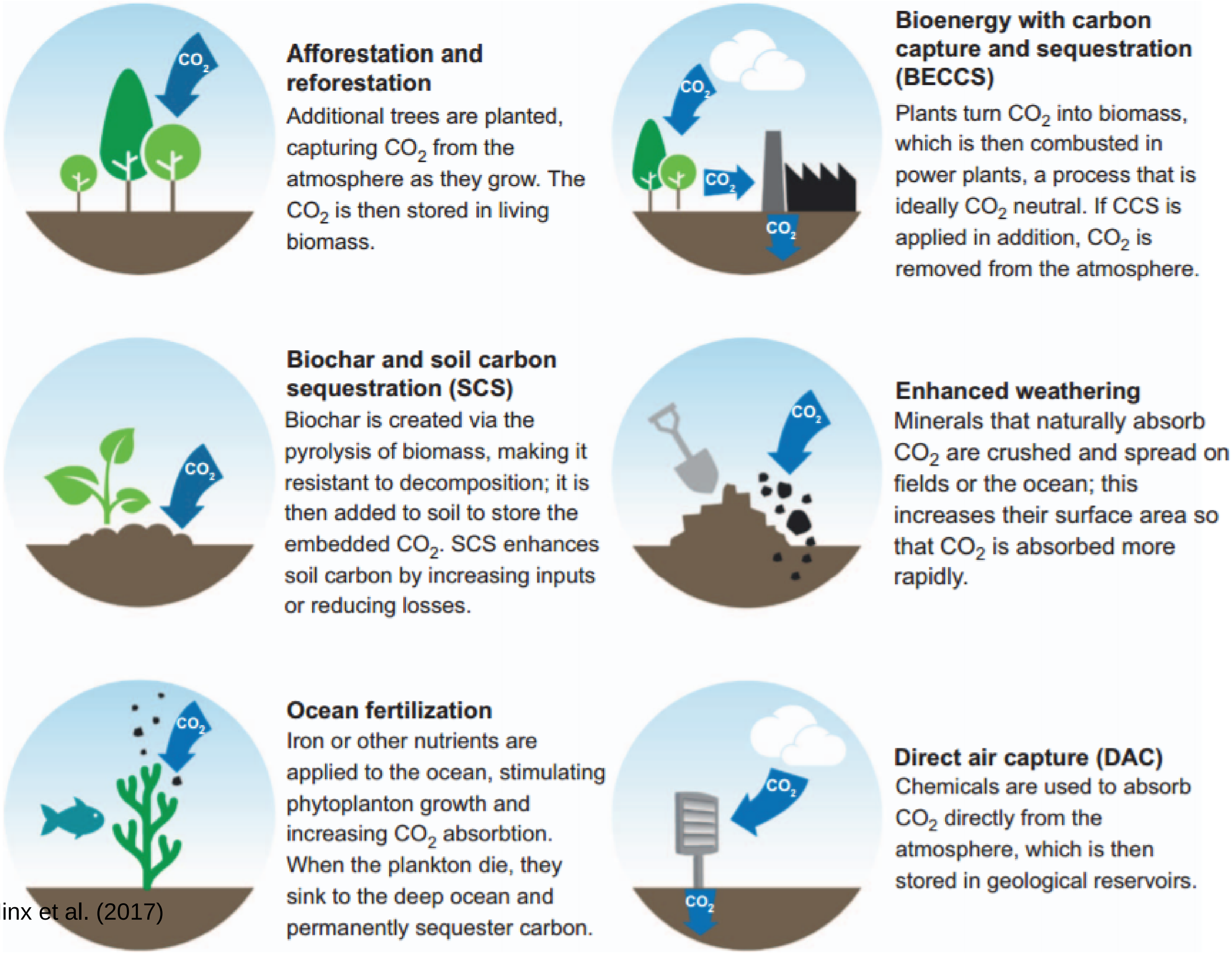
Projektname	Land	Inbetriebnahme	CO_2-Quelle	CO_2 Abscheidekapazität [Mio. t/a]	Speichertyp
Val Verde	USA	1972	Erdgasaufbereitung	1,3	EOR
Enid Fertilizer	USA	1982	Düngerproduktion	0,7	EOR
Shute Creek	USA	1986	Erdgasaufbereitung	7,0	EOR
Sleipner	Norwegen	1996	Erdgasaufbereitung	0,9	DSF
Snöhvit	Norwegen	2008	Erdgasaufbereitung	0,7	DSF
Great Plains Weyburn	Kanada	2000	Synthesegas	3,0	EOR
Boundary Dam	Kanada	2014	Kohleverstromung	1,0	EOR
Quest	Kanada	2015	Wasserstoffproduktion	1,0	DSF
Century Plant	USA	2010	Erdgasaufbereitung	8,4	EOR
Air Products Steam Methane	USA	2013	Wasserstoffproduktion	1,0	EOR
Coffeyville	USA	2013	Düngerproduktion	1,0	EOR
Lost Cabin	USA	2013	Erdgasaufbereitung	0,9	EOR
Petrobras Lula	Brasilien	2013	Erdgasaufbereitung	0,7	EOR
Uthmaniyah	Saudi-Arabien	2015	Erdgasaufbereitung	0,8	EOR
Abu Dhabi	VAE	2016	Stahlproduktion	0,8	EOR

Biomass + CCTS pilot projects are focussed on EOR-usage



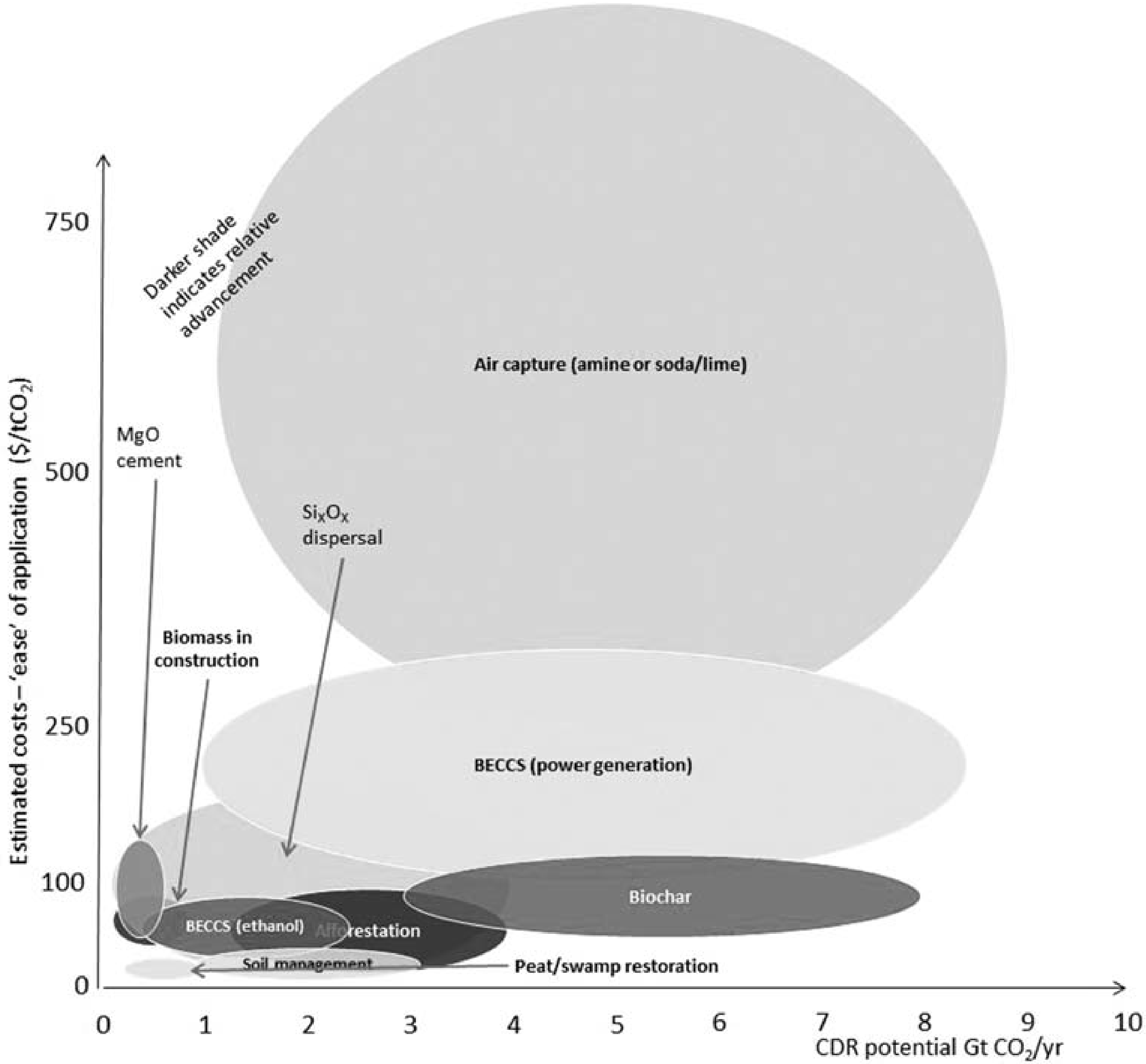
Source: Kemper (2015).

6 potential „negative emission technologies“



Source: Minx et al. (2017)

Estimated costs, CO_2 removal potential and maturity of technology for various CO_2 storage methods



Source: Harrison et al. (2014); darker shades indicate higher maturity.

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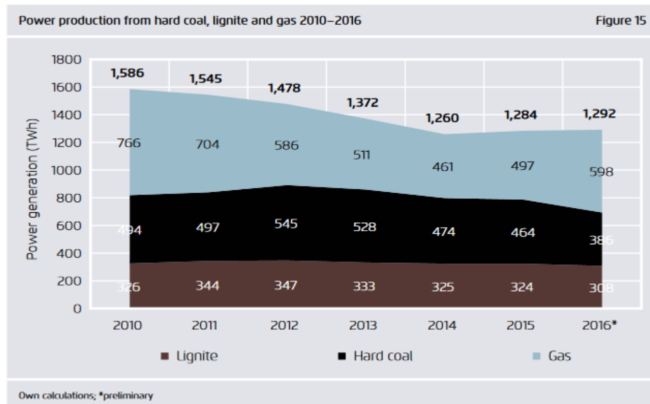

Research Outlook

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Neumann, Anne, and Christian von Hirschhausen: Natural Gas: An Overview of a Lower-Carbon Transformation Fuel. Review of Economic and Environmental Policy (REEP) 9 (2015), Iss. 1, p. 64–84.

Löffler, K. / Hainsch, K. / Burandt, T. / Oei, P. / Kemfert, C. / von Hirschhausen, C. (2017): Designing a Model for the Global Energy System - GENeSYS-MOD: An Application of the Open-Source Energy Modeling System (OSeMOSYS). *Energies 10 (2017), 1-28 .*

Schröder, Andreas, Maximilian Bracke, Clemens Gerbaulet, Roman Mendelevitch, Marco Islam, and Christian von Hirschhausen. 2013. "Current and Prospective Costs of Electricity Generation until 2050." DIW Berlin Data Documentation 68. Berlin, Germany: DIW Berlin, TU Berlin.

von Hirschhausen, Christian, Johannes Herold and Pao-Yu Oei (2013): How a "Low Carbon" Innovation Can Fail - Tales from a "Lost Decade" for Carbon Capture, Transport, and Sequestration (CCTS). EEEP, Vol. 1, No. 2.

von Hirschhausen, Christian (2017): Nuclear Power in the 21st Century – An Assessment (Part I). DIW Berlin Discussion Paper 1700.

Wealer, Ben, et al. (2017): *Nuclear* Energy Policy in the United States: Between Rocks and *Hard Places*. *IAEE* Energy Forum, 18(2), 19-22.

Agenda

1) Introduction

2) The setting for market and policy analysis

3) “Perfect competition”: The natural gas – coal switch

4) Idiosyncracies: Non-fossil fuel technologies: nuclear, renewables, negative emission technologies (NET)

5) Conclusions

4 Main Take-aways

1 **Energy market, policy & technology analysis is “particularly complex“, and makes it difficult to yield generally valid conlusions**

2 **Even the most competitive market segments may yield different outcome in different jurisdictions, i.e. the natural gas – coal switch**

3 **All non-fossil fuel technologies have undergone and are currently undergoing significant „directed technological change“, the outcomes of which are quite idiosyncratic**

4 **Energy economic research of the “energy transformation“ is particularly promising, but also challenging, with no mainstream consensus to be expected**

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2.2 … and so is policy …

- ~ National policies are diverse
  - ~ US – NOPR on "grid stability" (capacity payments for coal and nuclear power)
  - ~ OPEC-countries on fuel subsidies
  - ~ Sweden on CO_2 pricing in transportation
- ~ Regional policies are transaction-cost intensive
- ~ Cross-country and "seams" issues" are complex
  - ~ Legally binding
  - ~ Politically consistent?
- ~ Global policies are important, but difficult to implement
  - ~ Taxation, subsidies, etc.
  - ~ Carbon pricing
  - ~ Issue linking, e.g. with fiscal, social, other policies

2.3 … and technology

Past: Emergence of technologies nationally specific, e.g. gas turbine, nuclear power, solar energy

Present: uncertainty about existing technologies and costs

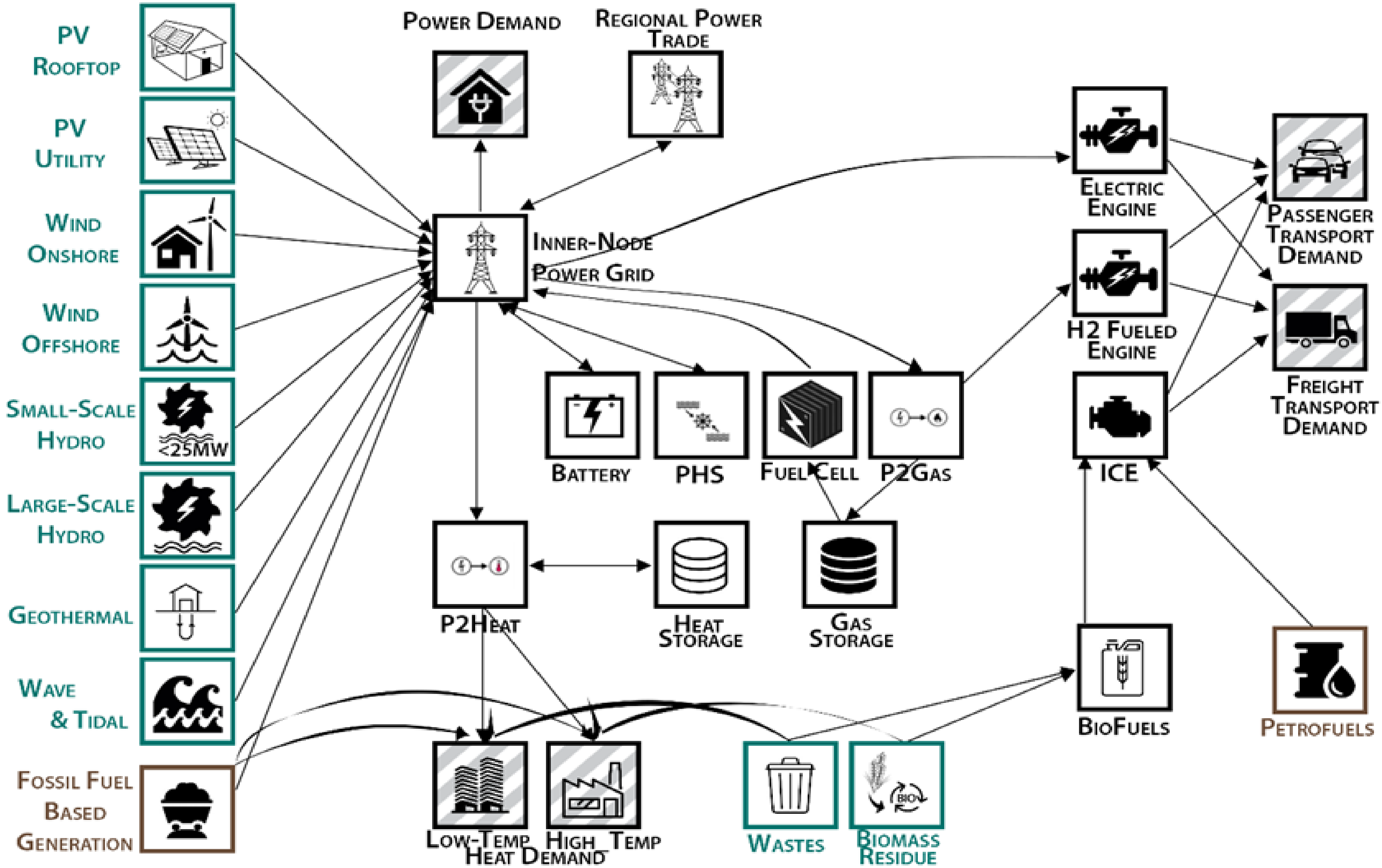
Future: technical and economic availability

~ Fossil technologies, negative emission technologies (NET), etc.

~ “low-carbon” technologies, e.g. nuclear power, renewables, etc.

~ Auxiliary technologies, e.g. storage

Technological convergence: “sector coupling“



Technology is political, too …

- Traditionally, energy system model predictions in line with ambitious climate targets relied on fossil fueled power plants equipped with carbon capture and nuclear plants to balance intermittent renewables energy sources.
- The future outlook for conventional energy carriers, however, is now challenged by the availability of low-cost storage technologies and other flexibility options.
- This leads to the recent controversy about the reliability of renewables-based energy:
  - Critical evaluation by Clack et al. (2017):

PNAS

Evaluation of a proposal for reliable low-cost grid power with 100% wind, water, and solar

Christopher T. M. Clack[a,b,1,2], Staffan A. Qvist[c], Jay Apt[d,e], Morgan Bazilian[f], Adam R. Brandt[g], Ken Caldeira[h], Steven J. Davis[i], Victor Diakov[j], Mark A. Handschy[b,k], Paul D. H. Hines[l], Paulina Jaramillo[d], Daniel M. Kammen[m,n,o], Jane C. S. Long[p,3], M. Granger Morgan[d], Adam Reed[q], Varun Sivaram[r], James Sweeney[s,t], George R. Tynan[u], David G. Victor[v,w], John P. Weyant[s,t], and Jay F. Whitacre[d]

[a]Earth System Research Laboratory, National Oceanic and Atmospheric Administration, Boulder, CO 80305; [b]Cooperative Institute for Research in Environmental Sciences, University of Colorado, Boulder, CO 80305; [c]Department of Physics and Astronomy, Uppsala University, 752 37 Uppsala, Sweden; [d]Department of Engineering and Public Policy, Carnegie Mellon University, Pittsburgh, PA 15213; [e]Tepper School of Business, Carnegie Mellon University,

  - Direct defense by Jacobsen et al. (2017):

PNAS

The United States can keep the grid stable at low cost with 100% clean, renewable energy in all sectors despite inaccurate claims

Mark Z. Jacobson[a,1], Mark A. Delucchi[b], Mary A. Cameron[a], and Bethany A. Frew[a]

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3.1 The natural gas – coal switch = f(…)

Invest CAPEX

Efficiency and operations (OPEX)

Relative fuel prices

Environmental constraints, e.g. CO_2, local pollutants, etc.

Taxes & subsidies

…

„Golden age“ of natural gas?
Previous Forecasts (IEA “Golden Age”, 2012, 78)

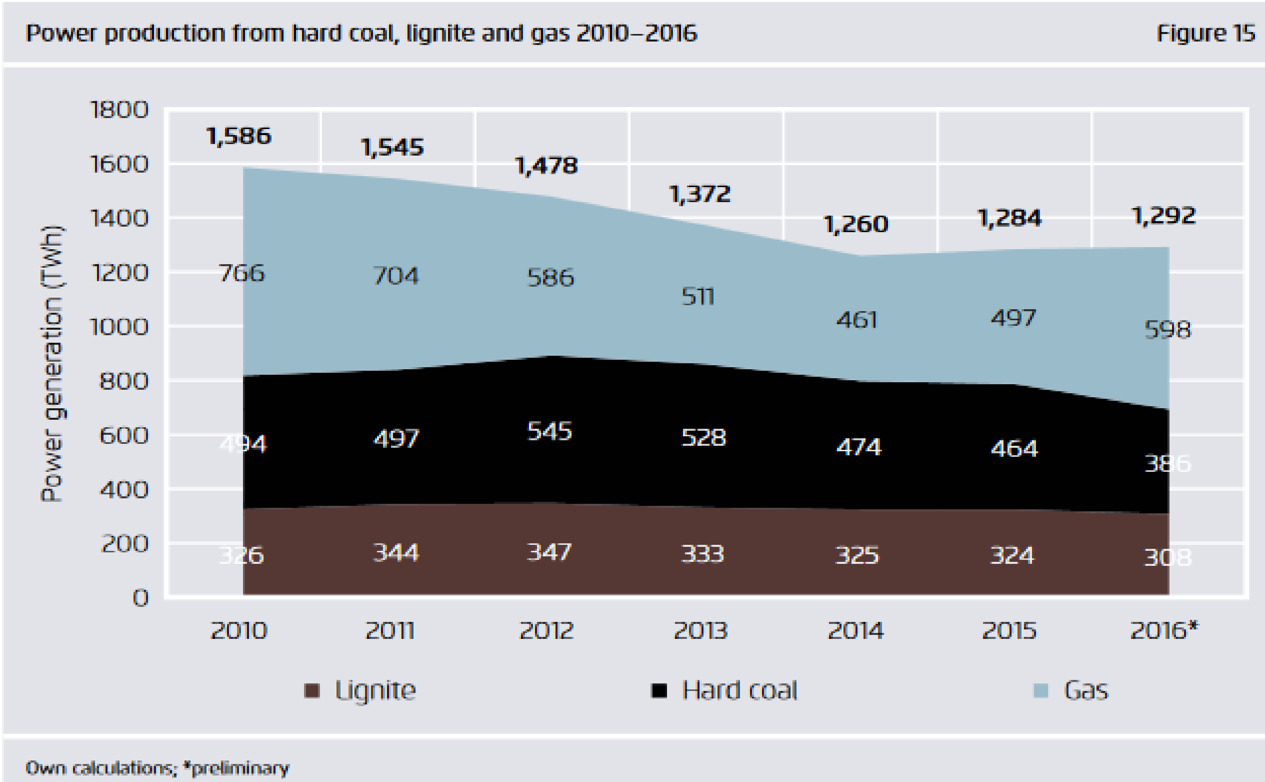
Natural gas demand by region in the Golden Rules Case (bcm)

Table 2.4 ▷ **Natural gas demand by region in the Golden Rules Case** (bcm)

	2010	2020	2035	2010-2035*
OECD	**1 601**	**1 756**	**1 982**	**0.9%**
Americas	841	921	1 051	0.9%
United States	*680*	*717*	*787*	*0.6%*
Europe	579	626	692	0.7%
Asia Oceania	180	209	239	1.1%
Japan	*104*	*130*	*137*	*1.1%*
Non-OECD	**1 670**	**2 225**	**3 130**	**2.5%**
E. Europe/Eurasia	662	736	872	1.1%
Russia	*448*	*486*	*560*	*0.9%*
Asia	398	705	1 199	4.5%
China	*110*	*323*	*593*	*7.0%*
India	*63*	*100*	*201*	*4.7%*
Middle East	365	453	641	2.3%
Africa	101	130	166	2.0%
Latin America	144	200	252	2.3%
World	**3 271**	**3 982**	**5 112**	**1.8%**
European Union	*547*	*592*	*644*	*0.7%*

* Compound average annual growth rate

3.2 Country-specific analyses: The EU context

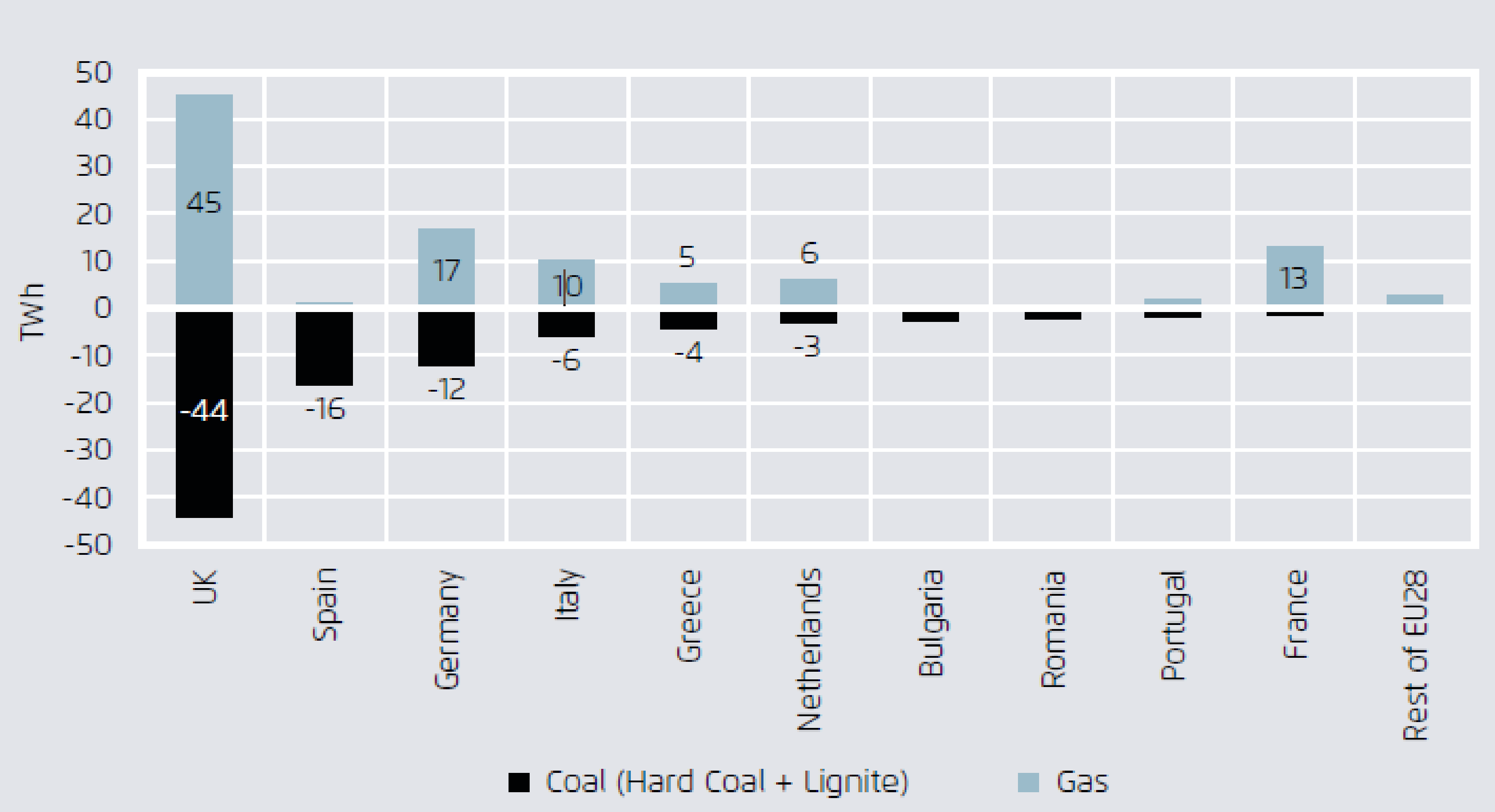


- EU coal generation fell by 94 TWh (-12%) and gas generation increased by 101 TWh (20%)
- Half of this happened in the UK, but also Germany, Italy, Netherlands and Greece switched from coal to gas
- Gas generation still 168 TWh below the 2010 level (more coal-gas switching is possible without new infrastructure.

https://sandbag.org.uk/wp-content/uploads/2017/01/Energy-Transition-in-the-Power-Sector-in-Europe-2016.pdf

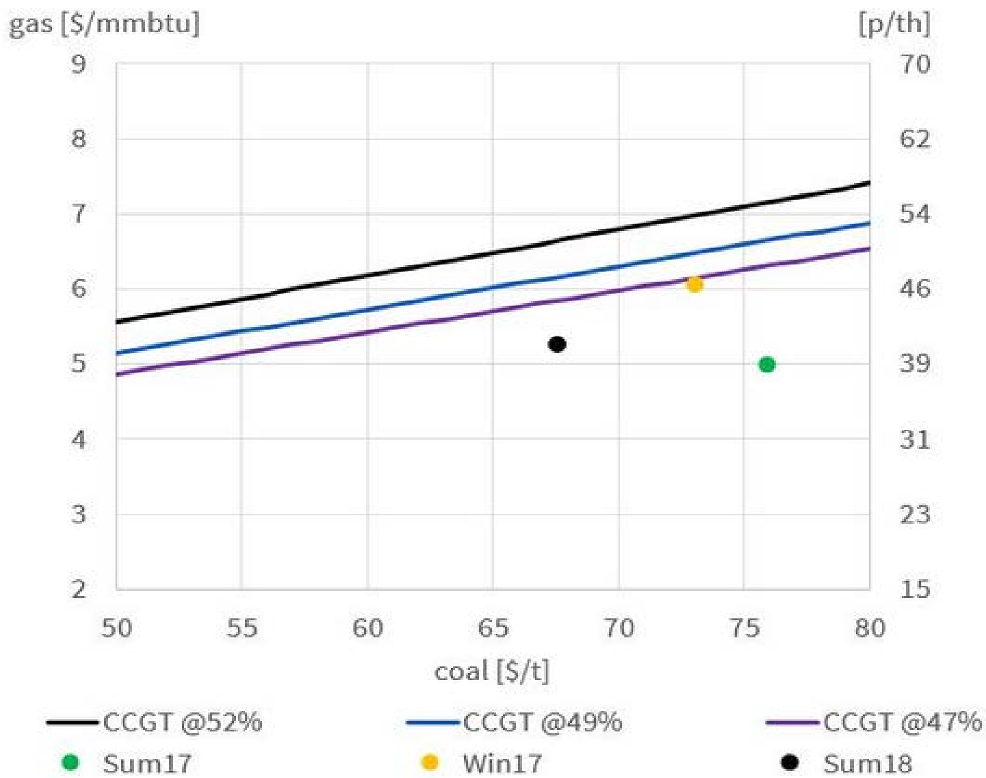
EU-wide coal to gas shift or UK phenomenon?

Changes in power generation of gas and coal from 2015 to 2016 — Figure 19



https://sandbag.org.uk/wp-content/uploads/2017/01/Energy-Transition-in-the-Power-Sector-in-Europe-2016.pdf

Economics of the Coal-Gas Switch UK



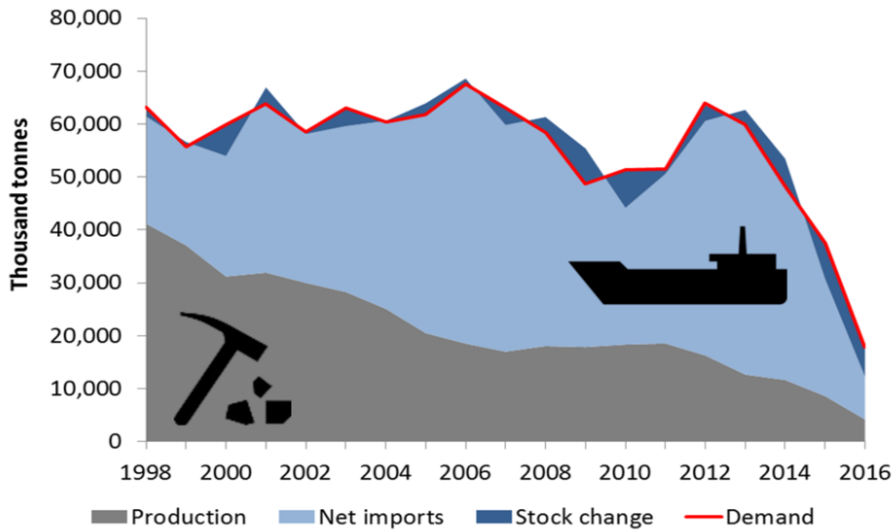
Source: Timera Energy (coal plant 36% HHV efficiency)

Source: https://www.timera-energy.com/european-gas-for-coal-switching-boundaries-in-2017/

Competitiveness of Gas with Coal in Power Generation

- UK first European market to switch: Gap between coal and gas marginal costs is narrower due to the ***carbon price floor (UKP 18/t)***.
- Further gas price falls will push more CCGTs into merit order for longer periods: Higher load factors and margin capture increase and running costs decrease.
- CCGTs have a structural variable cost advantage over coal in the UK (more pronounced in summer (lower gas prices)
- Colored dots represent different combinations of gas and coal prices for seasonal forward contracts; diagonal lines show the baseload switching boundaries for CCGT plants of different efficiencies; dots below the diagonal switching lines mean market prices favor gas burn

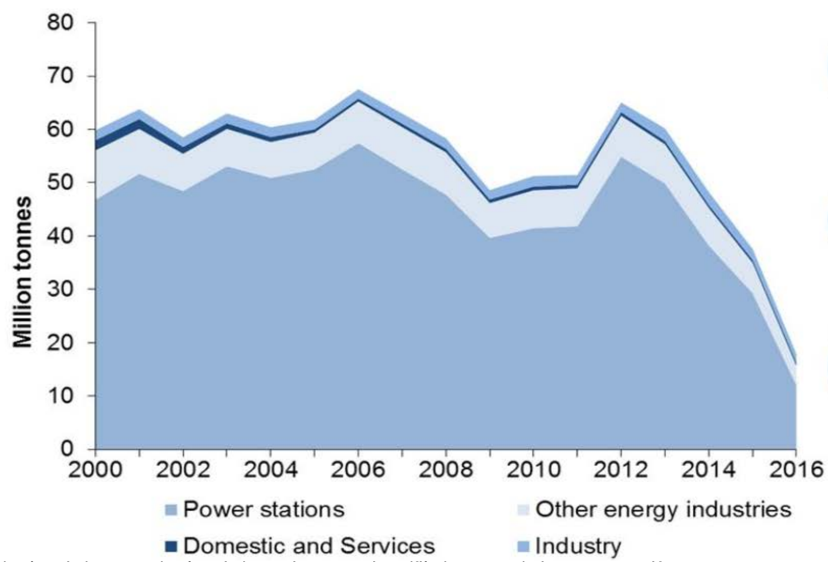
UK coal demand and supply



UK coal production fell to a tenth of 1998 production

Imports filled the gap until demand dropped from 2013

Demand in 2016 was just over a quarter of 1998 demand



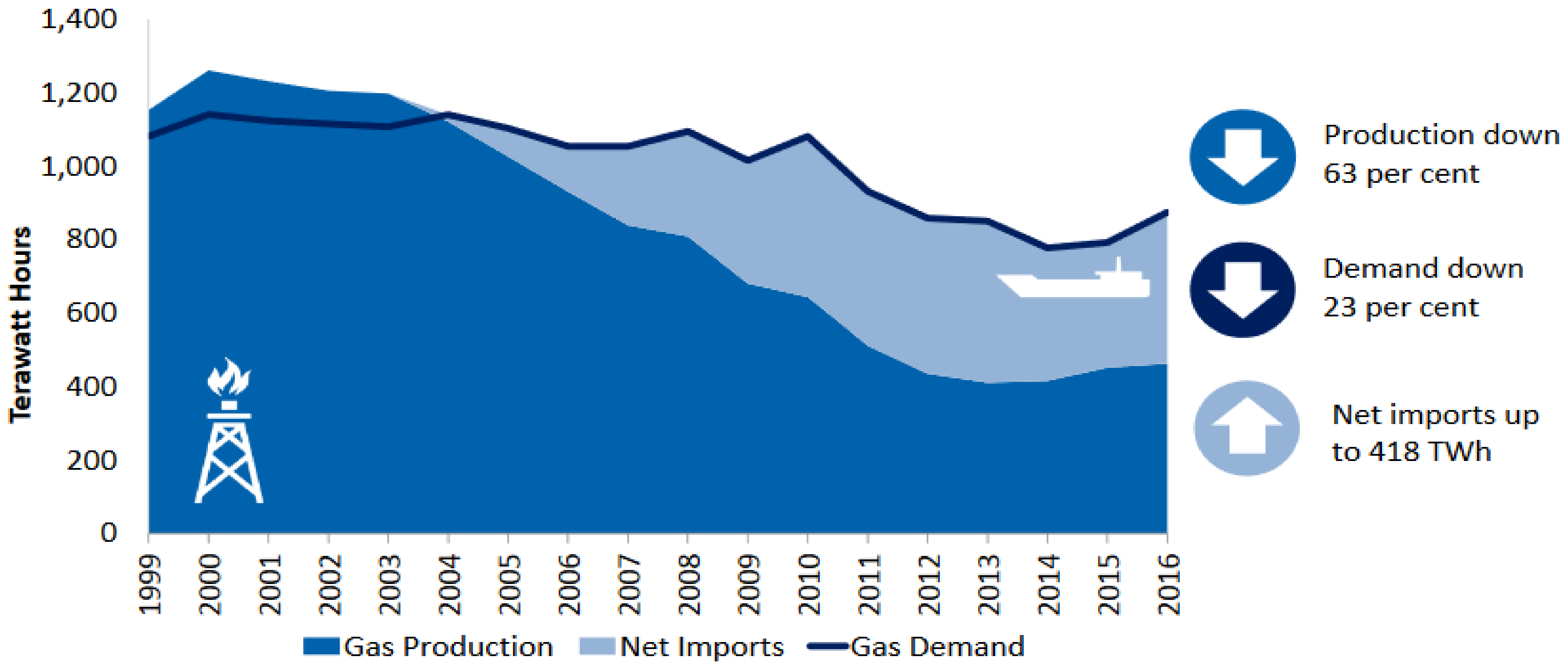
Total consumption down 42 million tonnes since 2000

Power station consumption fell to a quarter of 2000's figure

Domestic use down 70% since 2000

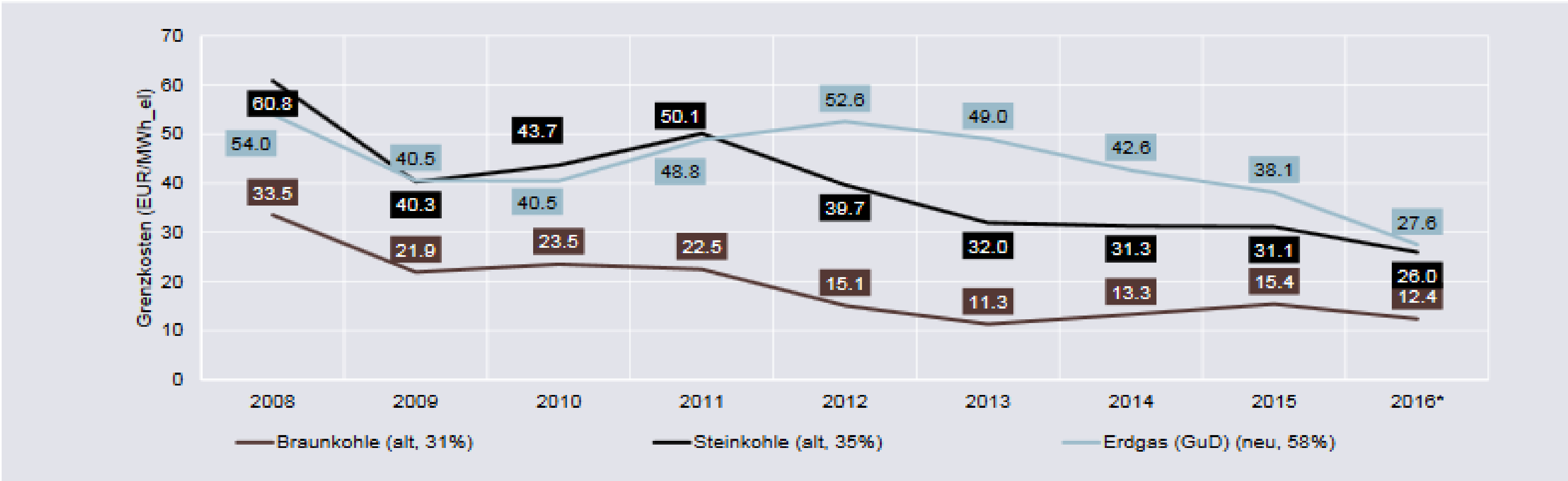
https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/632495/Chapter_2.pdf

Natural gas production and demand



https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/632523/Chapter_4.pdf

Germany: low-cost coal blocks natural gas



BAFA 2016a, BAFA 2016b, DEHSt 2016, EEA 2015, Lazard 2015, Statistisches Bundesamt 2015, UBA 2015, eigene Berechnungen

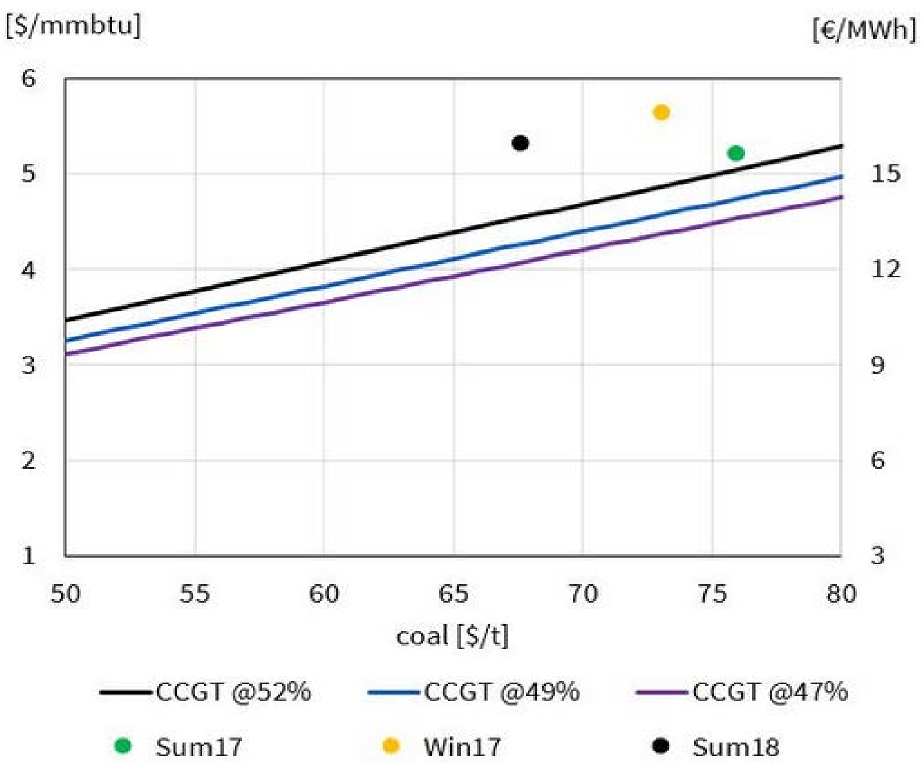
Marginal costs for new gas and old lignite as well as hard coal power plants (Efficiency in brackets)

Competitiveness of Gas with Coal in Power Generation

- For the first time since 2011 gas-fired power plants were competitive to old hard coal power plants
- Gas prices dropped further than hard coal prices
- Shift despite low CO_2 prices???

https://www.agora-energiewende.de/fileadmin/Projekte/2017/Jahresauswertung_2016/Die_Energiewende_im_Stromsektor_2016_DE.pdf

Economics of the Coal-Gas Switch in Germany: Natural gas hardly competitive



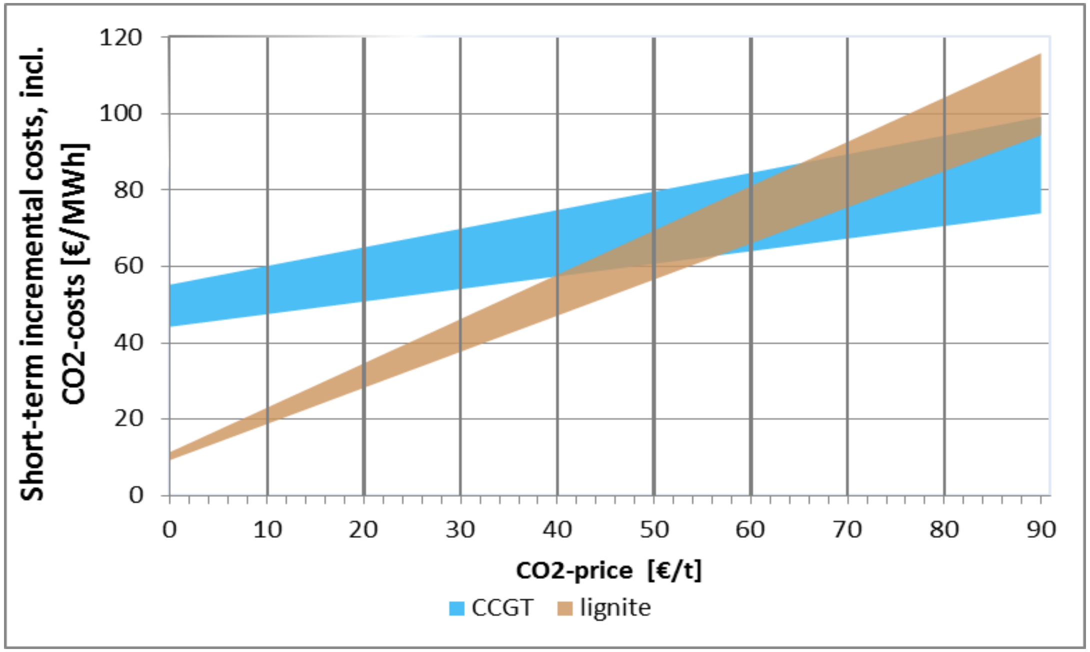
Source: Timera Energy (coal plant 36% HHV efficiency)

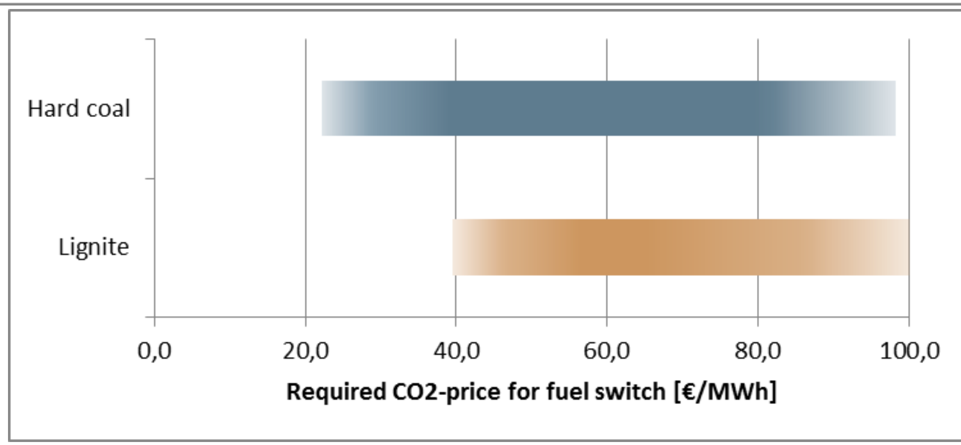
Competitiveness of Gas with Coal in Power Generation

- Lowest power prices of the major European power markets (excluding the hydro dominated Nordpool markets): Relatively low variable cost lignite capacity and high renewable penetration; CCGTs have been structurally out of merit for most of the last five years.
- Colored dots represent different combinations of gas and coal prices for seasonal forward contracts; diagonal lines show the baseload switching boundaries for CCGT plants of different efficiencies; dots below the diagonal switching lines mean market prices favor gas burn

Source: https://www.timera-energy.com/european-gas-for-coal-switching-boundaries-in-2017/

Only a CO_2 price well above >40€/t would lead to a lignite to gas switch

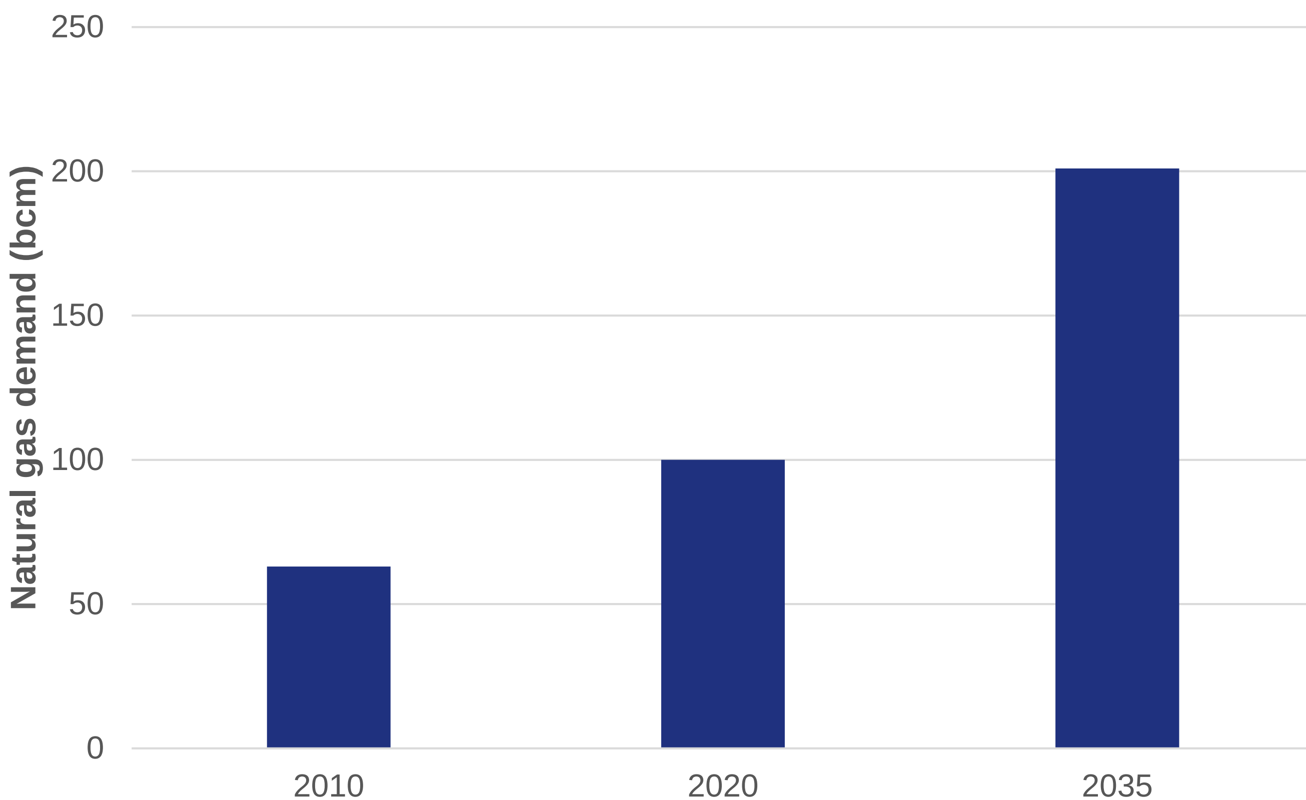




https://www.diw.de/documents/publikationen/73/diw_01.c.471589.de/diwkompakt_2014-084.pdf

India:
Previous Forecasts ("Golden Age")

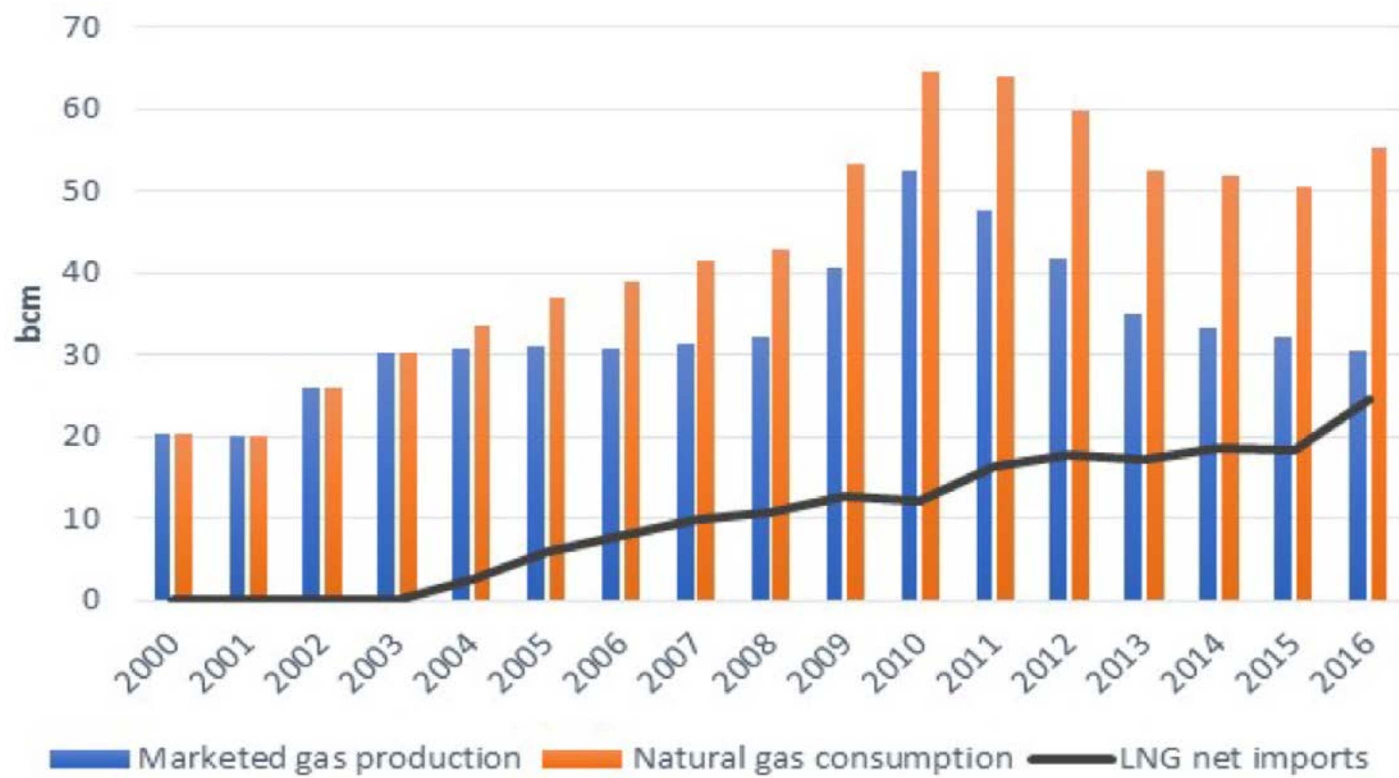
Natural gas demand by region in the Golden Rules Case (bcm)



Source: Own Illustration based on IEA (2012, 78, see table 2.4).

Gas Production, Consumption and Imports

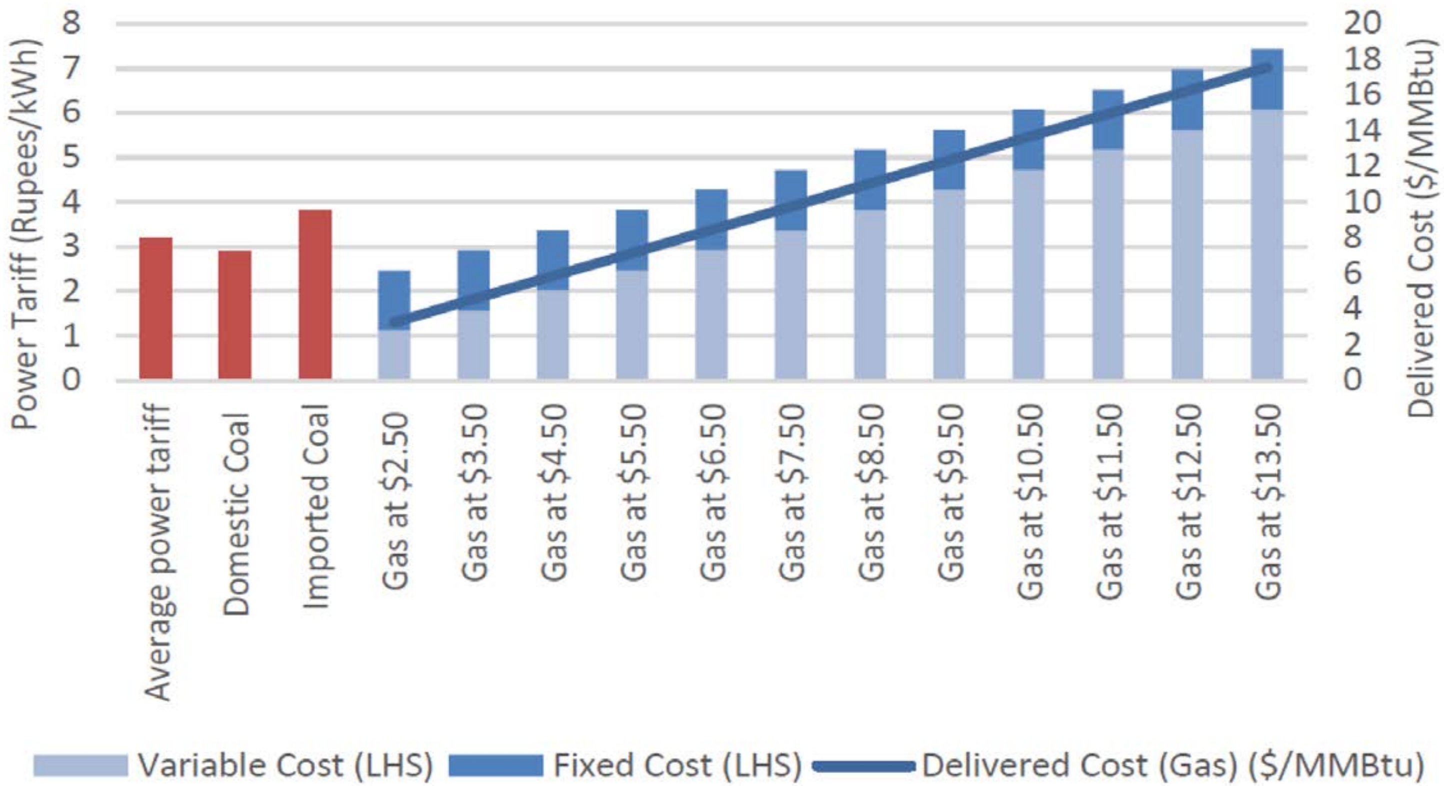
Natural gas production, consumption and LNG imports in India (2000-2016)



Source: Cornot-Gandolphe (2017, 7)

Economics of the Coal-Gas Switch

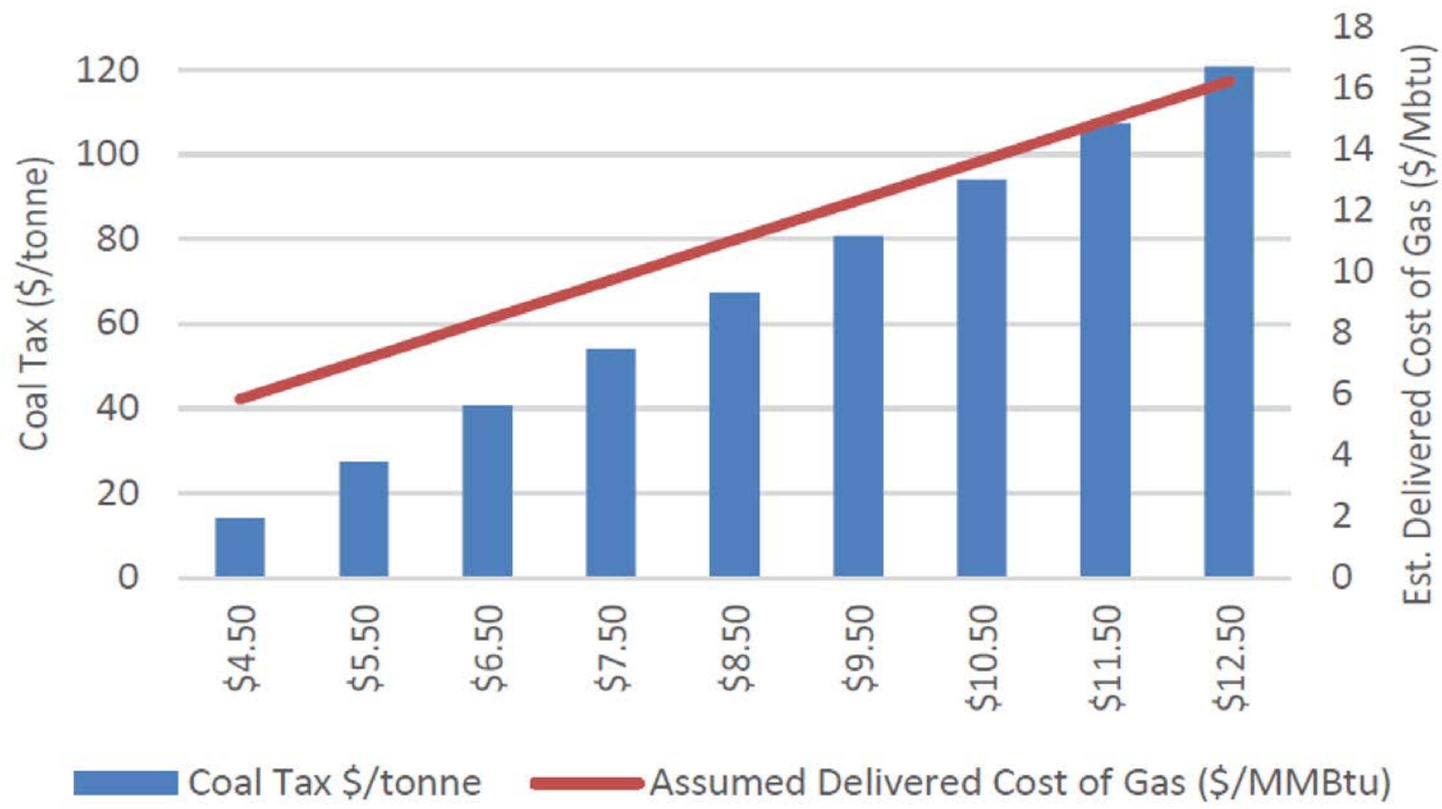
Competitiveness of Gas with Coal in Power Generation



Source: Sen (2017, 11)

Economics of the Coal-Gas Switch

Fiscal Measures to Encourage Coal to Gas Switching (author's estimates)



Source: Sen (2017, 16)

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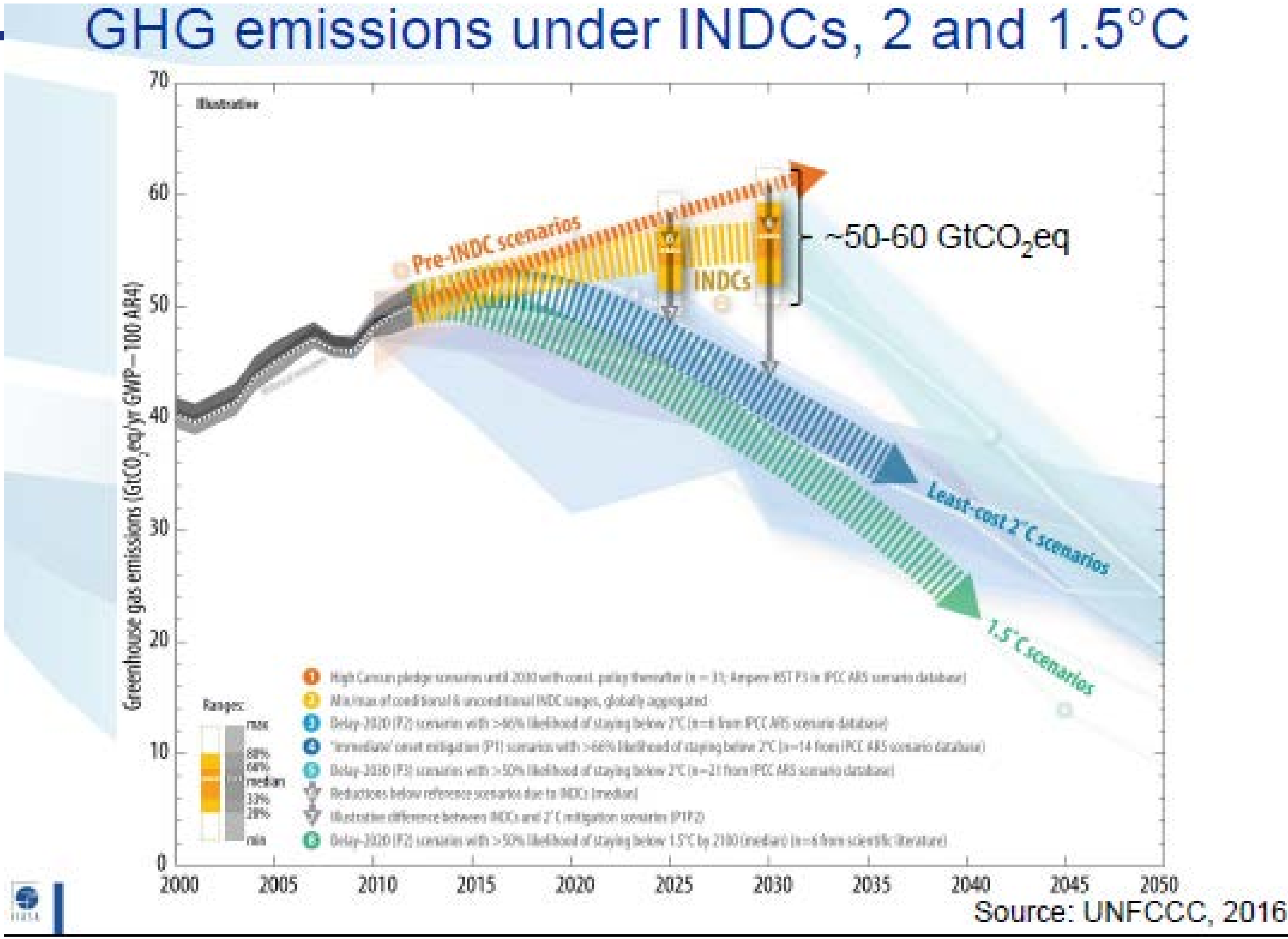
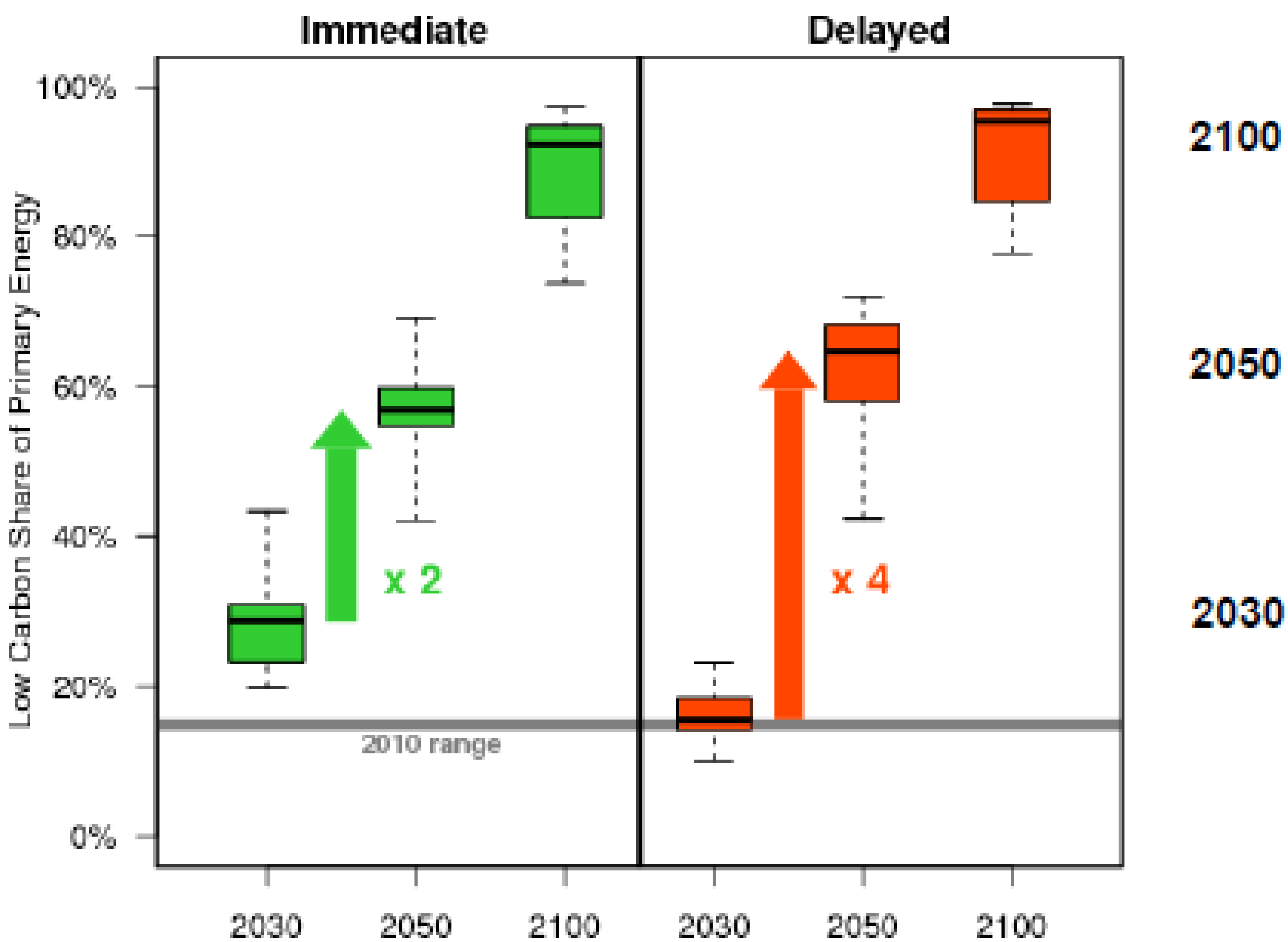
Paris Agreement



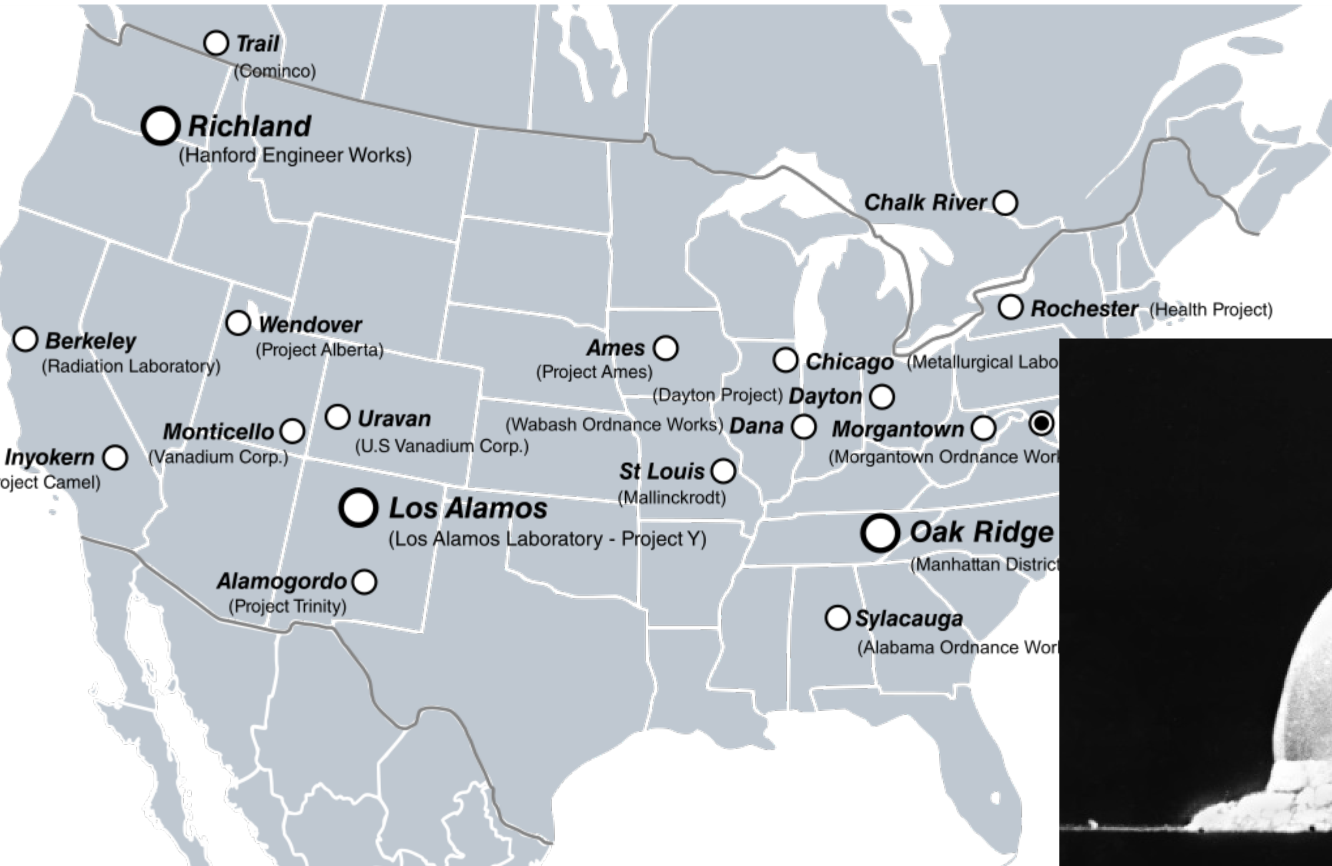
Contribution of Low-Carbon Energy
(Renewables, nuclear & fossil fuels with CCS)

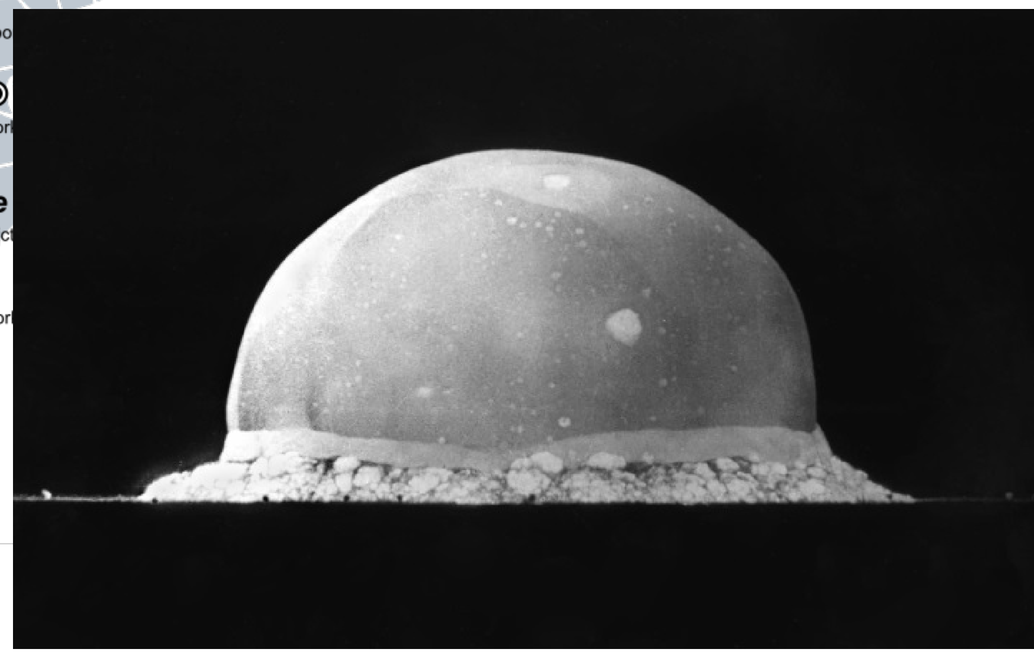


Source: Riahi et al. (2015)

3.1 Nuclear power
Science … and military, but litte economic considerations

Manhattan Project: 1942-1946: General Groves + Professor Oppenheimer (Lévêque, 2012, Jaensch and Herrmann, 2015)





First nuclear bomb: Trinity-Test, July 16, 1945

Davis (2012; JEP, p. 11): „70 years later …"

Table 3

Levelized Cost Comparison for Electricity Generation

	Levelized cost in cents per kWh		
Source	*Nuclear*	*Coal*	*Natural gas*
MIT (2009) baseline	8.7	6.5	6.7
Updated construction costs	10.4	7.0	6.9
Updated construction costs and fuel prices	10.5	7.4	5.2
With carbon tax of $25 per ton CO_2	10.5	9.6	6.2

Source: These calculations follow MIT (2009) except where indicated in the row headings.
Notes: All costs are reported in 2010 cents per kilowatt hour. Row 1 reports the base case estimates reported in MIT (2009), table 1. The cost estimates reported in row 2 incorporate updated construction cost estimates from U.S. Department of Energy (2010). Row 3, in addition, updates fuel prices to reflect the most recent available prices for uranium, coal, and natural gas reported in U.S. DOE (2011a). Finally, row 4 continues to incorporate updated construction costs and fuel prices and, in addition, adds a carbon tax of $25 per ton of carbon dioxide.

Nuclear power – profitability check

General assumptions:

- **Investment**
  - Overnight cost: 6.000 €/kW
  - Installed capacity: 1.100 MW
  - Initial investment: 20 years
  - Plant lifetime: 50 years
- **Fixed and variable costs**
  - Fixed operating costs:
    - Operation 20 €/kW/year
    - Maintenance 20 €/kW/year
    - Insurance 15 €/kW/year
  - Variable operating costs:
    - Operation 8 €/MWhel
    - Maintenance 7 €/MWhel
  - Fuel price: 1,5 €/MWhth
  - Electric efficiency: 38%
  - Full load Hours: 6.500 h

Calculation results:

- **Nuclear power is more expensive than competing technologies**
  - **Levelized cost of electricity generation:**
    - **10,2 cent/kWh**

$$\mathrm{NPV}(i, N) = \sum_{t=0}^{N} \frac{R_t}{(1+i)^t}$$

- **Assumed electricity retail price:**
  - **40 €/MWh**
- **Net present value very negative:**
  - **–13 bn €**
  - **To reach NPV = 0:**
  - **Retail price: ~100€/MWh**

Davis (2012; JEP, p. 11): „70 years later …“ current update for Europe (own calc.)

Table 3

Levelized Cost Comparison for Electricity Generation

Source	*Levelized cost in cents per kWh*		
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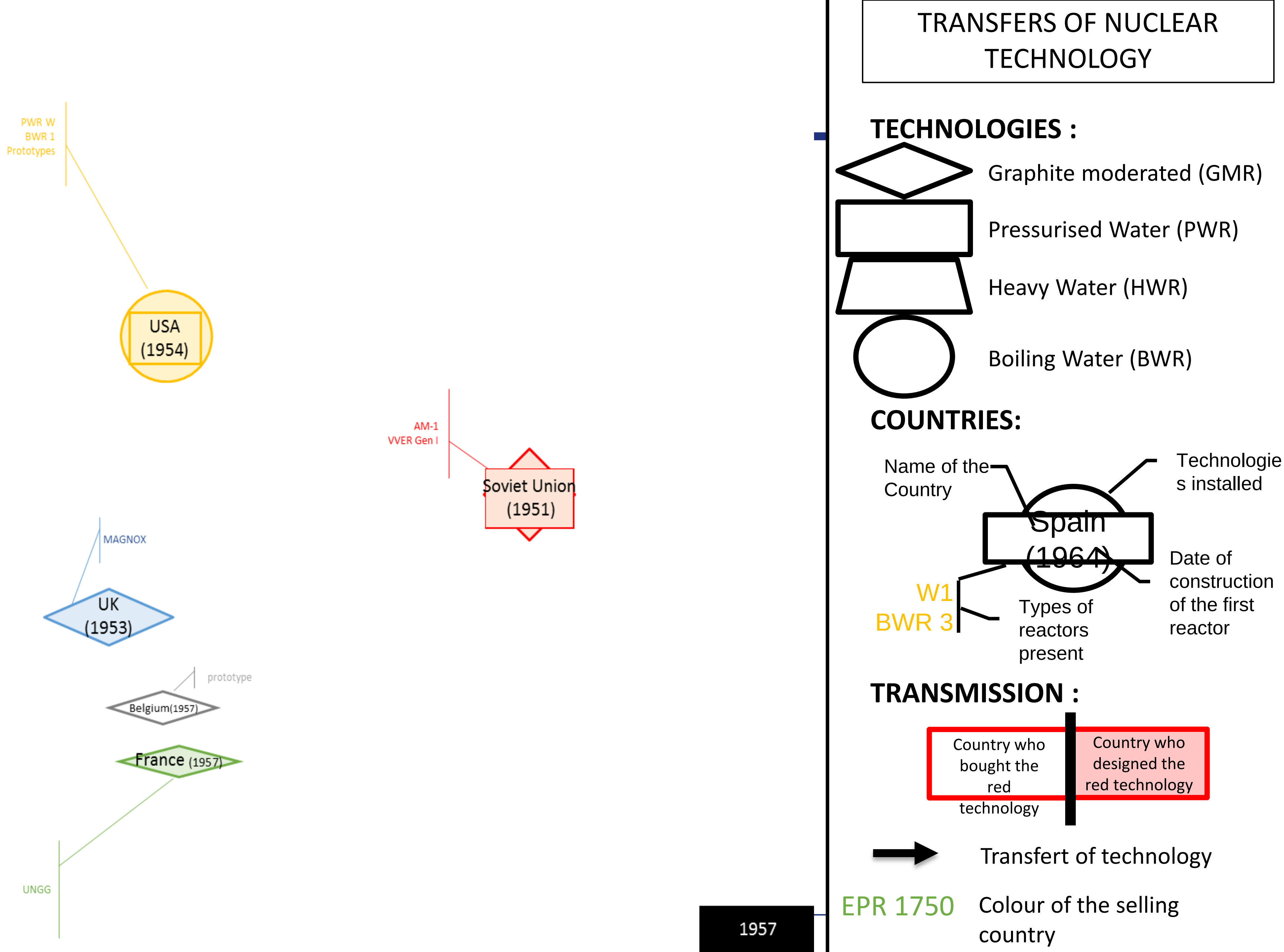
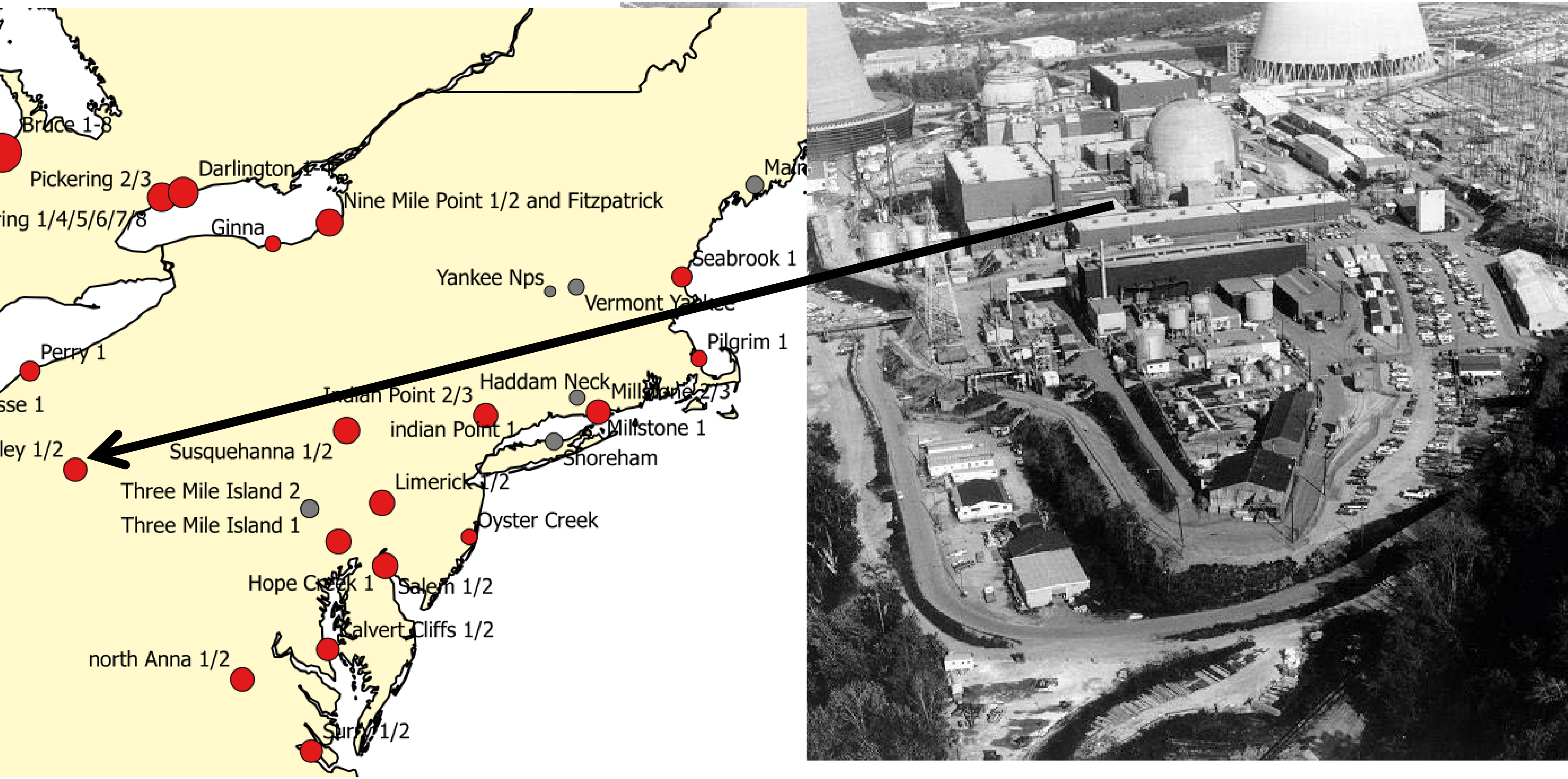
With carbon tax of $25 per ton CO_2	10.5	9.6	6.2

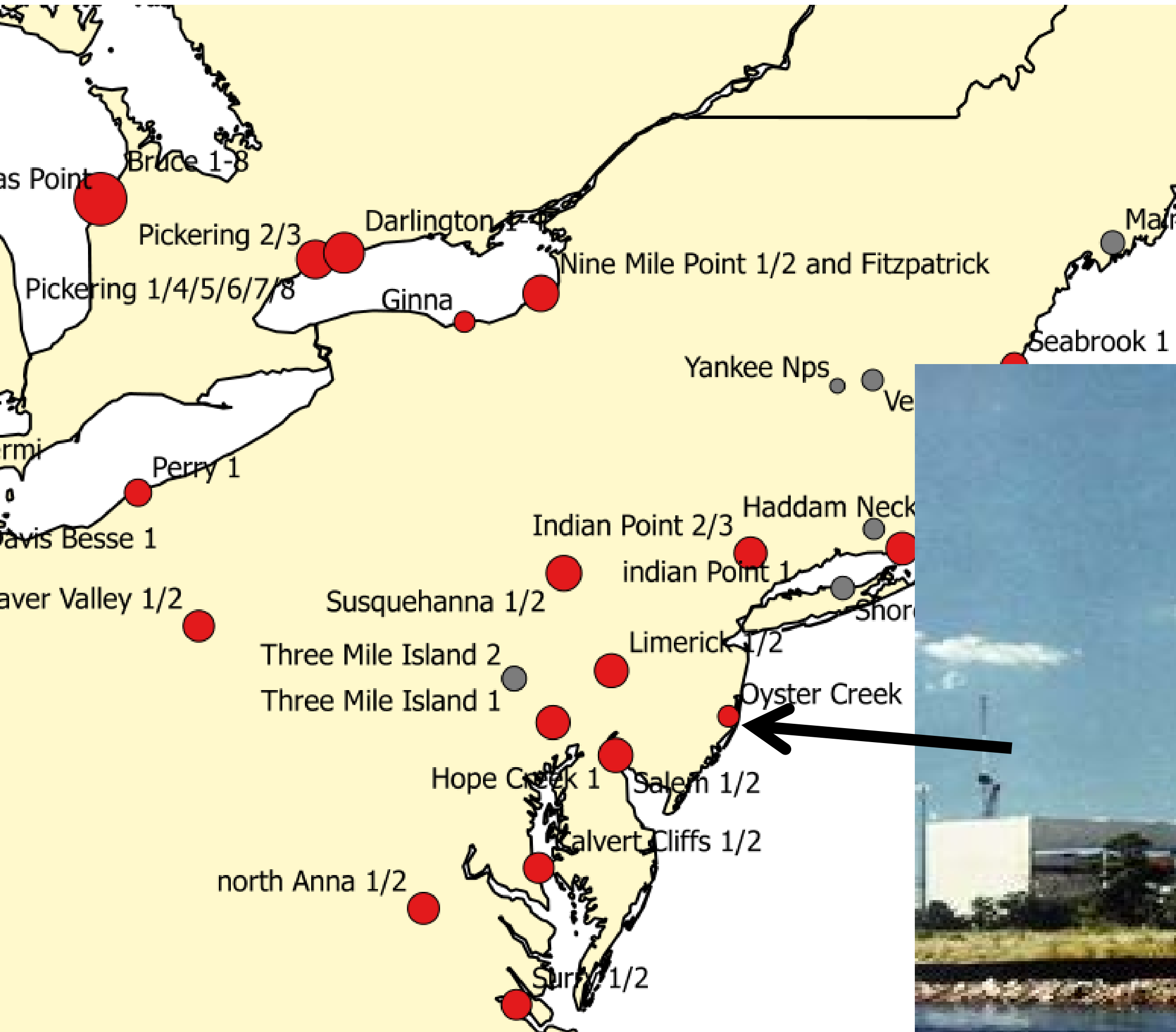
	Levelized costs in €cents/kWh		
	Nuclear	Coal	Natural Gas
Baseline (2016)	10,2	5,1	5,0
CO_2-price: 25 €/t	10,2	6,3	5,7
CO_2-price: 100 €/t	10,2	10,0	7,9

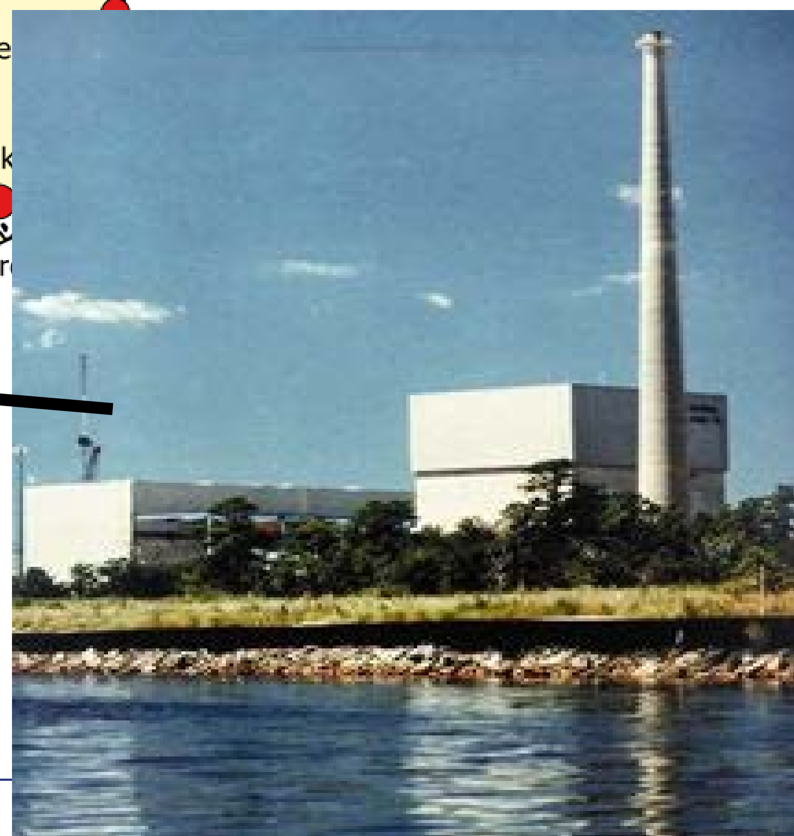

TRANSFERS OF NUCLEAR TECHNOLOGY
TECHNOLOGIES :
Graphite moderated (GMR)
Pressurised Water (PWR)
Heavy Water (HWR)
Boiling Water (BWR)
COUNTRIES:
Name of the Country
Technologies installed
Spain (1964)
Date of construction of the first reactor
W1
BWR 3
Types of reactors present
TRANSMISSION :
Country who bought the red technology
Country who designed the red technology
Transfert of technology
EPR 1750
Colour of the selling country
PWR W
BWR 1
Prototypes
USA (1954)
AM-1
VVER Gen I
Soviet Union (1951)
MAGNOX
UK (1953)
prototype
Belgium(1957)
France (1957)
UNGG
1957

II: $C_{O\text{-}LR}$: in historic retrospect: Shippingport (first „demonstrator“) huge cost overruns: (~ 8 times the costs of a coal plant) (Radkau, 1986)



Oyster Creek: First “commercial“ NPP (1962)

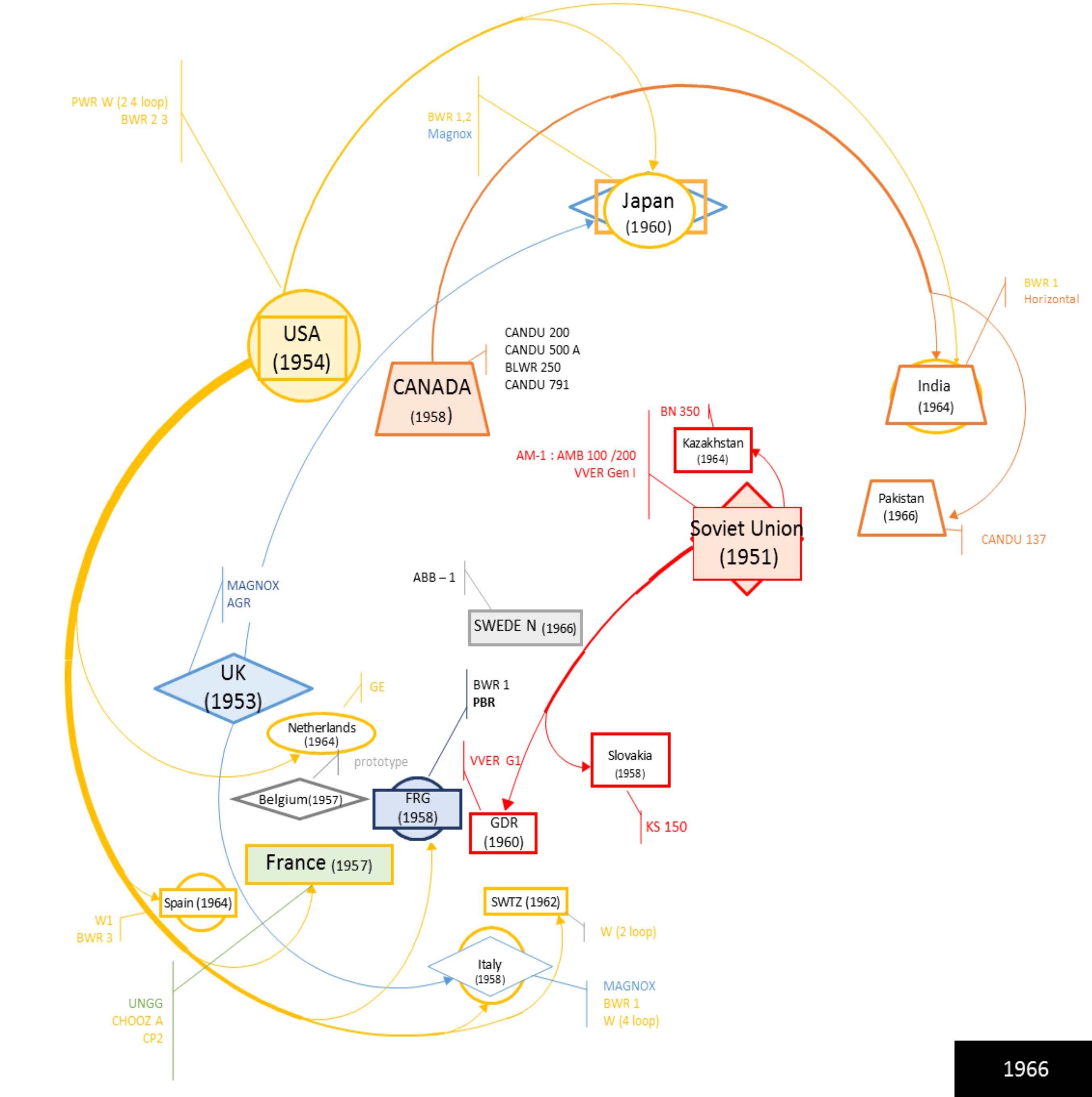


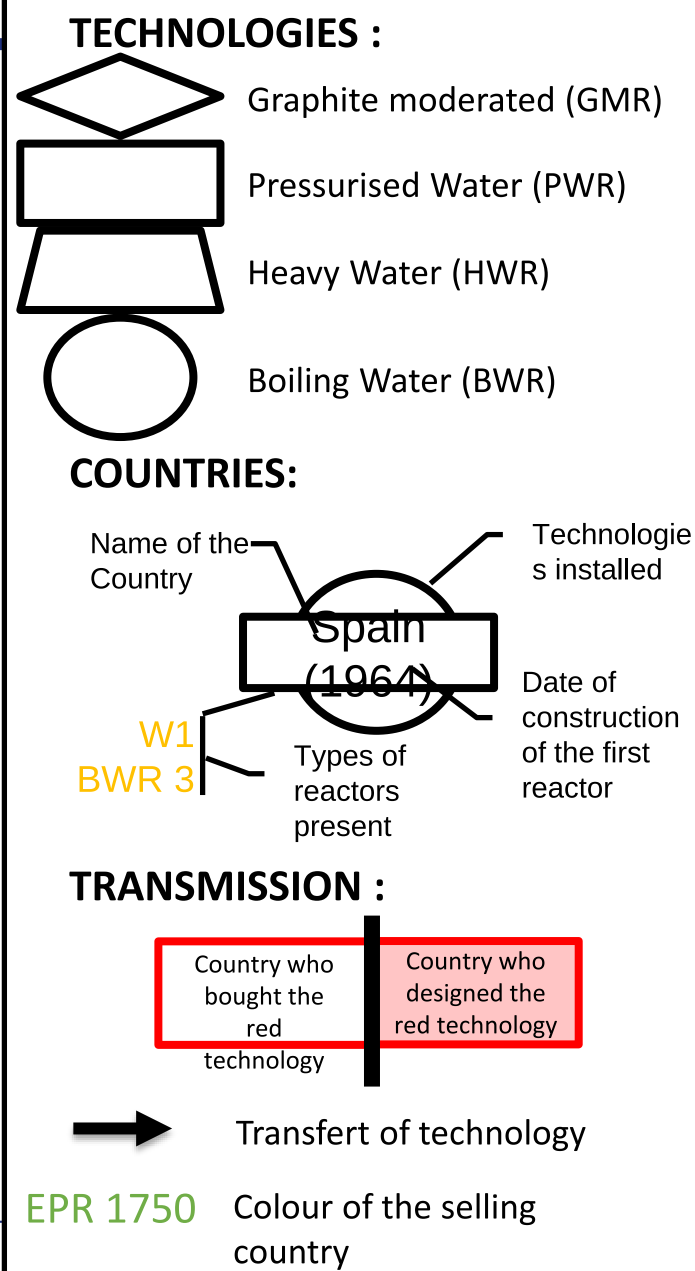


~ **Cost-of-service regulation**

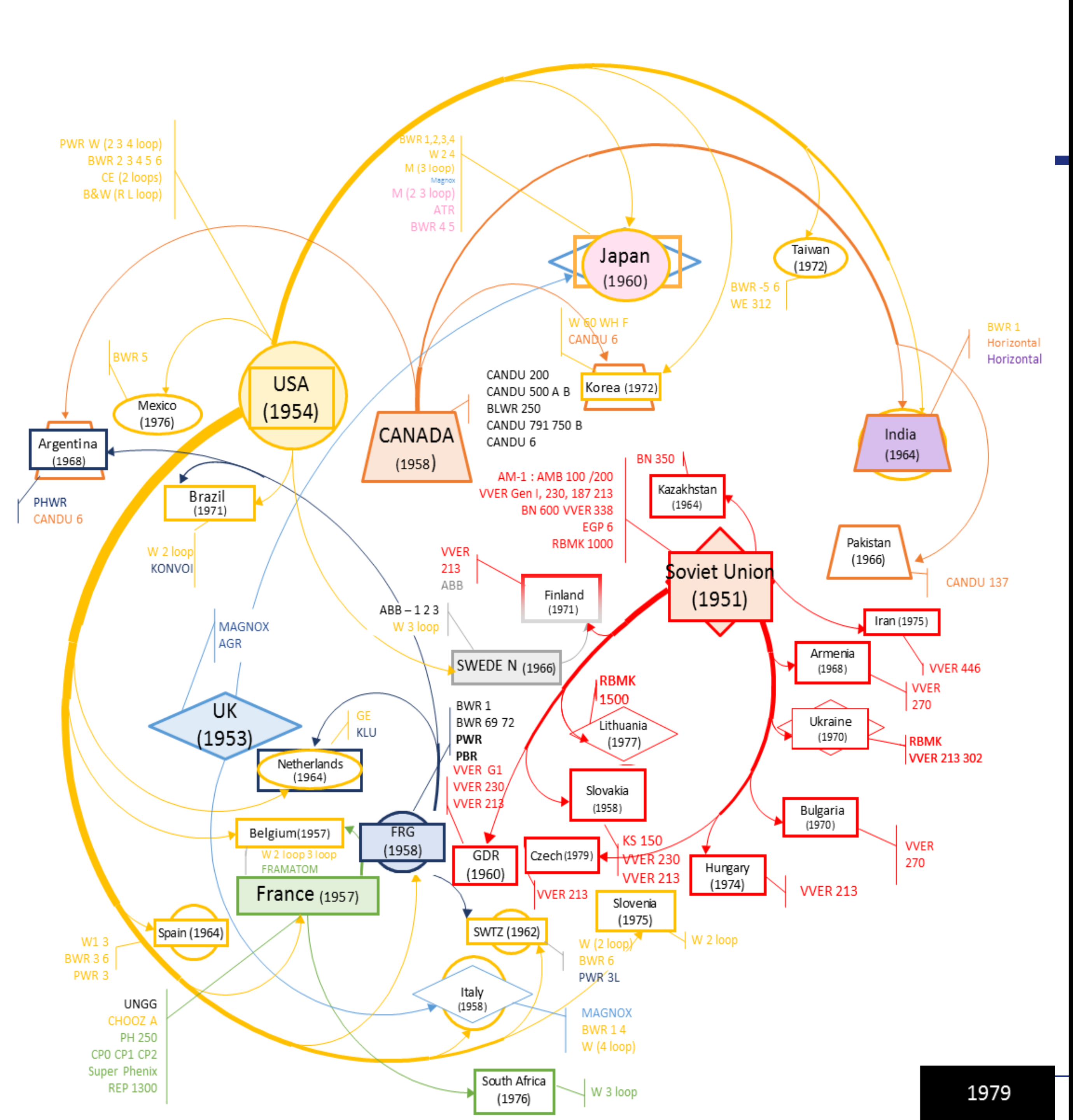
~ **Regulated utility (no risk)**

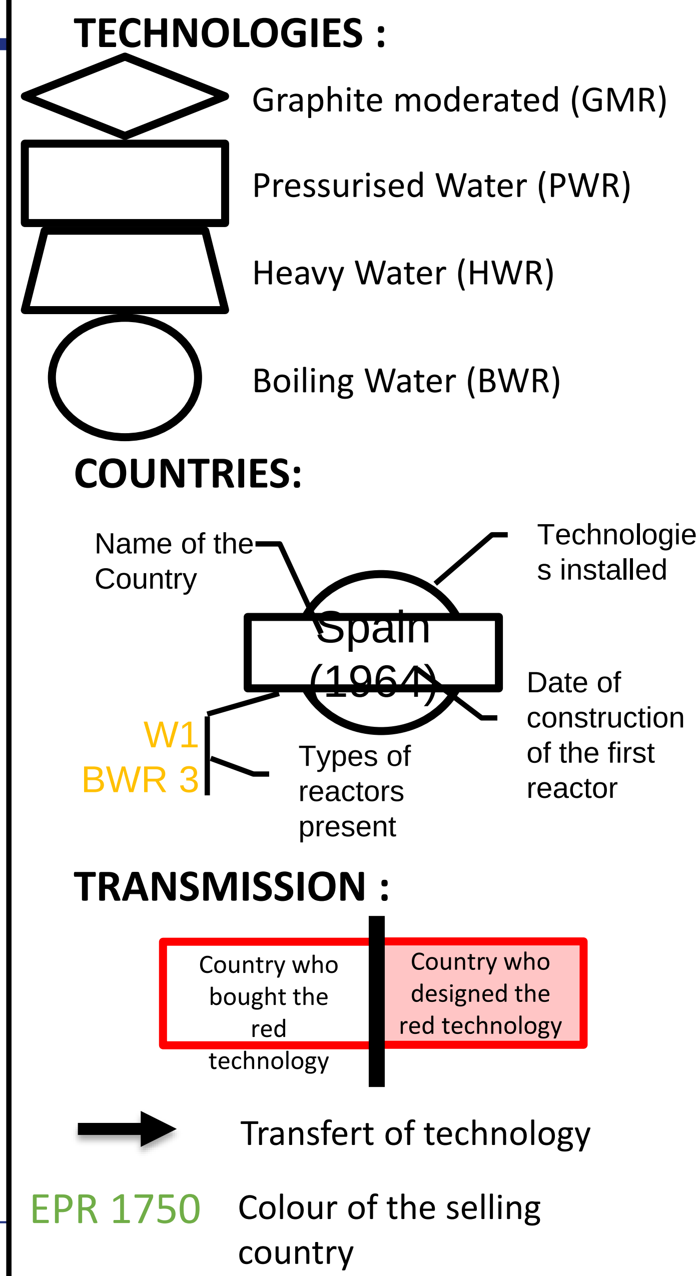
TRANSFERS OF NUCLEAR TECHNOLOGY

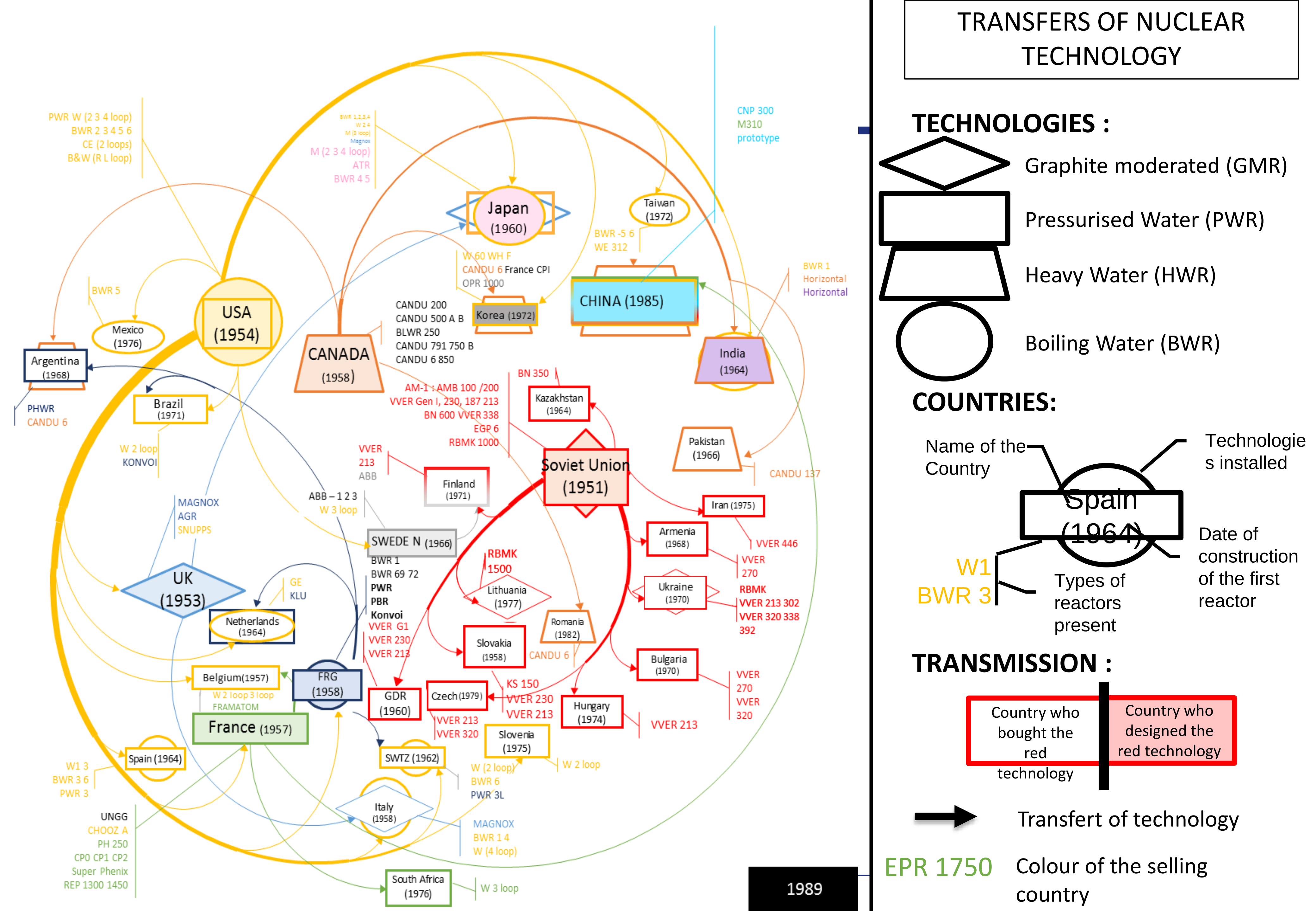




TRANSFERS OF NUCLEAR TECHNOLOGY







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Country who bought the red technology
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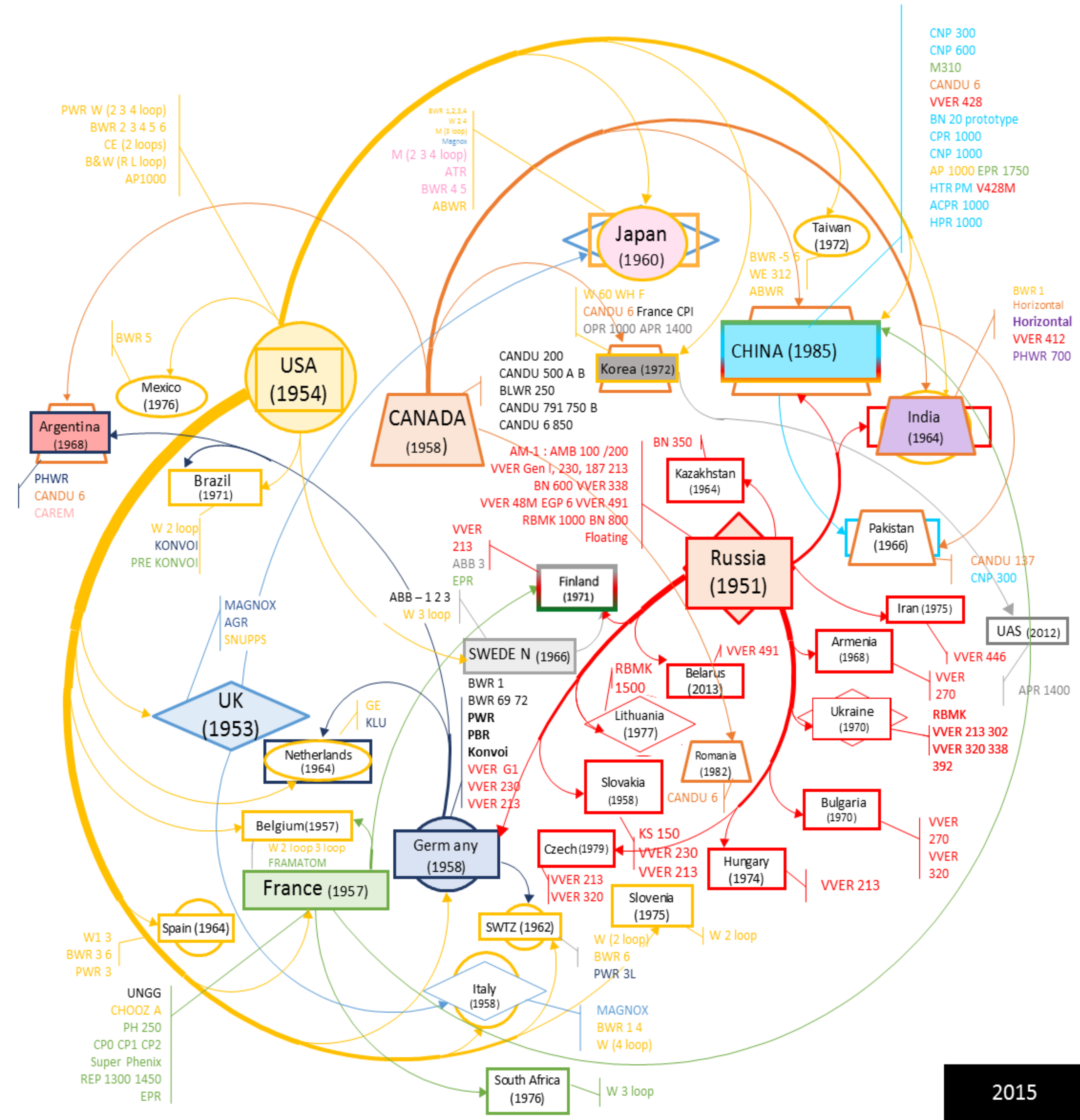
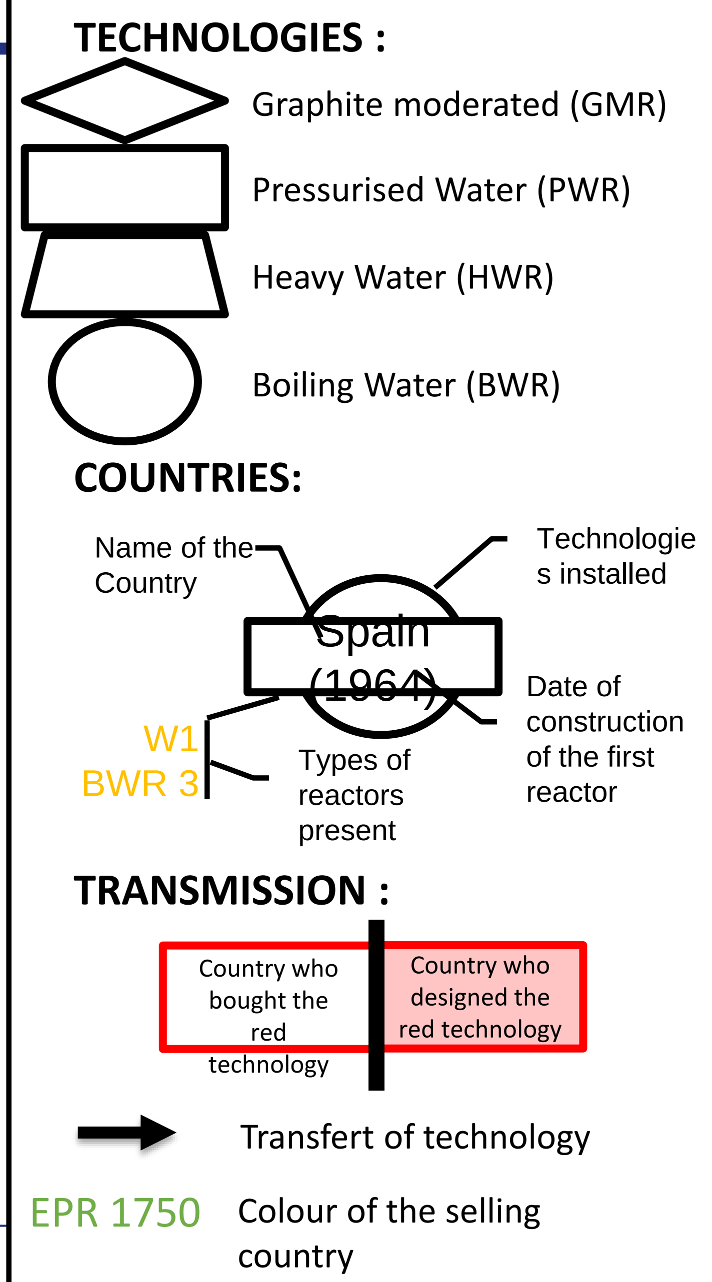
Transfert of technology
EPR 1750
Colour of the selling country
USA (1954)
PWR W (2 3 4 loop)
BWR 2 3 4 5 6
CE (2 loops)
B&W (R L loop)
CANADA (1958)
CANDU 200
CANDU 500 A B
BLWR 250
CANDU 791 750 B
CANDU 6 850
Japan (1960)
M (2 3 4 loop)
ATR
BWR 4 5
W 60 WH F
CANDU 6 France CPI
OPR 1000
Korea (1972)
Taiwan (1972)
BWR -5 6
WE 312
CHINA (1985)
CNP 300
M310
prototype
India (1964)
BWR 1
Horizontal
Horizontal
Pakistan (1966)
CANDU 137
Mexico (1976)
BWR 5
Argentina (1968)
PHWR
CANDU 6
Brazil (1971)
W 2 loop
KONVOI
Soviet Union (1951)
AM-1 : AMB 100 /200
VVER Gen I, 230, 187 213
BN 600 VVER 338
EGP 6
RBMK 1000
BN 350
Kazakhstan (1964)
Finland (1971)
VVER
213
ABB
SWEDE N (1966)
ABB – 1 2 3
W 3 loop
BWR 1
BWR 69 72
PWR
PBR
Konvoi
VVER G1
VVER 230
VVER 213
Iran (1975)
Armenia (1968)
VVER 446
VVER
270
Ukraine (1970)
RBMK
VVER 213 302
VVER 320 338
392
Lithuania (1977)
RBMK
1500
Romania (1982)
CANDU 6
Slovakia (1958)
Bulgaria (1970)
VVER
270
VVER
320
Hungary (1974)
VVER 213
UK (1953)
MAGNOX
AGR
SNUPPS
Netherlands (1964)
GE
KLU
Belgium(1957)
W 2 loop 3 loop
FRAMATOM
FRG (1958)
GDR (1960)
Czech (1979)
KS 150
VVER 230
VVER 213
VVER 213
VVER 320
Slovenia (1975)
W 2 loop
France (1957)
UNGG
CHOOZ A
PH 250
CP0 CP1 CP2
Super Phenix
REP 1300 1450
Spain (1964)
W1 3
BWR 3 6
PWR 3
SWTZ (1962)
W (2 loop)
BWR 6
PWR 3L
Italy (1958)
MAGNOX
BWR 1 4
W (4 loop)
South Africa (1976)
W 3 loop
1989

TRANSFERS OF NUCLEAR TECHNOLOGY





Decommissioning of nuclear power plants in the US

	Plant	State	Investor	Capacity (MWnet)	Date of closure
Realized shut down:	Crystal River-3	Florida	Duke Entergy	860	20.02.2013
	San Onofre-2	Kalifornien	Southern California Edison	1,070	07.06.2013
	San Onofre-3	Kalifornien	Southern California Edison	1,080	07.06.2013
	Kewaunee	Wisconsin	Dominion Generation	556	07.05.2013
	Vermont Yankee	Vermont	Entergy	620	29.12.2014
	Fort Calhoun-1	Nebraska	Omaha Public Power District	478	24.10.2016
			SUM of closed plants:	**4,664**	
Announced shut down:	Pilgrim	Mass.	Entergy	685	31.05.2019
	Diablo-Canyon-1	Cali	PG&E	1,122	2024
	Diablo-Canyon-2	Cali	PG&E	1,118	2025
	Palisades	Michigan	Entergy	778	01.10.2018
	Indian Point	New York	Entergy	1,022	30.04.2020
	Oyster Creek	New Jersey	Exelon	615	2019
			SUM of announced closures:	**5,340**	
Under discussion:	Prairie Island	Minnesota	Xcel Energy	1,100	
	Perry	Ohio	First Entergy	1,205	
	Davis Besse-1	Ohio	First Entergy	894	2018
			SUM of closures currently discussed:	**3,199**	
			SUM of plants closed, announced or discussed closures	**13,203**	

Sources: WNISR (2017), webpages of operators

Policy Issue 2: Decommissioning of nuclear power plants

High number of shut down reactors (100) by 2050.

- A total of 35 NPPs have been shut down and are in different stages:
  - 13 decommissioned
  - 12 in long-term enclosure
  - 6 in decommissioning
  - 1 in post-operations
  - 3 in entombment

There are concerns, that the decommissioning trust funds are sufficient.

- High variance in actual decommissioning costs:
  - US$280/kW (Trojan, OR)
  - US$1,500/kW (Connecticut Yankee, CT)

- US$53 bn (2014) in the decommissioning trust funds, US$600/kW on average per reactor

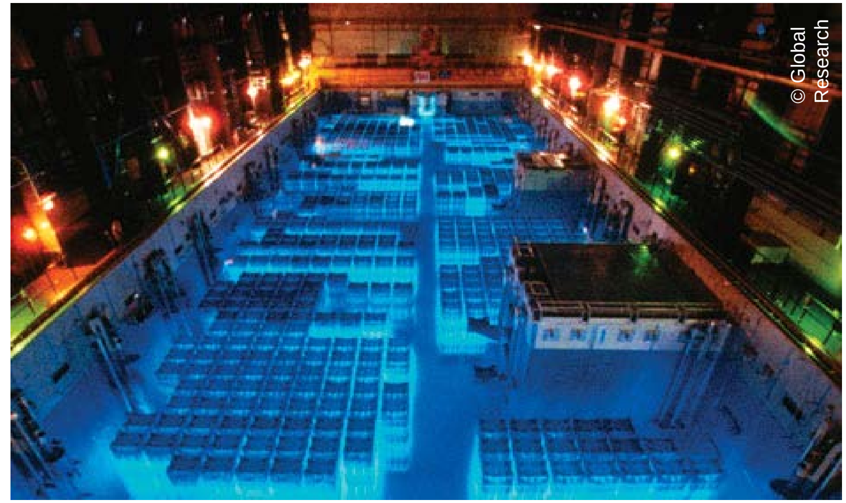
- NRC decommissioning formula is outdated (NRC audit: in one case NRC-formula estimate US$600 million vs. site-specific cost estimate done by the operator US$2.2 billion).

- Exelon reported shortfalls in the decommissioning funds ranging from US$6 million to US$83 million.

Policy Issue 3: Spent fuel storage in the U.S.

Spent fuel pools (~78% of overall HLW)

- Used in all U.S. nuclear power plants
  - Robust constructions made of reinforced, several-feet-thick concrete with steel liners
  - Approximately 40 feet deep
  - Water for shielding the radiation and cooling the rods

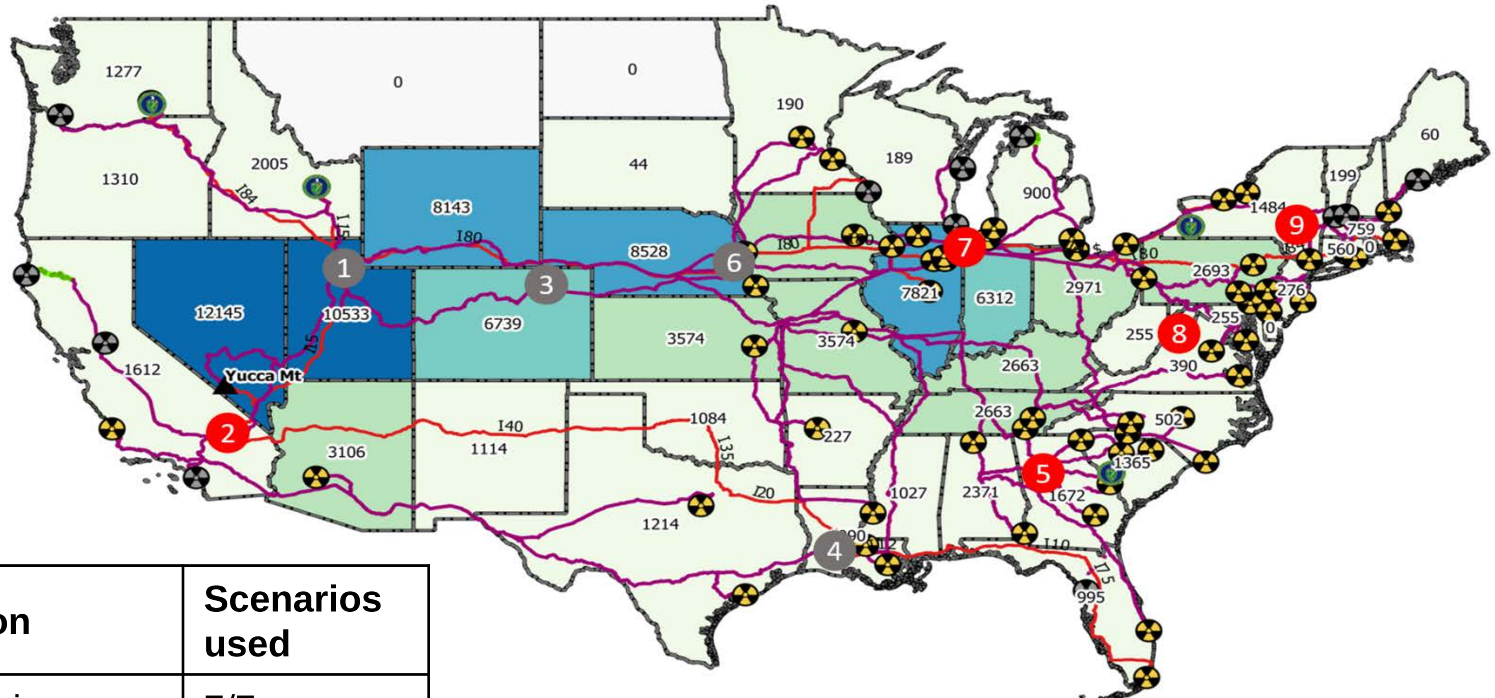


Dry cask storage (ISFSI, ~22%)

- Independent spent fuel storage installations
- Used when pools reach capacity, above ground
- Fuel is cooled for at least 5 years in pools before being transferred to casks
- NRC has authorized transfers as early as 3 years, industry norm is 10 years
- Special, one-car-garage-sized canisters filled with inert gas

Source: U.S. NRC (2015)

Centralized interim storage facility locations (CISF)



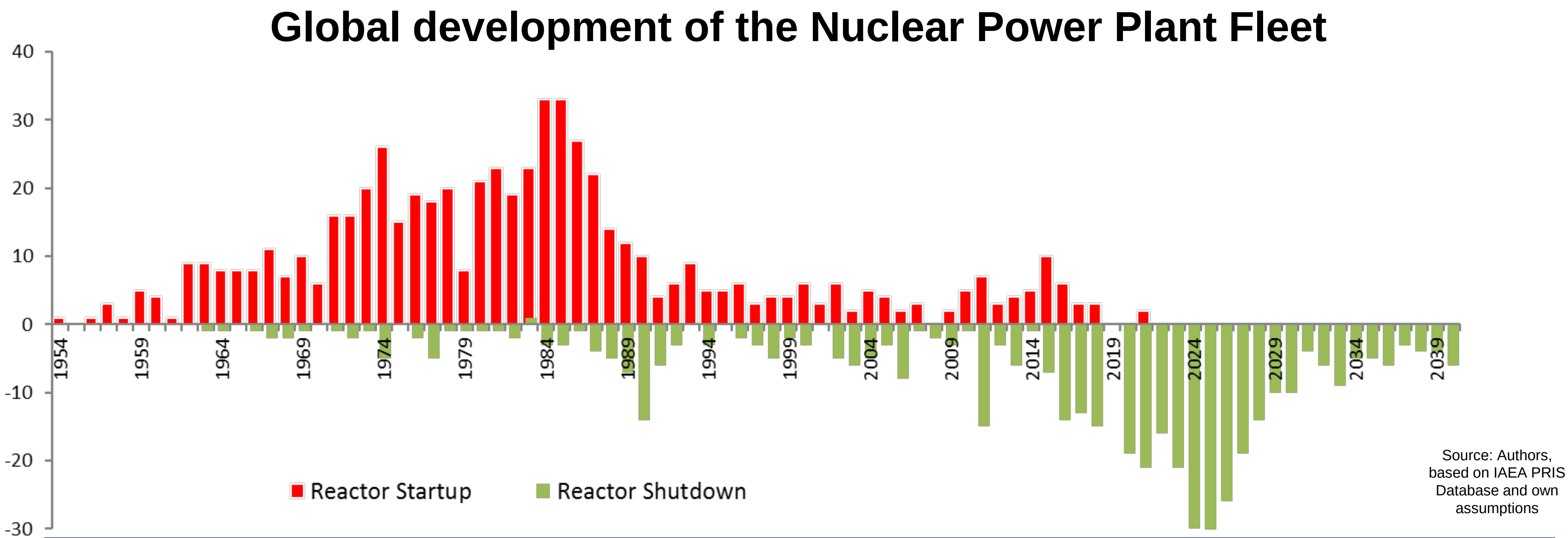
#	Name of location	Scenarios used
2	Barstow, California	7/7
5	Barnsville, Georgia	4/7
7	Lasalle, Illinois	5/7
8	Newville, Pennsylvania	7/7
9	Old Chatham, New York	4/7

1 = chosen locations for CISF

1 = possible locations for CISF that have not been chosen

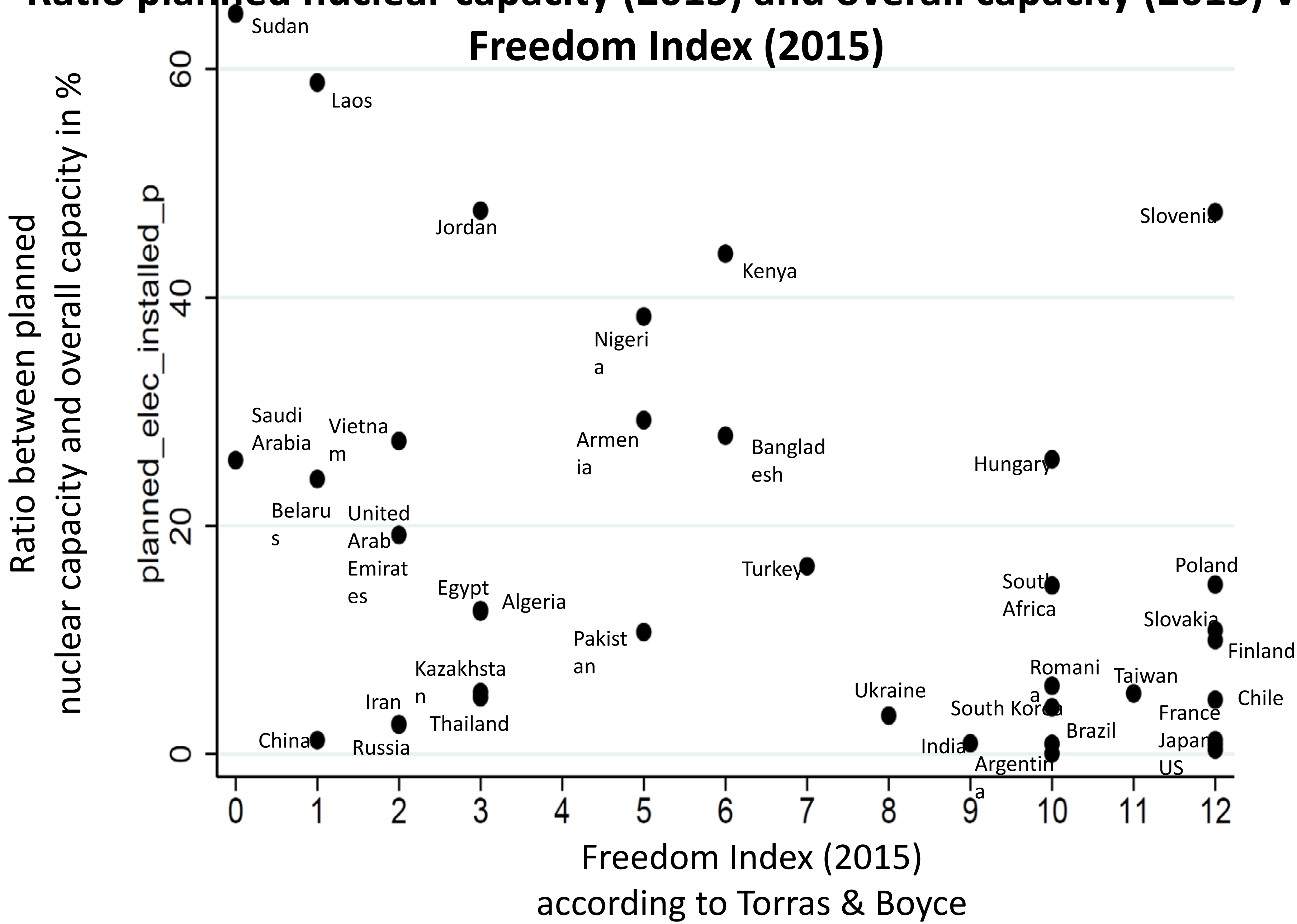
=> Mostly located at the East cost close to reactors and one close to final repository

Nuclear power is unlikely to go away…



- Increasing demand for decommissioning and waste management.
- About 440 commercial reactors are currently operating. Most of them constructed during the 1970s and 1980s.
- Many reactors will reach their technical-lifetime very soon, which causes a growing demand for decommissioning and dismantling service in all countries with nuclear power.
- The search for High Level waste disposal facilities is on-going. In Finland the construction licence of the 1st DGF was granted in 2015.

… but it goes different places:
Ratio planned nuclear capacity (2015) and overall capacity (2015) vs. Freedom Index (2015)



3.3 Renewables (here: solar)
Cost development of technologies in M€/GW (Loeffler, et al., 2017)

Technology	2015	2020	2025	2030	2035	2040	2045	2050
CSP	4100	3800	3500	3200	2900	2600	2300	2000
PV	1000	800	650	550	490	440	400	380
Geothermal	5263	4903	4542	4182	3821	3461	3100	2740
Solarthermal	5263	4903	4542	4182	3821	3461	3100	2740
Wind onsh.	1400	1250	1095	1035	1000	975	950	925
Wind offsh.	3300	3106	2911	2717	2522	2328	2134	1939
Lion Battery	1500	1300	1300	1000	1000	800	800	700
Heatpump	1300	1286	1271	1257	1243	1229	1214	1200

Model: dynELMOD
Determining cost-effective pathways in the electricity sector

dynELMOD (Gerbaulet and Lorenz, 2017):

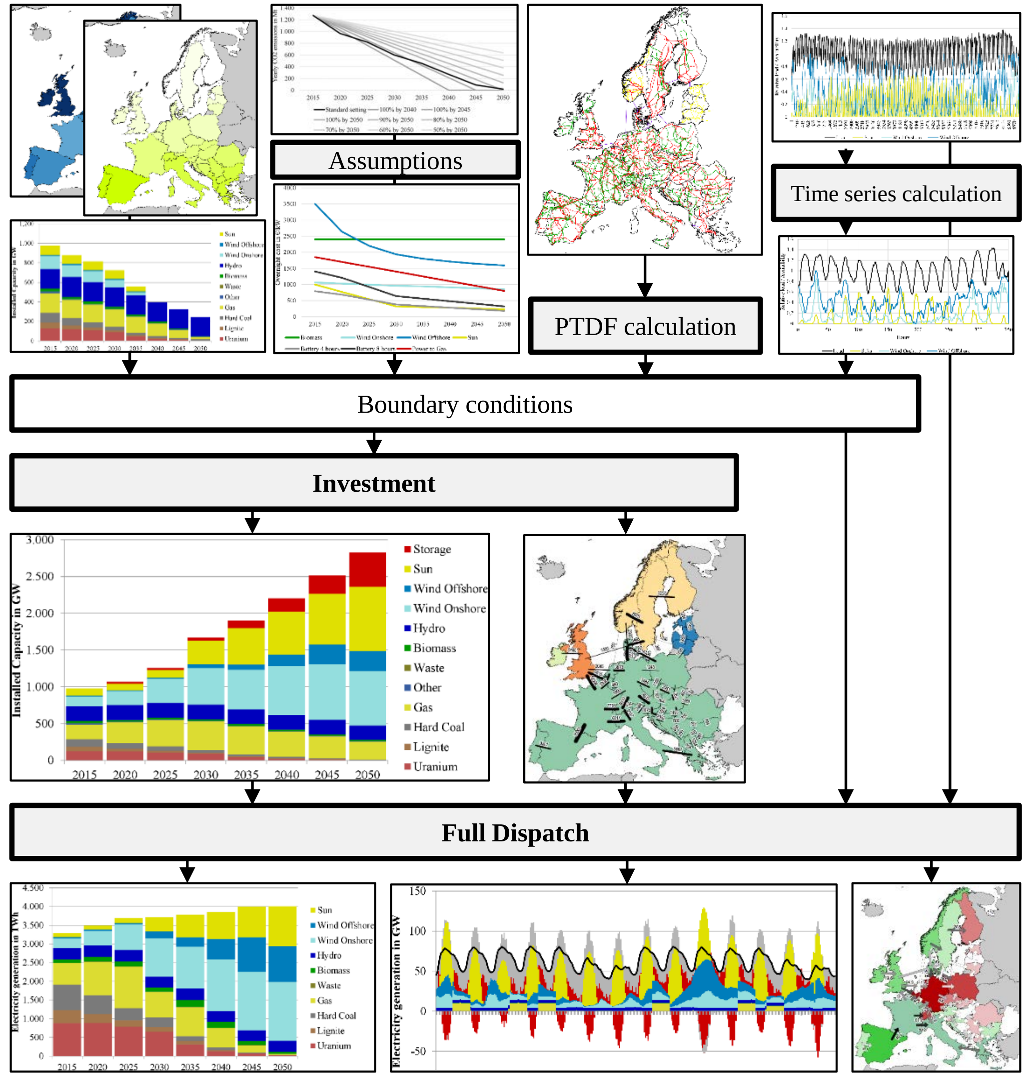
Linear program to determine cost-effective development pathways in the European electricity sector

Model:
33 European countries
31 conventional or renewable generation and storage technologies
9 investment periods, five-year steps 2020 – 2050
Good storage representation (including reservoirs, DSM)
Approximation of loop-flows in the HVAC electricity grid
CCTS and CO2 storage constraints

1. **Investment**
   - Investment into Conventional and renewable generation, cross-border capacities
   - Reduced time series used
2. **Dispatch**
   - Investment result from step 1 fixed
   - Time series with 8760 hours (validate result adequacy)

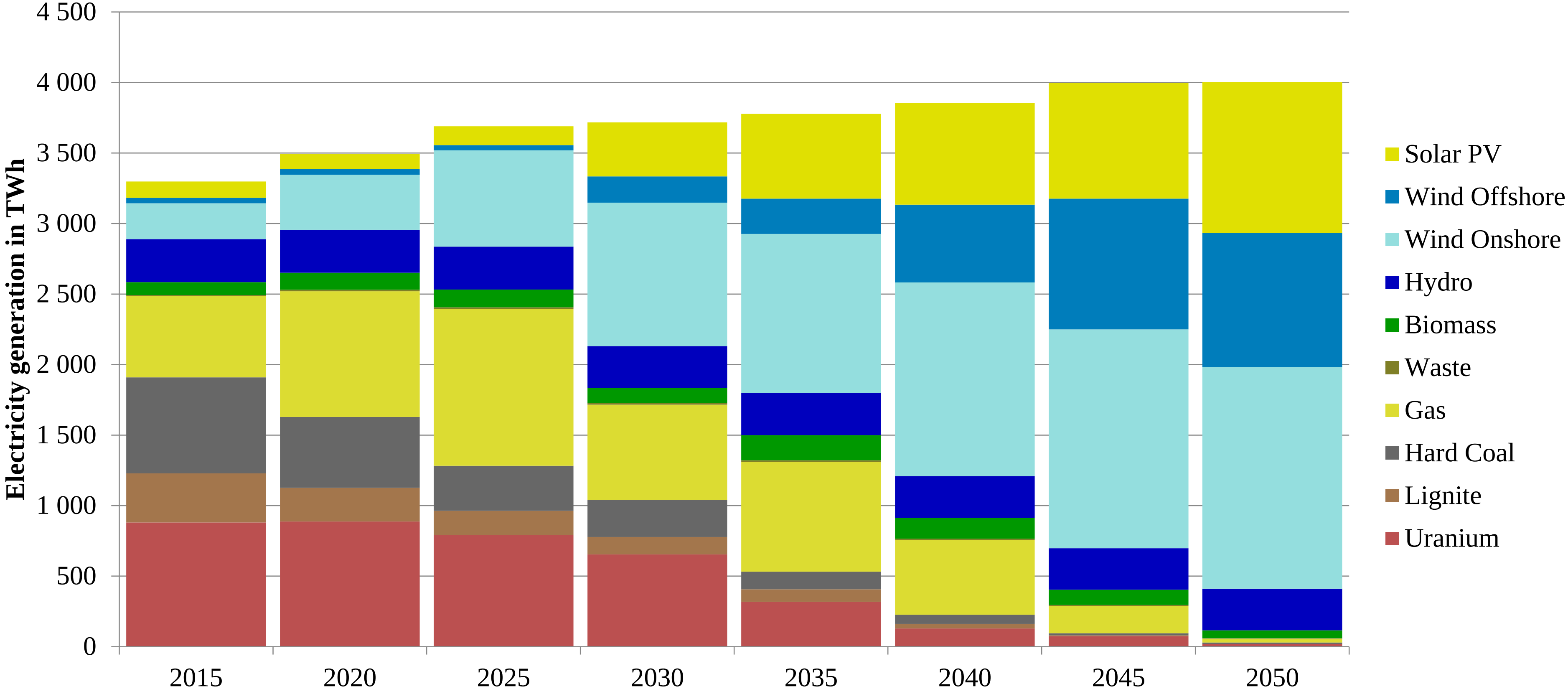
Outputs

- Investment into generation capacities, storage, transmission capacities
- Generation and storage dispatch
- Emissions by fuel
- Flows, imports, exports



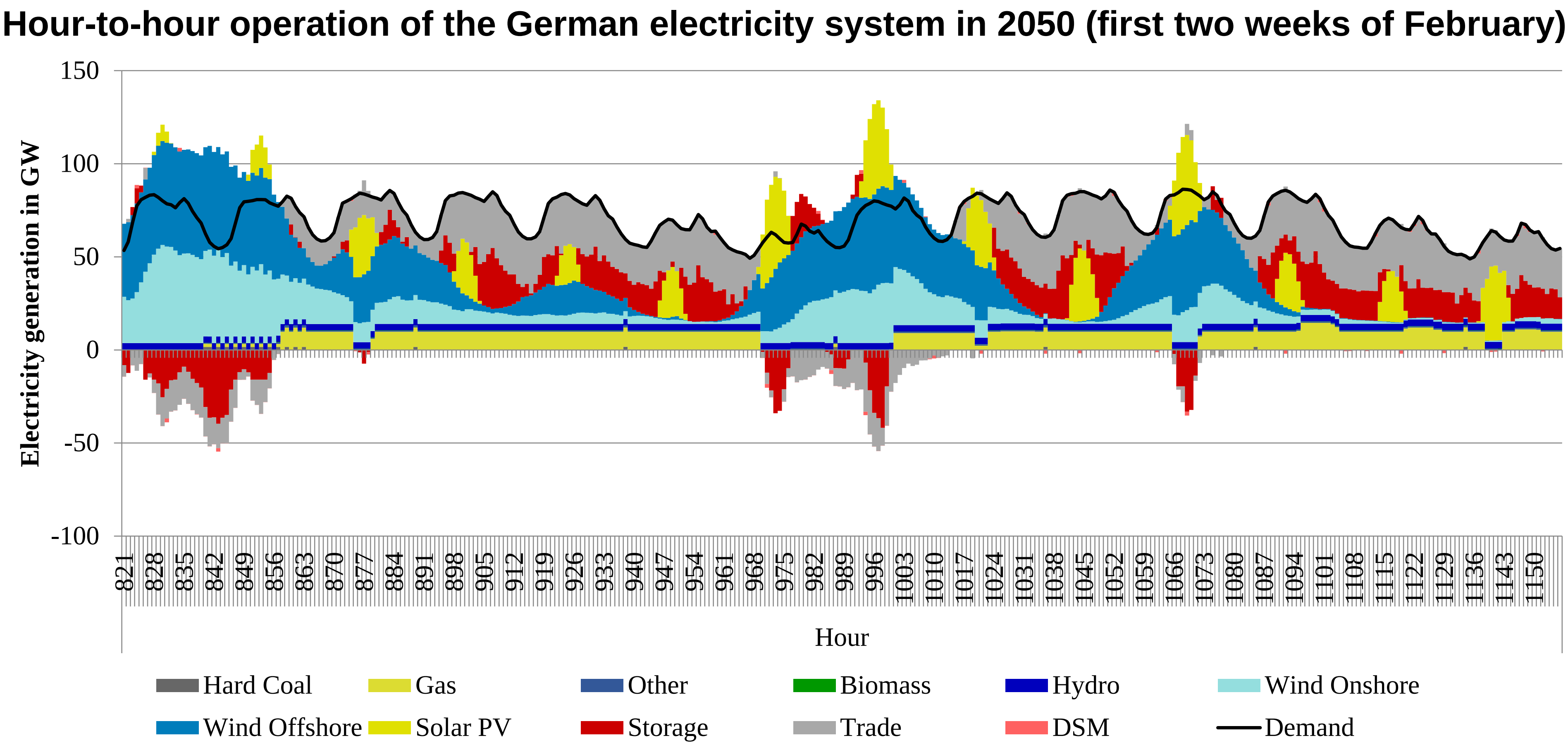
Renewables become dominant electricity source in Europe

Electricity Generation in Europe 2015 – 2050



- **No new nuclear, hard coal, or lignite power plants emerge**
- **Natural gas usage reduces after 2030 to become backup technology**
- **Renewables become dominant electricity source**
- **Storage capacities (>400GW installed in Europe) balance fluctuations**

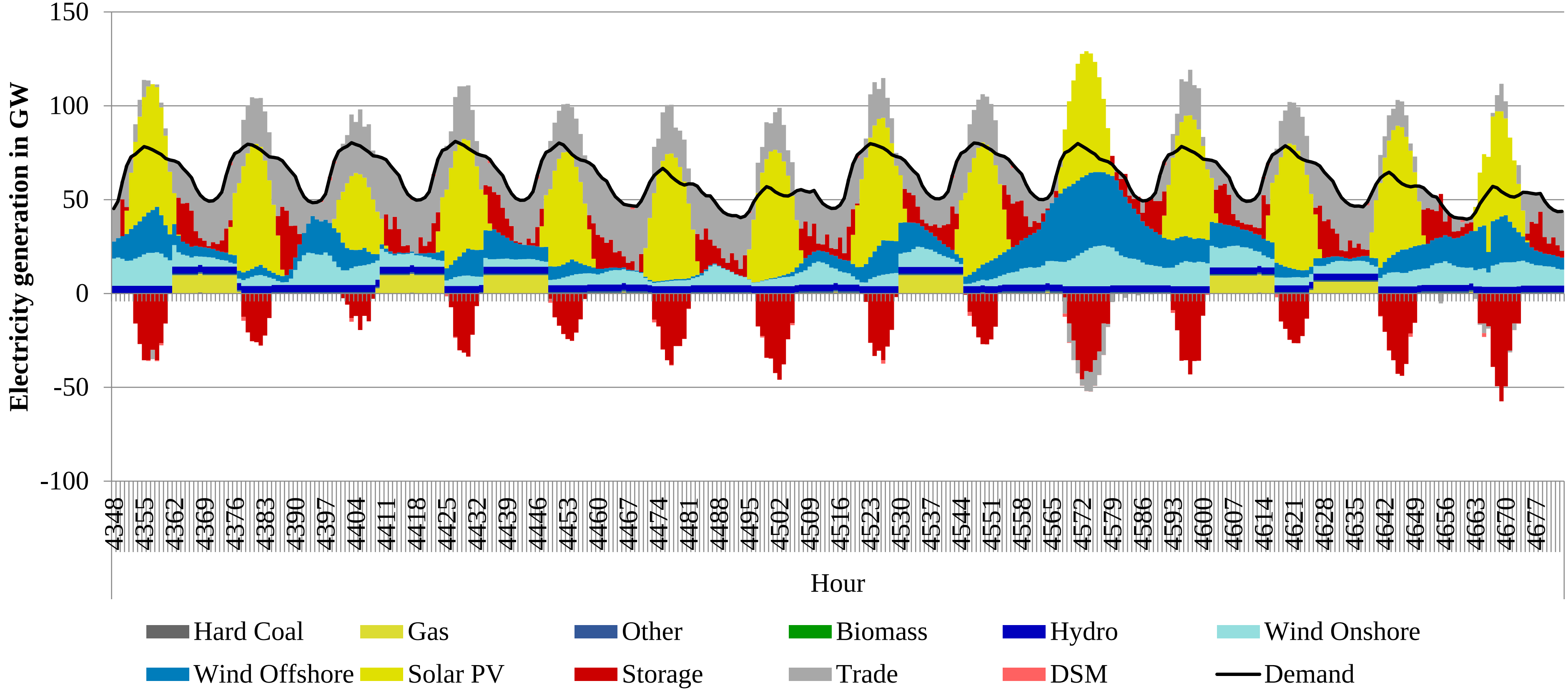
Dispatch 2050 Germany in Februar



- German electricity imports in February 2050 are from Denmark, Switzerland, Netherland, France and Austria.
- The imports and exports with Sweden and Poland are even in total
- Germany exports 960MW on average to the Czech Republic.

Hour-to-hour operation of the Italian electricity system in 2050 (first two weeks of February)

Hour-to-hour operation of the Italian electricity system in 2050 (first two weeks of February)



- **In February 2050 Italy is also dependent on Storage and Imports**
- **Solar infeed is higher than in Germany**

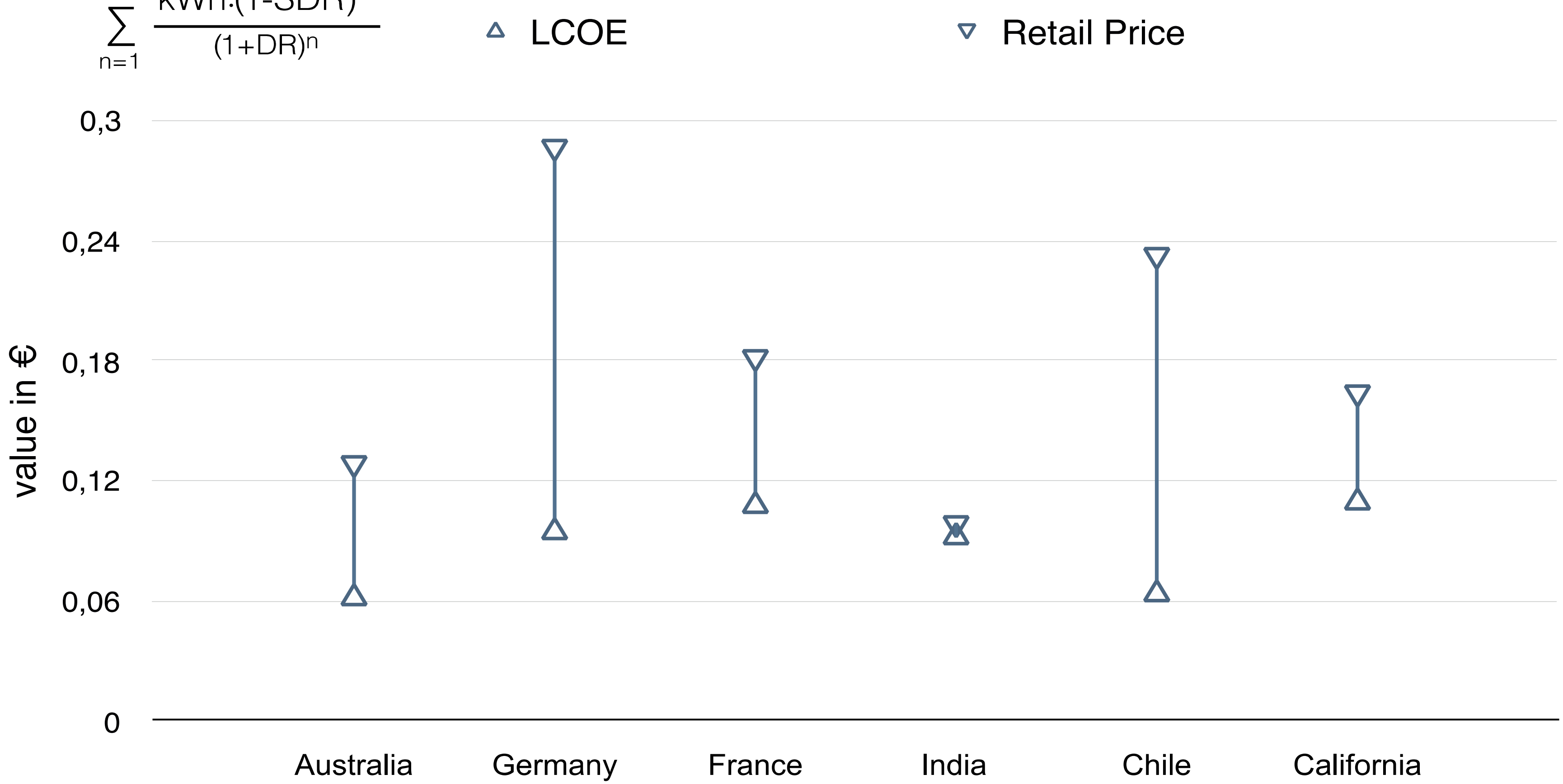
Scenarios for the Break-through of the PV-Battery Pack

Scenario for 2033	Basis (NEP 2013, B 2033)	PV-Battery-Break-through
Grid Expansion	delayed	fast
Installed Capacity (GW)		
PV	65	150
Home Storage	~0	40
Wind Onshore	66	65
Wind Offshore	25	7
Sum Wind	91	72
Generation (TWh)		
PV	67	147
Wind Onshore	190	185
Wind Offshore	103	29
Cost difference to Base-Scenario (Million €/Year)		
Renewables Expansion PV		n.a.
Storage Expansion		n.a.
Renewables Expansion Wind		-7.5
Distribution grid expansion (high voltage)		64
Distribution grid expansion (medium voltage)		-15
Distribution grid expansion (low voltage)		20
Transmission grid expansion		-35
Residual generation cost		-1.6

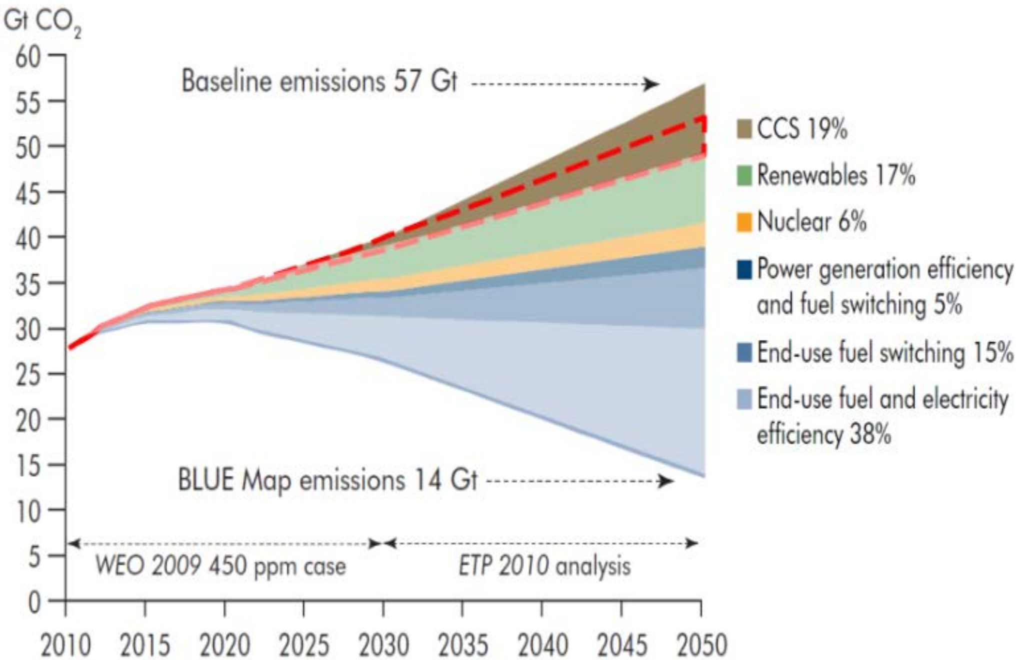
Source: Deutsch and Graichen (2015): „was wäre wenn ein flächendeckender Rollout von Solar-Speicher-Systemen Stattfä[illegible]de?“

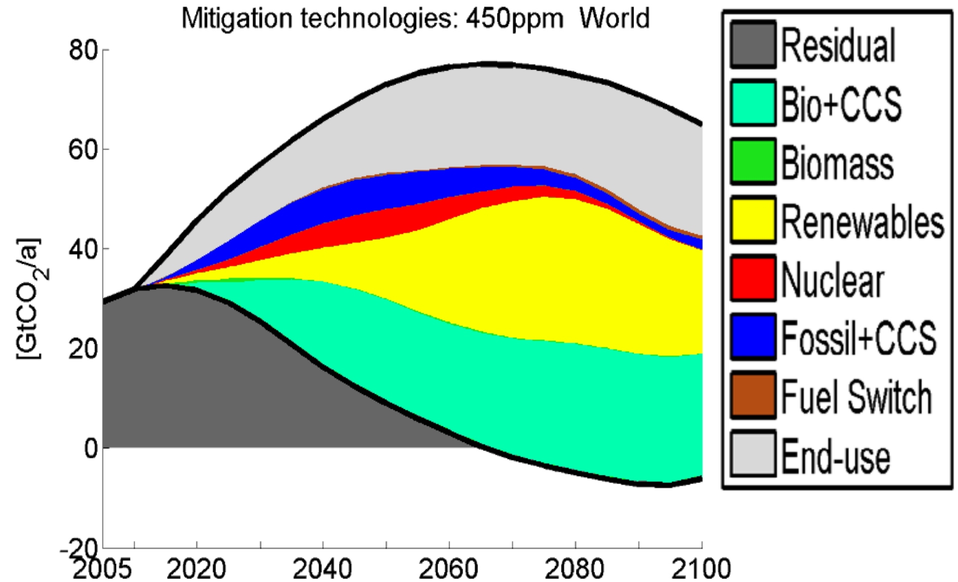
Retail prices and LCOE

$$LCOE = \frac{PCI + \sum_{n=1}^{N} \frac{AO}{(1+DR)^n}}{\sum_{n=1}^{N} \frac{kWh \cdot (1-SDR)^n}{(1+DR)^n}}$$



3.3 Negative emission technologies: CCTS and others





Source: OECD/IEA (2010) & Luderer, Edenhofer et al. (2011)

Installed capacity equipped with Carbon Capture in GW from different studies:

	Year	
Study	2020	2050
IEA (2012)	4.9	77
Capros et al. (2011)	3	108

… creates attention in „The Economist“

… and amount of research on negative emissions increased substantially over the last decades

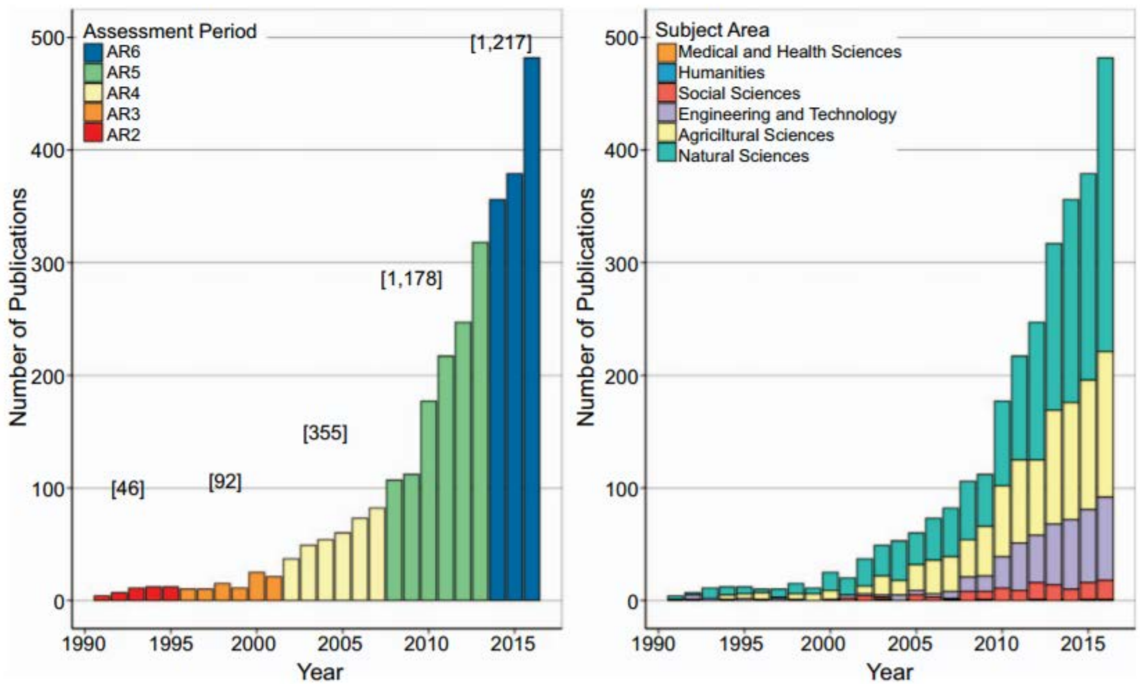


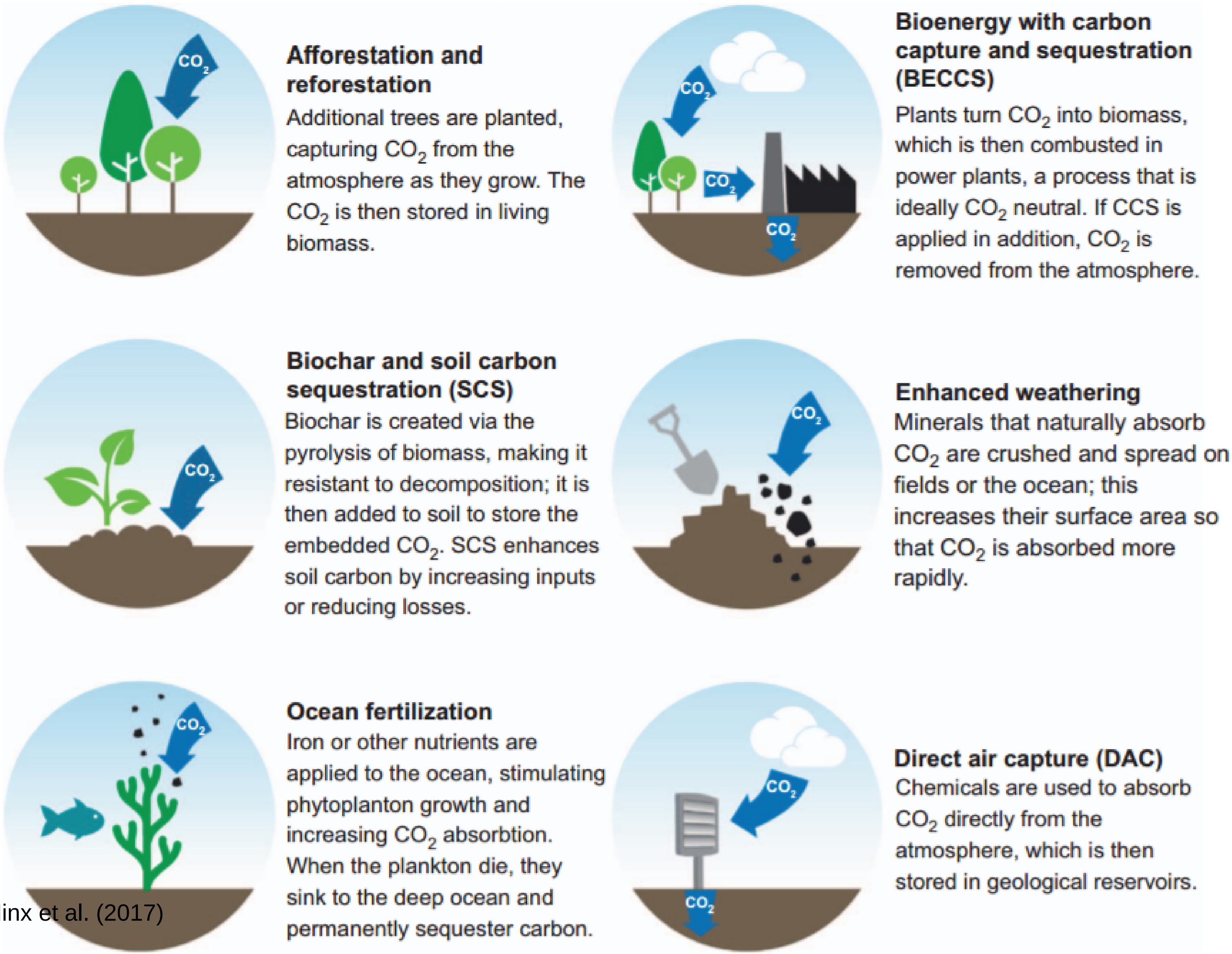
Figure 2. Development of the literature on NETs 1991–2016. The left panel shows the annual number of publications in the Web of Science across the different IPCC assessment periods from the second assessment report (AR2) onwards. The right panel shows annual publications by scientific domain using the OECD Field of Science and Technology classification (OECD 2007).

Fast growing research on negative emissions

- Negative emission technologies (NETs) have attracted growing attention in climate change research over the last decade.
- A total number of about 2900 studies have accumulated between 1991 and 2016 with almost 500 new publications in 2016.
- However, NETs research is relatively marginal in the wider climate change discourse despite its importance for global climate policy.

Source: Minx et al. (2017)

6 potential „negative emission technologies“



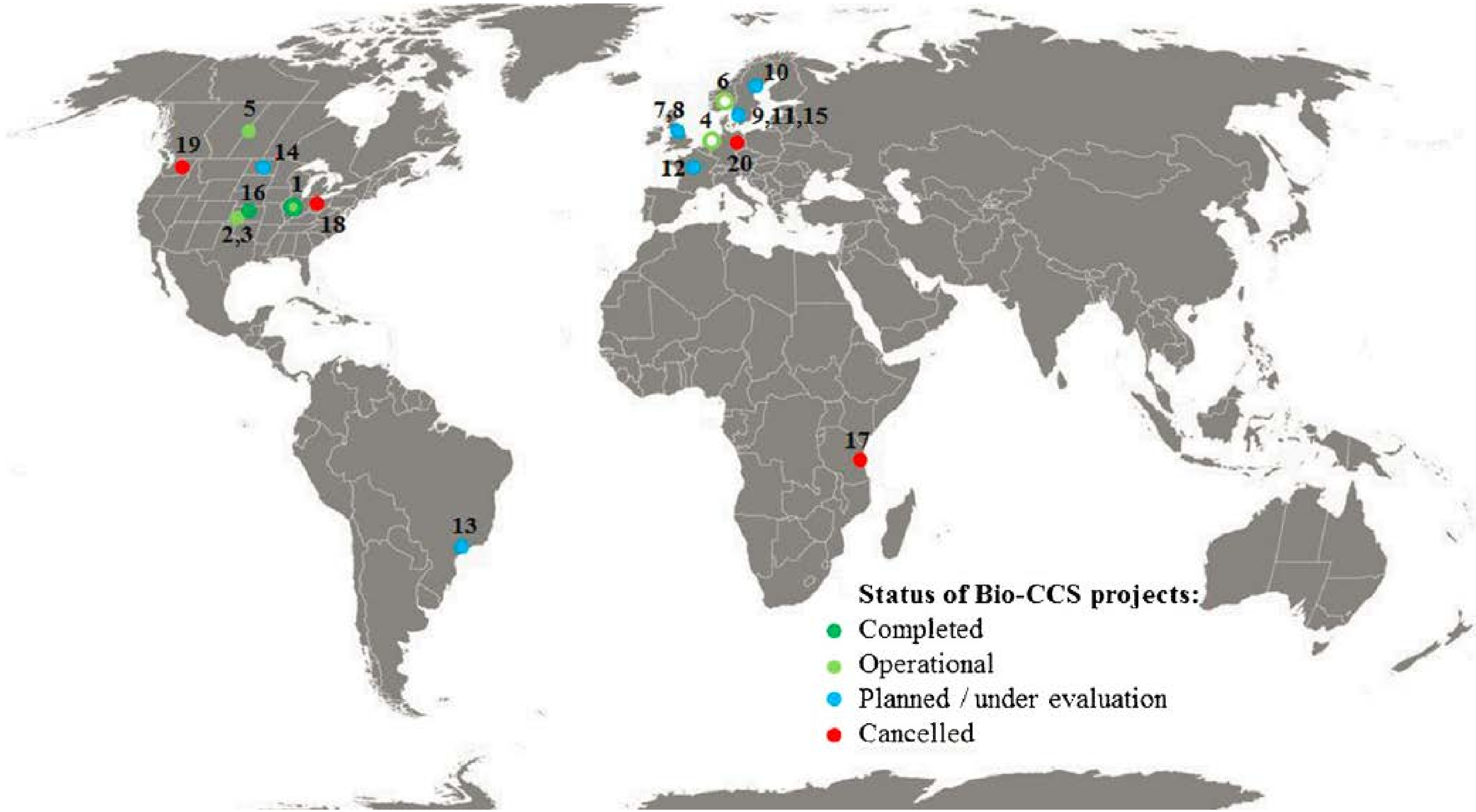
Source: Minx et al. (2017)

Large-scale CCTS Projects world-wide (IEA, 2017, Schiffer and Thielemann, 2017)

Tab.: Große laufende CCS-Projekte weltweit

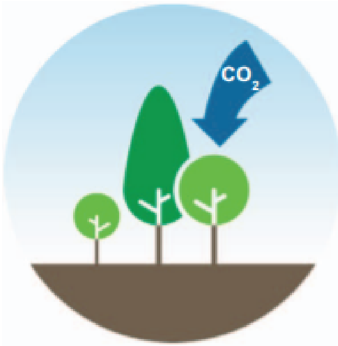
Projektname	Land	Inbetriebnahme	CO_2-Quelle	CO_2 Abscheidekapazität [Mio. t/a]	Speichertyp
Val Verde	USA	1972	Erdgasaufbereitung	1,3	EOR
Enid Fertilizer	USA	1982	Düngerproduktion	0,7	EOR
Shute Creek	USA	1986	Erdgasaufbereitung	7,0	EOR
Sleipner	Norwegen	1996	Erdgasaufbereitung	0,9	DSF
Snöhvit	Norwegen	2008	Erdgasaufbereitung	0,7	DSF
Great Plains Weyburn	Kanada	2000	Synthesegas	3,0	EOR
Boundary Dam	Kanada	2014	Kohleverstromung	1,0	EOR
Quest	Kanada	2015	Wasserstoffproduktion	1,0	DSF
Century Plant	USA	2010	Erdgasaufbereitung	8,4	EOR
Air Products Steam Methane	USA	2013	Wasserstoffproduktion	1,0	EOR
Coffeyville	USA	2013	Düngerproduktion	1,0	EOR
Lost Cabin	USA	2013	Erdgasaufbereitung	0,9	EOR
Petrobras Lula	Brasilien	2013	Erdgasaufbereitung	0,7	EOR
Uthmaniyah	Saudi-Arabien	2015	Erdgasaufbereitung	0,8	EOR
Abu Dhabi	VAE	2016	Stahlproduktion	0,8	EOR

Biomass + CCTS pilot projects are focussed on EOR-usage



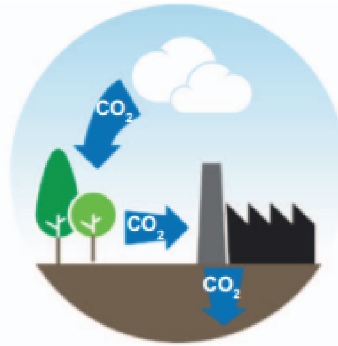
Source: Kemper (2015).

6 potential „negative emission technologies“



Afforestation and reforestation

Additional trees are planted, capturing CO_2 from the atmosphere as they grow. The CO_2 is then stored in living biomass.



Bioenergy with carbon capture and sequestration (BECCS)

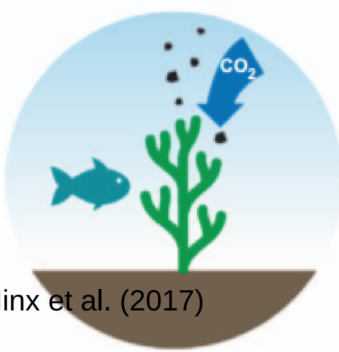
Plants turn CO_2 into biomass, which is then combusted in power plants, a process that is ideally CO_2 neutral. If CCS is applied in addition, CO_2 is removed from the atmosphere.

Biochar and soil carbon sequestration (SCS)

Biochar is created via the pyrolysis of biomass, making it resistant to decomposition; it is then added to soil to store the embedded CO_2. SCS enhances soil carbon by increasing inputs or reducing losses.

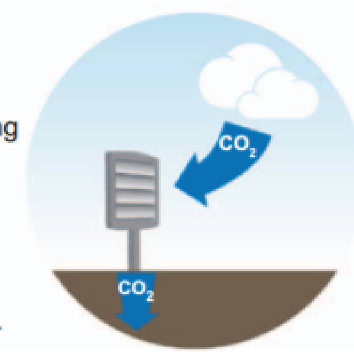
Enhanced weathering

Minerals that naturally absorb CO_2 are crushed and spread on fields or the ocean; this increases their surface area so that CO_2 is absorbed more rapidly.



Ocean fertilization

Iron or other nutrients are applied to the ocean, stimulating phytoplanton growth and increasing CO_2 absorbtion. When the plankton die, they sink to the deep ocean and permanently sequester carbon.

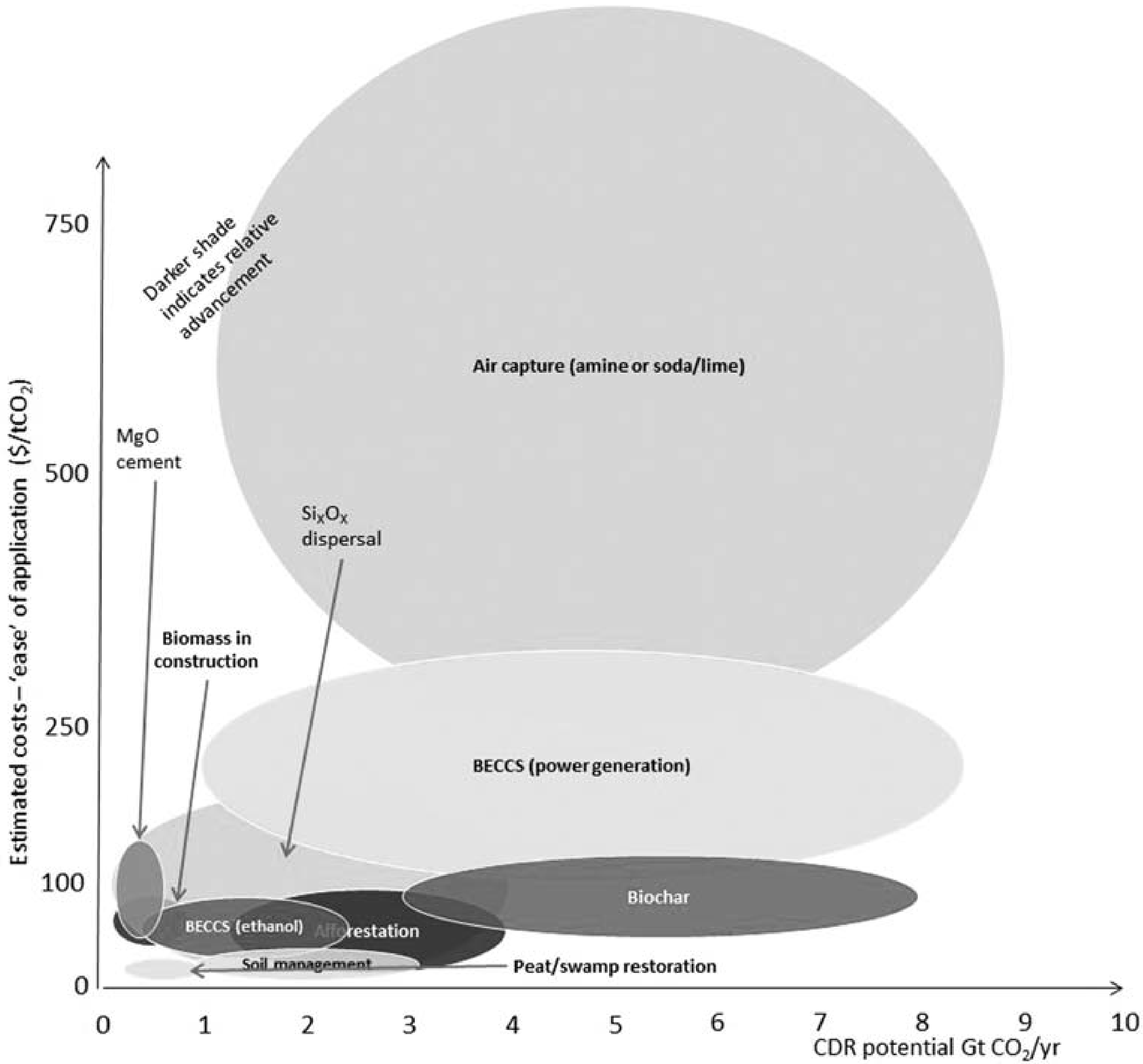


Direct air capture (DAC)

Chemicals are used to absorb CO_2 directly from the atmosphere, which is then stored in geological reservoirs.

Source: Minx et al. (2017)

Estimated costs, CO_2 removal potential and maturity of technology for various CO_2 storage methods



Source: Harrison et al. (2014); darker shades indicate higher maturity.

Agenda

1) Introduction

2) The setting for market and policy analysis

3) “Perfect competition”: The natural gas – coal switch

4) Idiosyncracies: Non-fossil fuel technologies: nuclear, renewables, negative emission technologies (NET)

5) Conclusions

Conclusions: 4 Main Take-aways

1. **Energy market, policy & technology analysis is “particularly complex“, and makes it difficult to yield generally valid conlusions**
2. **Even the most competitive market segments may yield different outcome in different jurisdictions, i.e. the natural gas – coal switch**
3. **All non-fossil fuel technologies have undergone and are currently undergoing significant „directed technological change“, the outcomes of which are quite idiosyncratic**
4. **Energy economic research of the “energy transformation“ is particularly promising, but also challenging, with no mainstream consensus to be expected**