ELEC0080-1 Energy Networks, Part 1

Introduction to Sector Coupling

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23/11/2021

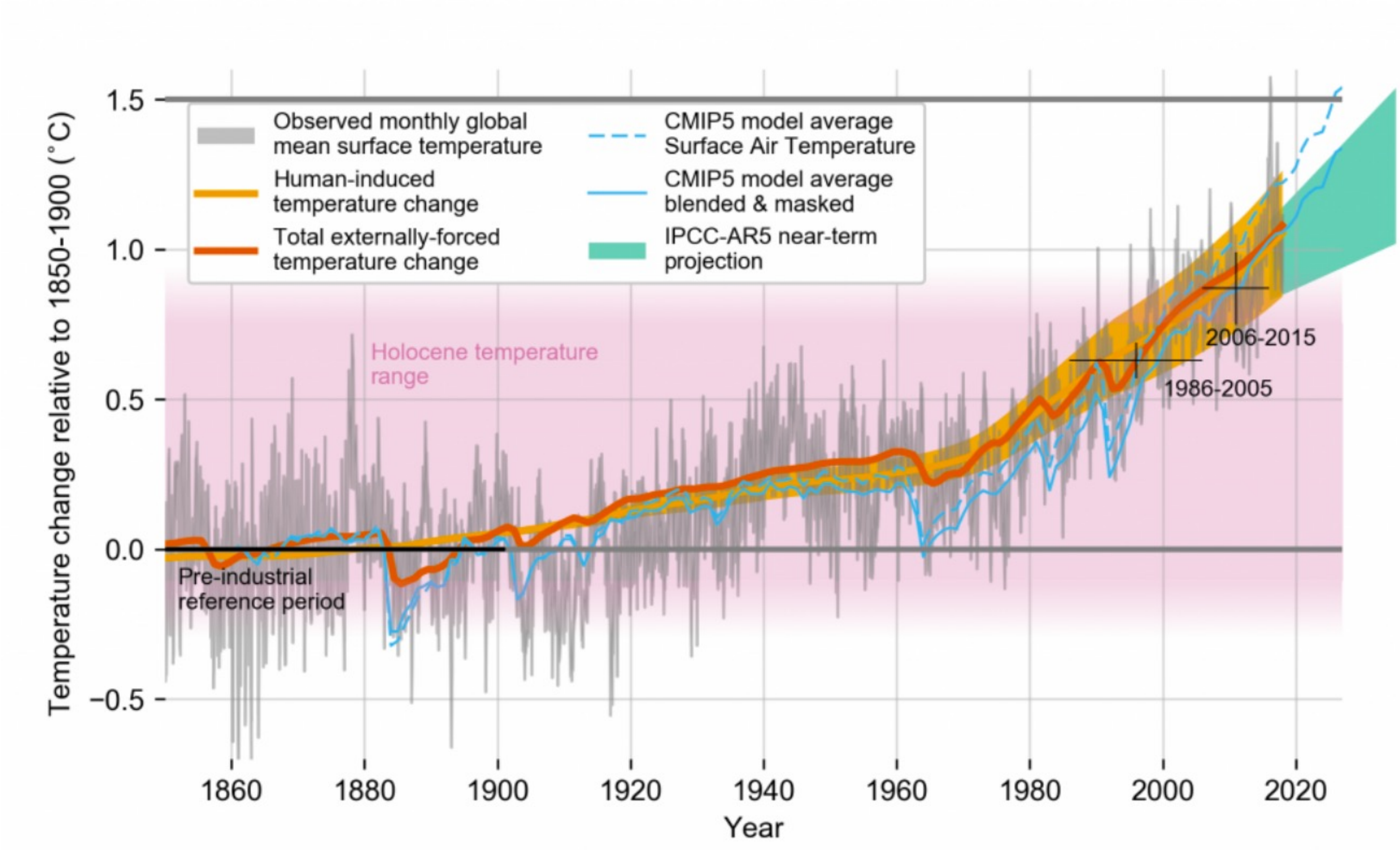
Arlon, Belgium

Lecture Plan

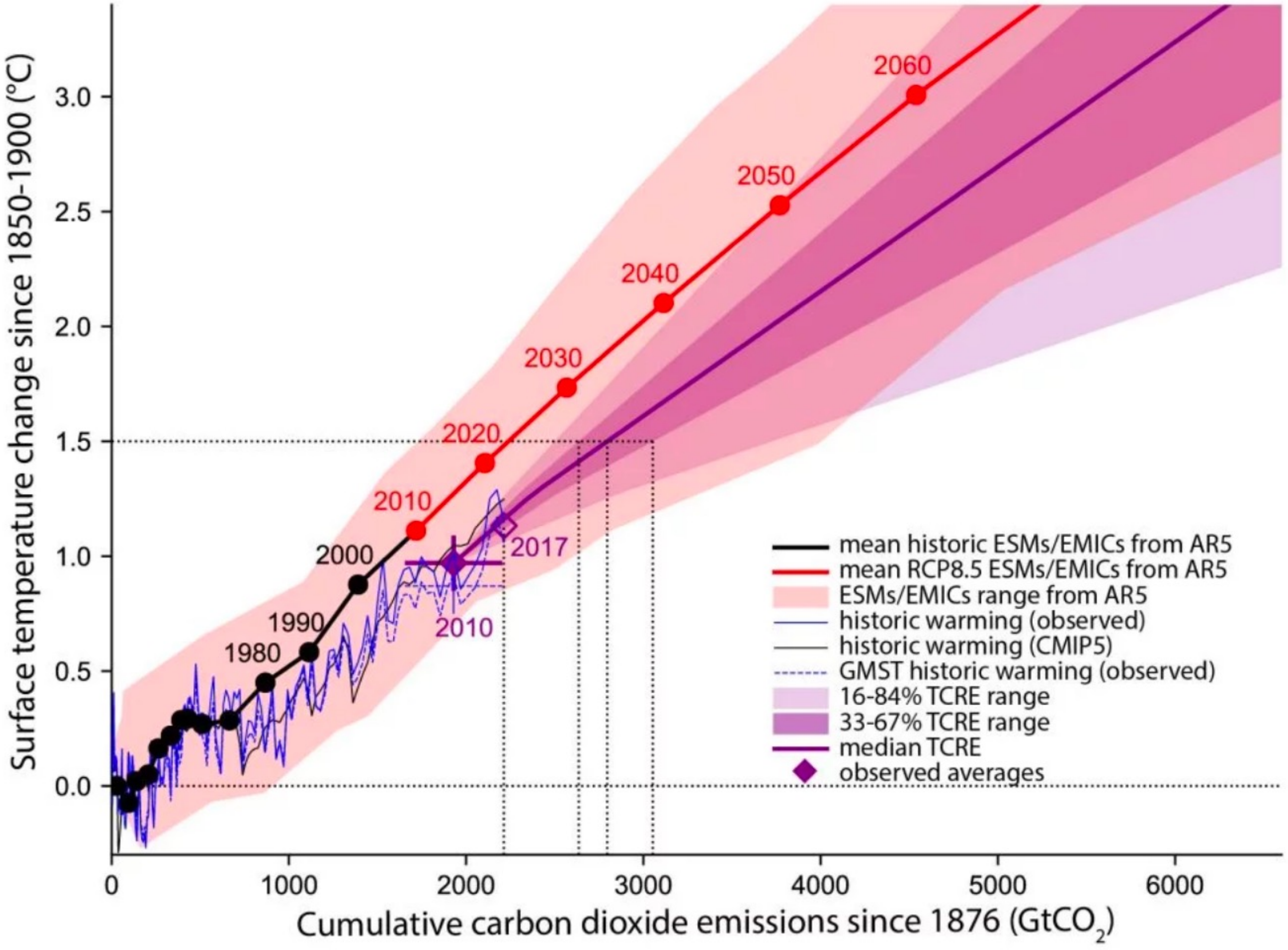
- The rationale behind sector coupling
- Definitions of sector coupling
- Enabling processes and technologies
- Going beyond technologies: energy system integration
- Sector coupling in the Belgian context: a case study
- Summary

The Rationale behind Sector Coupling

They see me risin'…

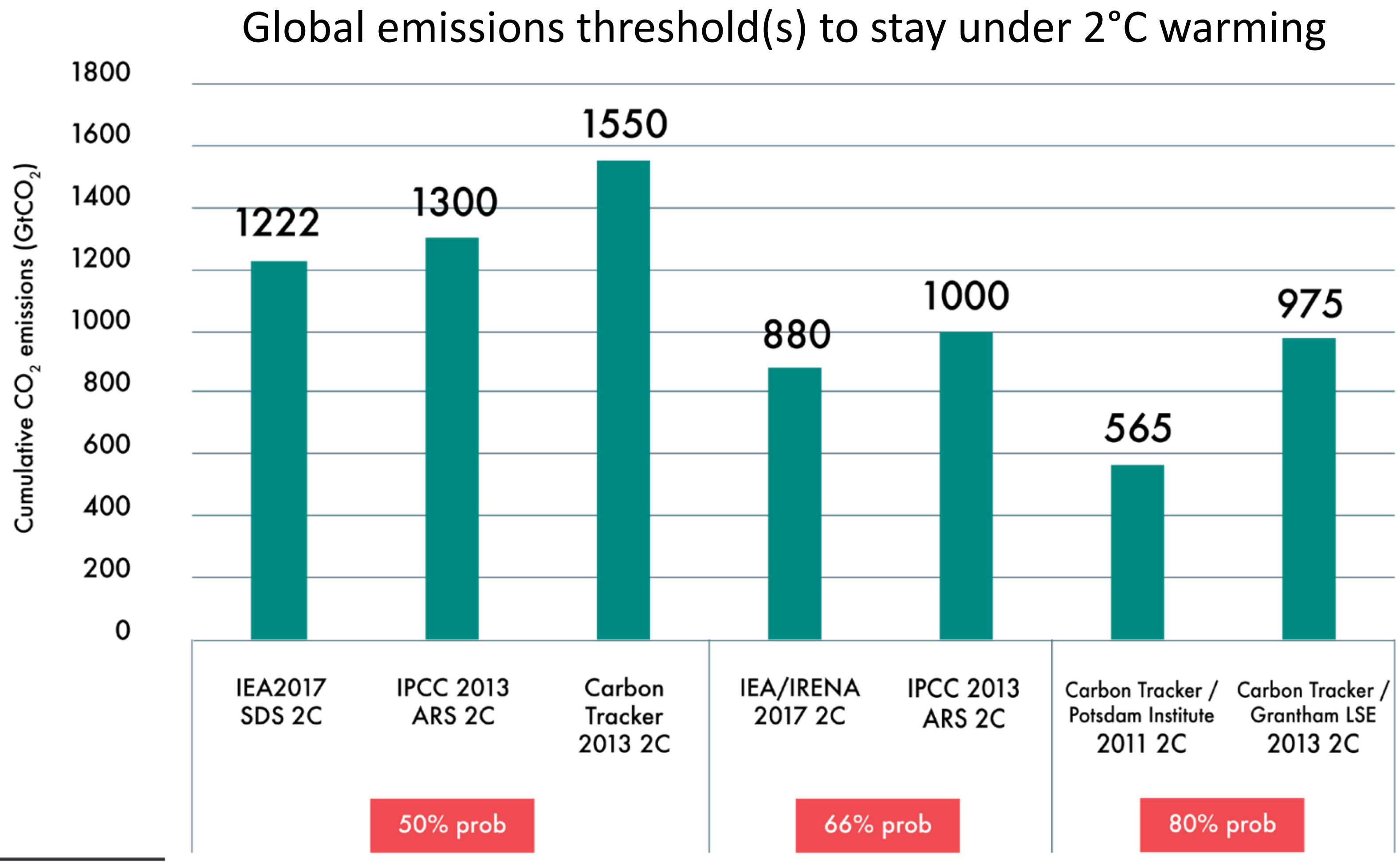


… they hatin’



Source: https://www.ipcc.ch/sr15/graphics/

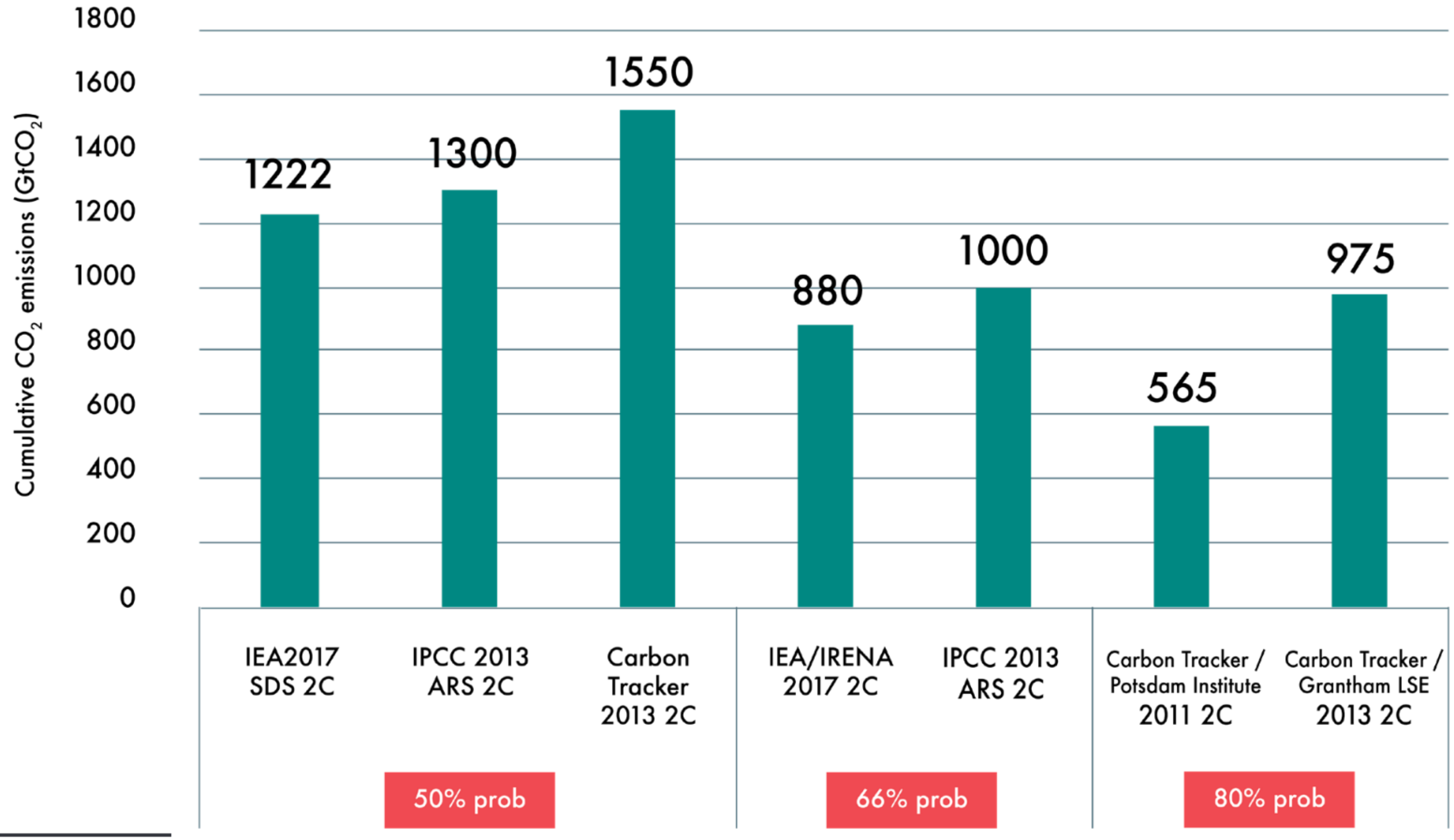
We're on a (carbon) budget



Source: https://carbontracker.org/carbon-budgets-explained/

We’re on a (carbon) budget

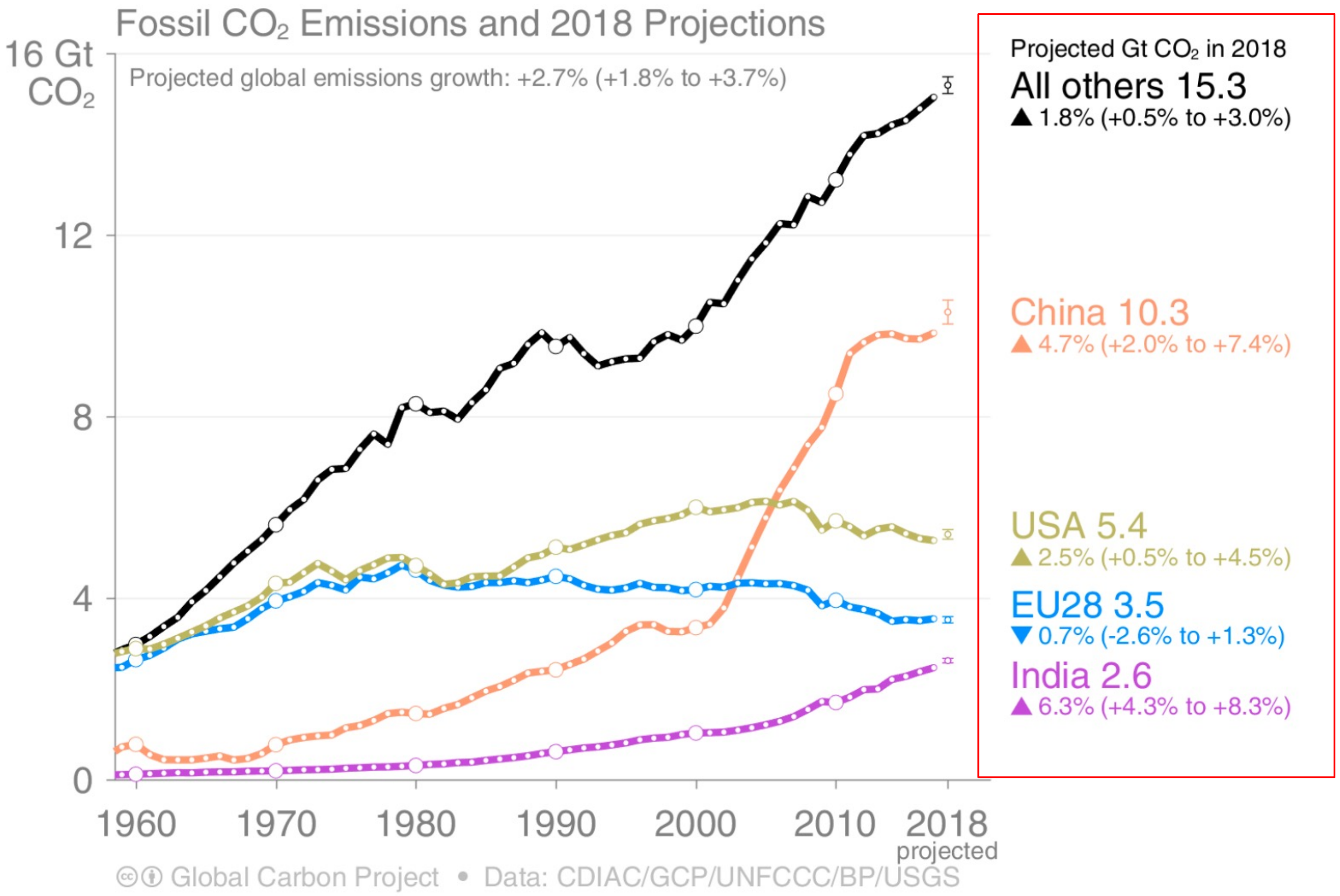
For Europe: 90 Gt for +2°C, 50 Gt for +1.5°C



Source: https://www.europarl.europa.eu/RegData/etudes/STUD/2018/626091/IPOL_STU(2018)626091_EN.pdf

Where are we standing?

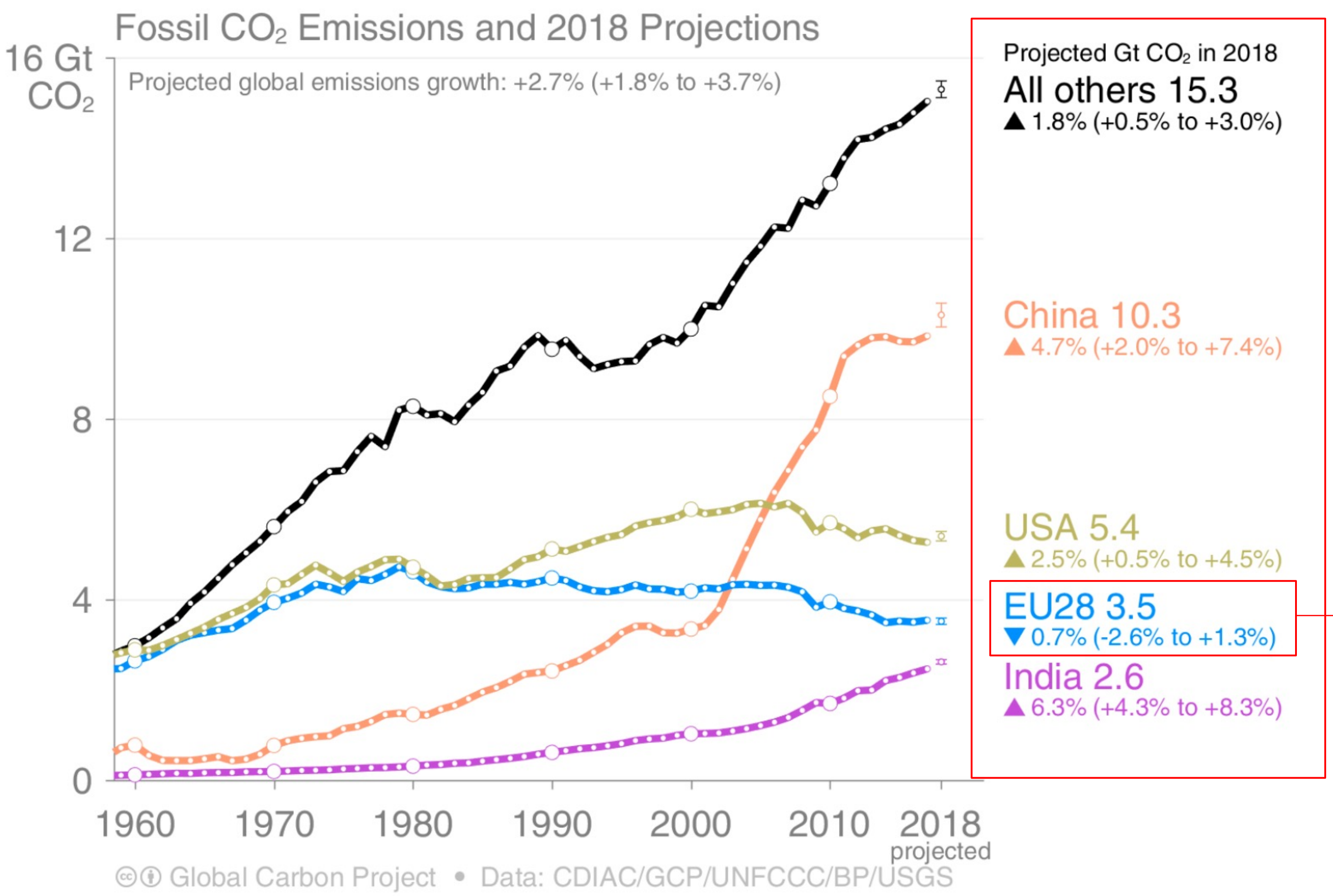
Sums to 37.1 Gt



Source: https://www.globalcarbonproject.org/carbonbudget/18/files/GCP_CarbonBudget_2018.pdf

What about Europe?

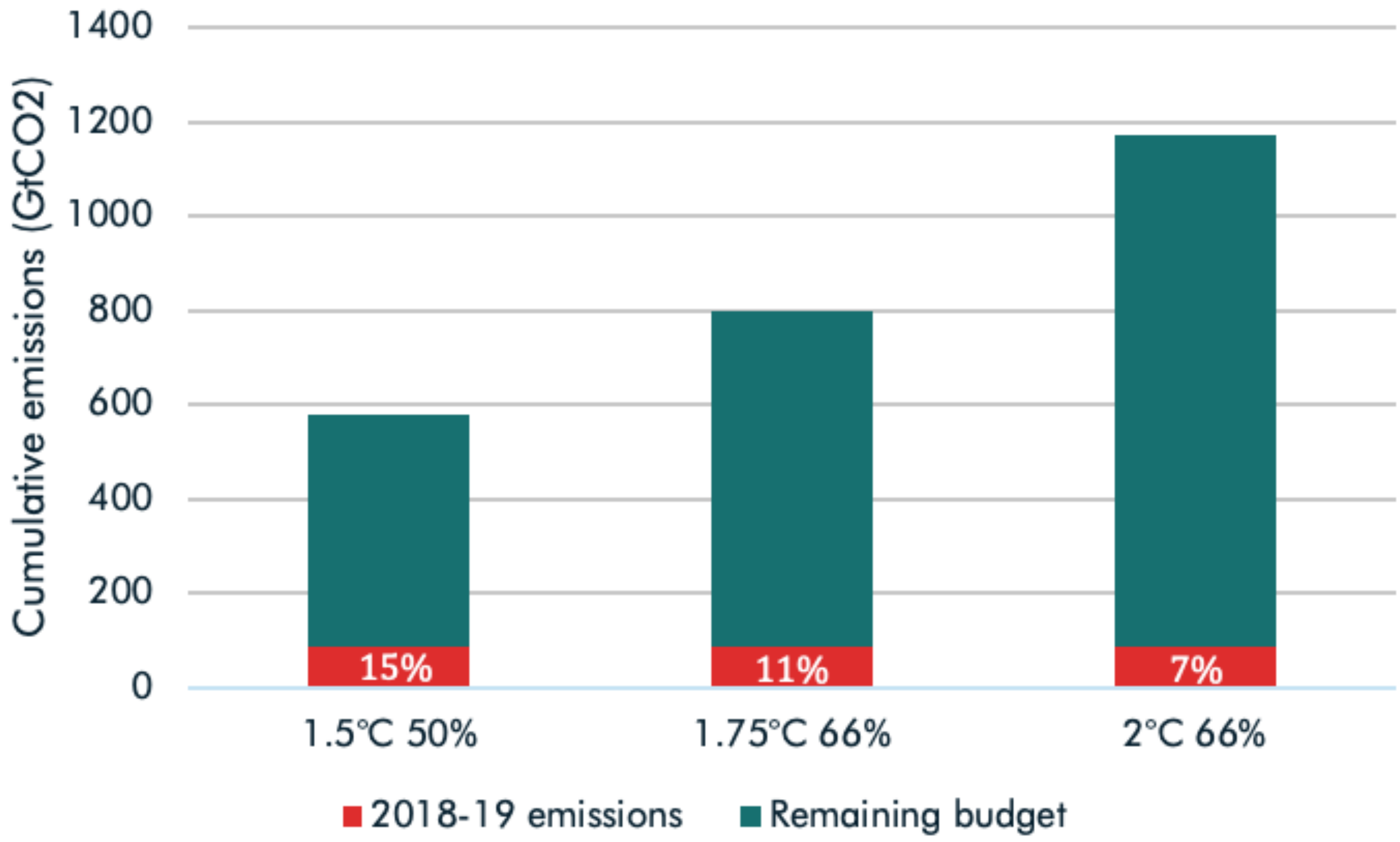
Sums to 37.1 Gt



Budget exhausted in < 25 years

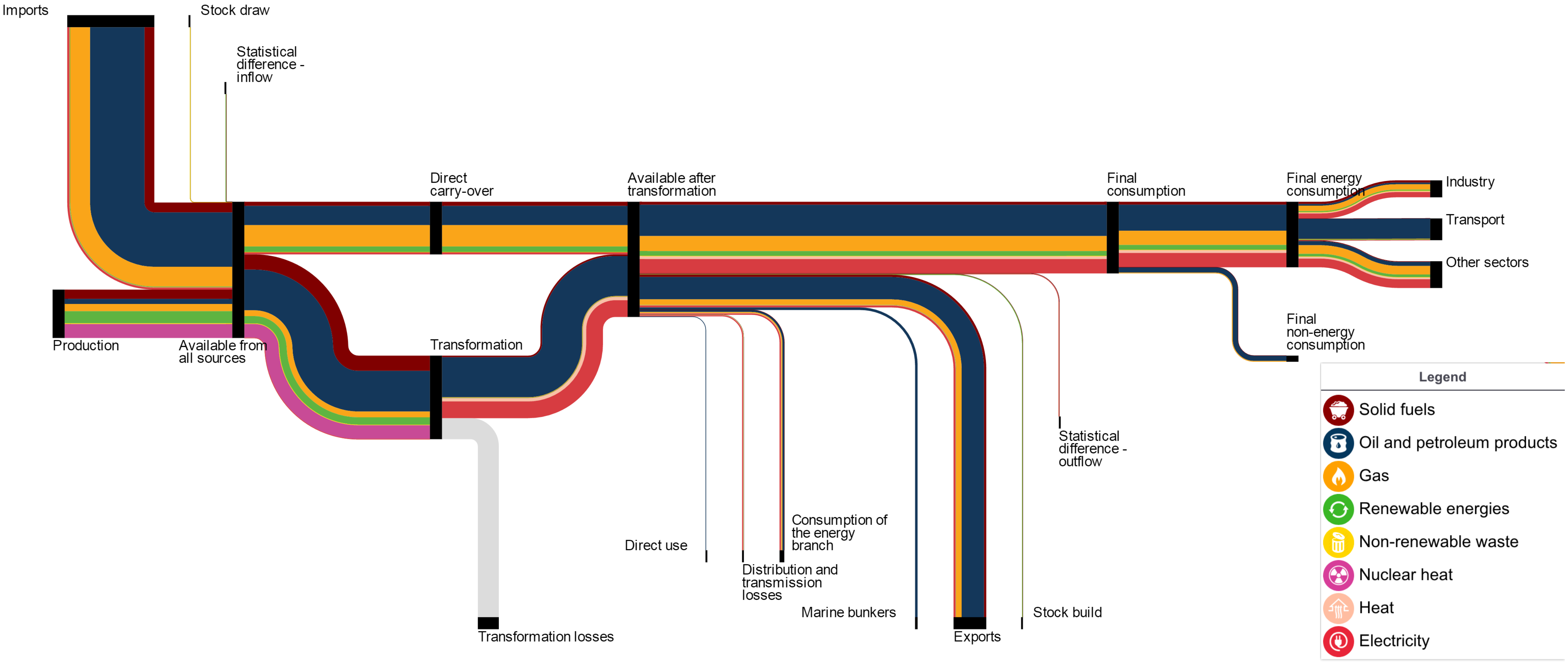
Source: https://www.globalcarbonproject.org/carbonbudget/18/files/GCP_CarbonBudget_2018.pdf

We're on a (carbon) budget, revisited



Source: https://carbontracker.org/carbon-budgets-where-are-we-now/

The oil and gas binge goes on

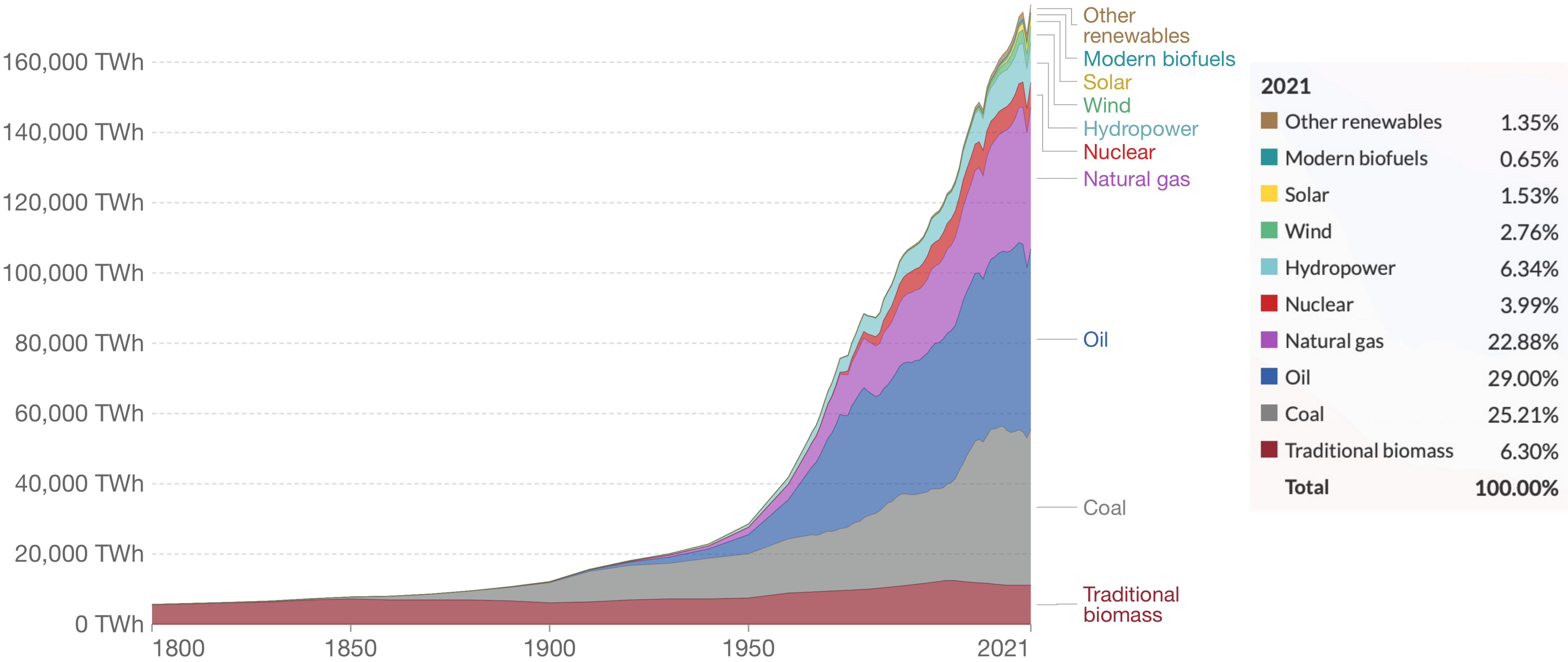


Source: https://ec.europa.eu/eurostat/web/energy/energy-flow-diagrams

Global primary energy consumption by source

Primary energy is calculated based on the 'substitution method' which takes account of the inefficiencies in fossil fuel production by converting non-fossil energy into the energy inputs required if they had the same conversion losses as fossil fuels.

Our World in Data



Source: Our World in Data based on Vaclav Smil (2017) and BP Statistical Review of World Energy

OurWorldInData.org/energy •

The solution?

Source: https://physicsworld.com/a/the-relentless-march-of-renewables/

Possibly, but …

<u>Full electrification</u> may not be the best option

1. serving the energy demand across all economic sectors with electricity will require a complete and incredibly **costly** overhaul of the electricity **transmission and distribution infrastruct**ure, notably to absorb vast volumes of decentralised electricity production.
2. the **public acceptance** of new infrastructure projects has become a show-stopper in several regions.
3. the **renewable energy sources** are inherently **intermittent** on time scales ranging from minutes to years, and flexibility options will be required to balance the power system in the short, medium and long-run, e.g., technologies to absorb production peaks and store electricity.
4. besides hydro, which is already saturated or almost saturated in some regions of the world, **no long-term electricity storage technologies** are currently available or foreseen in the near future.
5. some **sectors** of the economy are **inherently difficult to electrify**, e.g., aviation, industrial processes requiring high-temperature heat, industrial processes requiring carbon-based feedstocks, some surface transport such as road freight transport.

Sector coupling to the rescue?

The value proposition of sector coupling includes

1. **converting some electricity** produced by renewable energy sources **into** so-called “renewable” or “green” **gases** and **liquids**.
2. on the one hand, some of the **existing oil and gas infrastructure** could be used to transport these gases and liquids over large distances at a relatively low cost, thereby reducing the need to develop electricity transmission infrastructure and avoiding public acceptance issues.
3. on the other hand, these **gases and liquids have high energy densities**, and can be readily stored, providing an affordable option for seasonal energy storage.
4. gas networks in particular have some built-in flexibility, and **coupling electricity and gas** networks by conversion technologies **may provide flexibility** to the former.
5. combined **with carbon capture technologies**, some of **these gases <u>may</u> be carbon neutral**, providing high-density energy vectors to decarbonise sectors which are difficult to electrify.

Definitions of Sector Coupling

What does it mean in the end?

For folks **in** the **power business**, it usually **means electrifying everything** that can possibly be electrified and has not yet been electrified.

For people **in** the **gas sector**, it usually **means supplying low-carbon, renewable gas or liquids produced from electricity** to applications and sectors that cannot be easily electrified.

For the **European Commission**, it usually has to do with the **interconnection between gas and electricity networks**, and possibly the co-optimisation of both.

In summary, there is **no clear and unified definition**.

For our purpose

We will think of sector coupling as pertaining to the integration of different energy vectors, their underlying networks, and how this integration influences the planning, operation and regulation of the subsystems and the resulting interconnected system.

Enabling Processes and Technologies

Processes and Technologies

- Power-to-Gas
  1. Water Electrolysis
  2. Methane Synthesis (Methanation)
- Power-to-Liquids
  1. Fischer-Tropsch Synthesis
  2. Methanol Synthesis
  3. Ammonia Synthesis
- Gas/Liquids-to-Power
  1. Fuel Cells
  2. Gas Turbines
- Carbon Capture
  1. Pre/Post-Combustion Carbon Capture
  2. Direct Air Carbon Capture

Water Electrolysis

Decomposition of water into oxygen and hydrogen due to passage of electric current

$$2\,H_2O_{(l)} \xrightarrow{e^-} O_{2(g)} + 2H_{2(g)}$$

1 kilogram   0.89 kilogram   0.11 kilogram

Water Electrolysis Technologies

Three main technologies:

1. alkaline (AEL), which is mature and relatively cheap
2. proton exchange/polymer electrolyte membrane (PEMEL), which is commercialised but expensive
3. solid oxide (SOEL), which is still under development and very expensive

	AEL	PEMEL	SOEL
Temperature (°C)	60 - 80	50 - 80	650 - 1000
Pressure (bar)	< 20	< 200	<25
Lifetime (hr)	60k - 90k	20k - 60k	< 10k
Efficiency Degradation	0.25 - 1.5%/yr	0.5 - 2.5 %/yr	0.4-6%/1000h
Load Range (%)	20 - 100	0 - 100	-100 - 100
System Response	seconds	milliseconds	seconds
Cold Start-Up Time	mins or hrs	5 - 10 mins	hrs
Warm Start-Up Time	1 - 5 mins	seconds	15 mins
Stand-By Losses	negligible	negligible	high

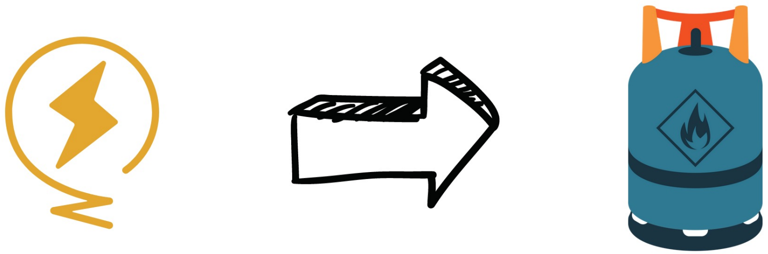
Methane Synthesis (Methanation)

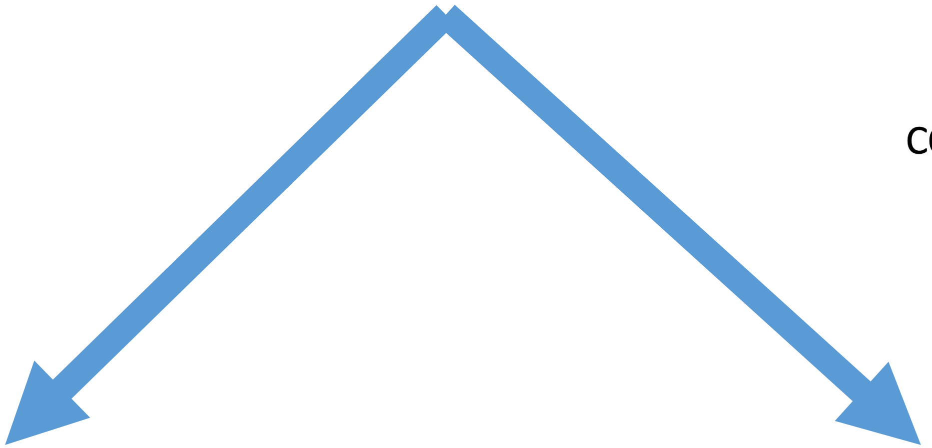
Hydrogenation of carbon dioxide (**Sabatier reaction**)

$$CO_{2(g)} + 4H_{2(g)} \longrightarrow CH_{4(g)} + 2H_2O_{(g)}$$

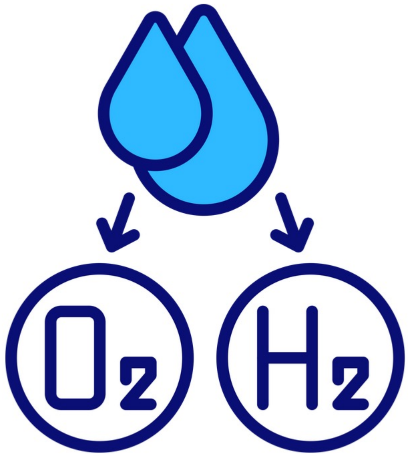
Two technologies exist, namely catalytic methanation and biological methanation

Power-to-Gas





$$2\ H_2O_{(l)} \xrightarrow{e^-} O_{2(g)} + 2H_{2(g)}$$



Water Electrolysis

$$CO_{2(g)} + 4H_{2(g)} \longrightarrow CH_{4(g)} + 2H_2O_{(g)}$$

Methane Synthesis

Fischer-Tropsch Synthesis

Alkane (hydrocarbon) formation from hydrogen and carbon monoxide

$$(2n+1)H_{2(g)} + nCO_{(g)} \longrightarrow C_nH_{2n+2(l)} + nH_2O$$

In the original process, feedstocks were obtained via coal or biomass gasification. To produce carbon monoxide sustainably, carbon capture technologies would be required.

Methanol Synthesis

Hydrogenation of carbon monoxide and carbon dioxide (variant of Sabatier reaction)

$$CO_{(g)} + 2H_{2(g)} \longrightarrow CH_3OH_{(g)}$$

$$CO_{2(g)} + 3H_{2(g)} \longrightarrow CH_3OH_{(g)} + H_2O_{(g)}$$

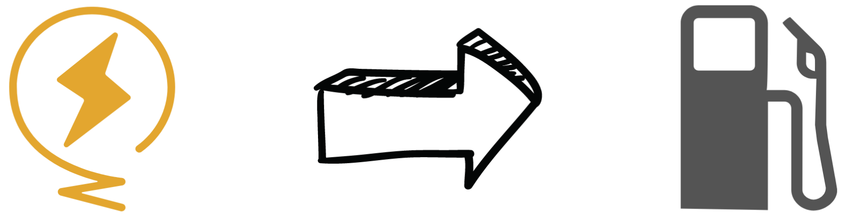
Ammonia Synthesis

Combination of hydrogen and nitrogen (Haber-Bosch process)

$$3H_{2(g)} + N_{2(g)} \longrightarrow 2\ NH_{3(g)}$$

Other processes include the solid-state ammonia synthesis process.

Power-to-liquids



1 - Fischer-Tropsch Synthesis:

$$(2n+1)H_{2(g)} + nCO_{(g)} \longrightarrow C_nH_{2n+2(l)} + nH_2O$$

2 - Methanol Synthesis:

$$CO_{(g)} + 2H_{2(g)} \longrightarrow CH_3OH_{(g)}$$

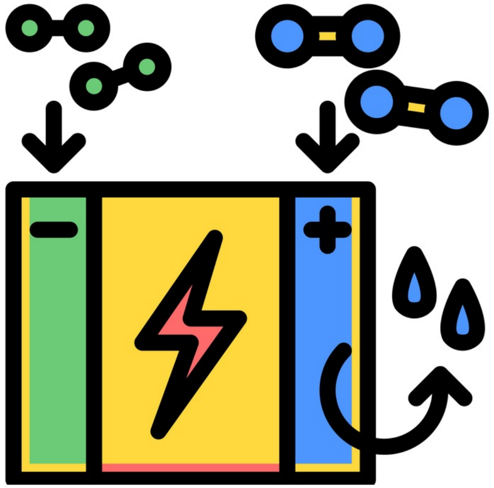
$$CO_{2(g)} + 3H_{2(g)} \longrightarrow CH_3OH_{(g)} + H_2O_{(g)}$$

3 - Ammonia Synthesis:

$$3H_{2(g)} + N_{2(g)} \longrightarrow 2\,NH_{3(g)}$$

Processes 2 and 3 require liquefaction

Fuel Cells



Fuel cells are key to re-power gas and liquids, in particular

1. Hydrogen
2. Synthetic Methane
3. Methanol
4. Ammonia

Alternative to fuel cells include gas turbines (for synthetic methane and hydrogen)

Pre/Post-Combustion Carbon Capture

In the context of power generation and industrial processes, (at least) two carbon capture technologies exist, namely pre and post-combustion carbon capture:

1. Pre-combustion carbon capture is used in plants with integrated gasification units, i.e, where solid fuels are gasified, carbon dioxide is captured, and syngas is then burnt/used
2. Post-combustion carbon capture units “filter” flue gases resulting from the combustion of fuels in order to extract carbon dioxide (and possibly other compounds, e.g., nitrogen oxides)

These processes consume non-negligible amounts of energy/electricity, and **reduce** the **efficiency** of power plants equipped with such capture units **by 5-10%.**

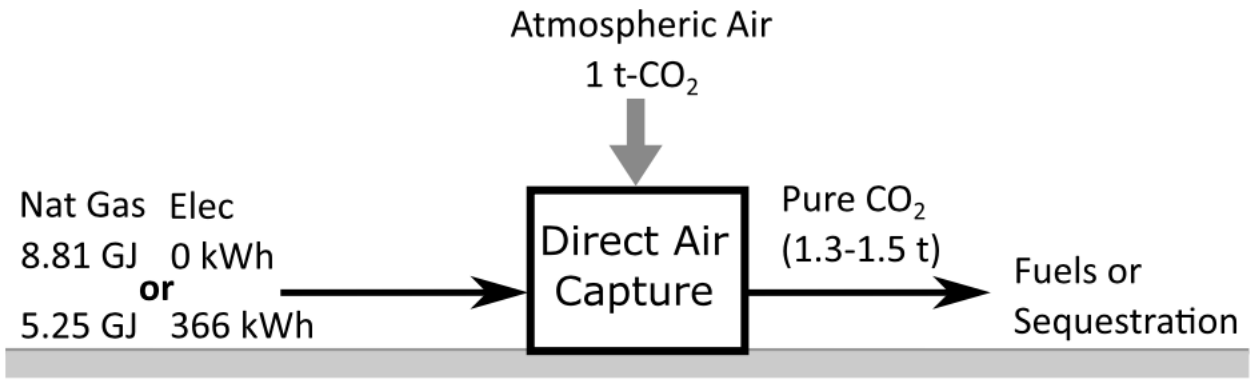
Capture units also lead to **extra investment and operating costs**, often on the order of that of the electric generator itself

Direct Air Carbon Capture

Technologies exist that capture carbon dioxide directly from the atmosphere

Relatively few companies work on this, most notable Carbon Engineering and Climeworks

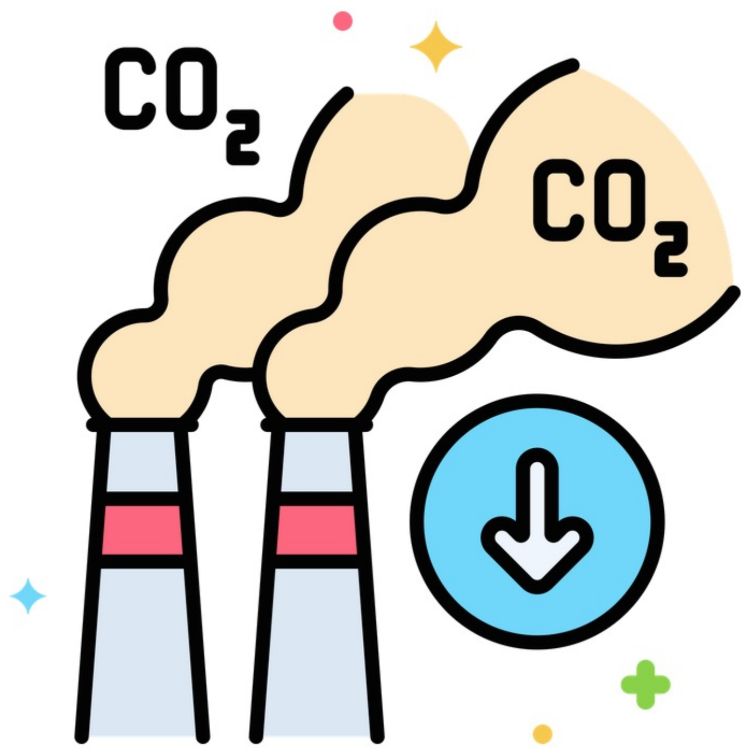
The cost of these technologies remains prohibitive and they consume a lot of energy



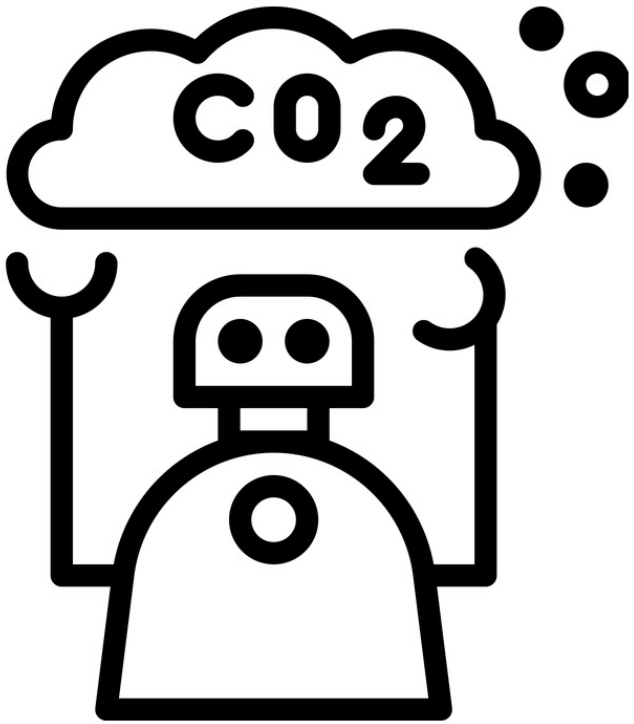
Source: Keith et al., "A process for capturing CO_2 from the atmosphere", Joule 2, 1573-1594, 2018

Capture technologies

Pre/Post Combustion Capture



Direct Air Capture (DAC)



Going beyond technologies: energy system integration

Going beyond individual technologies

Recall that in our definition, sector coupling has to do with the integration of energy carriers, networks, and how this impacts the planning, operation and regulation of the resulting interconnected system.

It has become increasingly obvious that interconnecting systems may have benefits but major drawbacks can also emerge if this integration is only partial and ineffective, e.g., if subsystems are operated and planned independently of one another.

In fact, the coordination of planning and operation of integrated energy systems and the establishment of regulatory frameworks supporting these activities is essential to guarantee the reliability and proper functioning of these systems.

A winter in New England: heating or lighting?

2013 Special Reliability Assessment:

Accommodating an Increased Dependence on Natural Gas for Electric Power

Phase II: A Vulnerability and Scenario Assessment for the North American Bulk Power System

Source: https://www.nerc.com/pa/RAPA/ra/Reliability%20Assessments%20DL/NERC_PhaseII_FINAL.pdf

A winter in New England, revisited

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Cascading risks: Understanding the 2021 winter blackout in Texas

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ABSTRACT

The Texas freeze of February 2021 left more than 4.5 million customers (more than 10 million people) without electricity at its peak, some for several days. The freeze had cascading effects on other services reliant upon electricity including drinking water treatment and medical services. Economic losses from lost output and damage are estimated to be $130 billion in Texas alone. In the wake of the freeze, there has been major fallout among regulators and utilities as actors sought to apportion blame and utilities and generators began to settle up accounts. This piece offers a retrospective on what caused the blackouts and the knock-on effects on other services, the subsequent financial and political effects of the freeze, and the implications for Texas and the country going forward. Texas failed to sufficiently winterize its electricity and gas systems after 2011. Feedback between failures in the two systems made the situation worse. Overall, the state faced outages of 30 GW of electricity as demand reached unprecedented highs. The gap between production and demand forced the non-profit grid manager, the Electric Reliability Council of Texas (ERCOT), to cut off supply to millions of customers or face a systems collapse that by some accounts was minutes away. The 2021 freeze suggests a need to rethink the state's regulatory approach to energy to avoid future such outcomes. Weatherization, demand response, and expanded interstate interconnections are potential solutions Texas should consider to avoid generation losses, reduce demand, and tap neighboring states' capacity.

A winter in New England, revisited

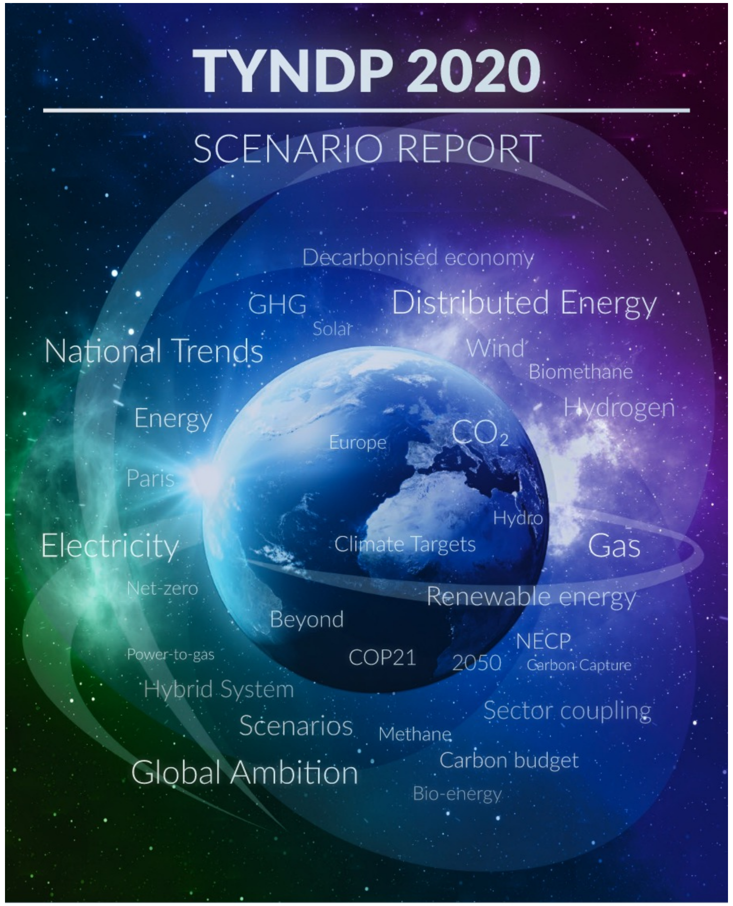
A B S T R A C T

The Texas freeze of February 2021 left more than 4.5 million customers (more than 10 million people) without electricity at its peak, some for several days. The freeze had cascading effects on other services reliant upon electricity including drinking water treatment and medical services. Economic losses from lost output and damage are estimated to be $130 billion in Texas alone. In the wake of the freeze, there has been major fallout among regulators and utilities as actors sought to apportion blame and utilities and generators began to settle up accounts. This piece offers a retrospective on what caused the blackouts and the knock-on effects on other services, the subsequent financial and political effects of the freeze, and the implications for Texas and the country going forward. Texas failed to sufficiently winterize its electricity and gas systems after 2011. Feedback between failures in the two systems made the situation worse. Overall, the state faced outages of 30 GW of electricity as demand reached unprecedented highs. The gap between production and demand forced the non-profit grid manager, the Electric Reliability Council of Texas (ERCOT), to cut off supply to millions of customers or face a systems collapse that by some accounts was minutes away. The 2021 freeze suggests a need to rethink the state's regulatory approach to energy to avoid future such outcomes. Weatherization, demand response, and expanded interstate interconnections are potential solutions Texas should consider to avoid generation losses, reduce demand, and tap neighboring states' capacity.

Source: https://www.sciencedirect.com/science/article/pii/S2214629621001997

We’re on the right track but not quite there yet

ENTSO-G and ENTSO-E released joint scenario assessments for future network development plans



Association of gas transmission system operators

entsog

entsoe

Association of electricity transmission system operators

Sector Coupling in the Belgian Context

Motivation

- Belgian nuclear power plants to be decommissioned by end of 2025. Low-carbon alternatives must be selected, make **economic sense** and promote **energy security**.

- Electrification often presented as only means of achieving deep decarbonisation of energy system, including transport and heating.

- Power-to-gas may play role by offering seasonal storage and supplying some of energy demand for transport and heating.

Problem Statement and Formulation

Which generation, conversion and storage technologies should be deployed, and in what quantities, to supply load at minimum cost whilst satisfying technical constraints and pre-specified policy targets?

Input

- Technology costs and performance
- Renewable resource quality and availability
- Future electricity, gas and hydrogen demands
- Regional wholesale electricity and gas prices
- Hydrogen industry and transport prices
- Policy targets (CO_2 and energy import quotas)

Formulation

Central Planner
(system cost minimization)

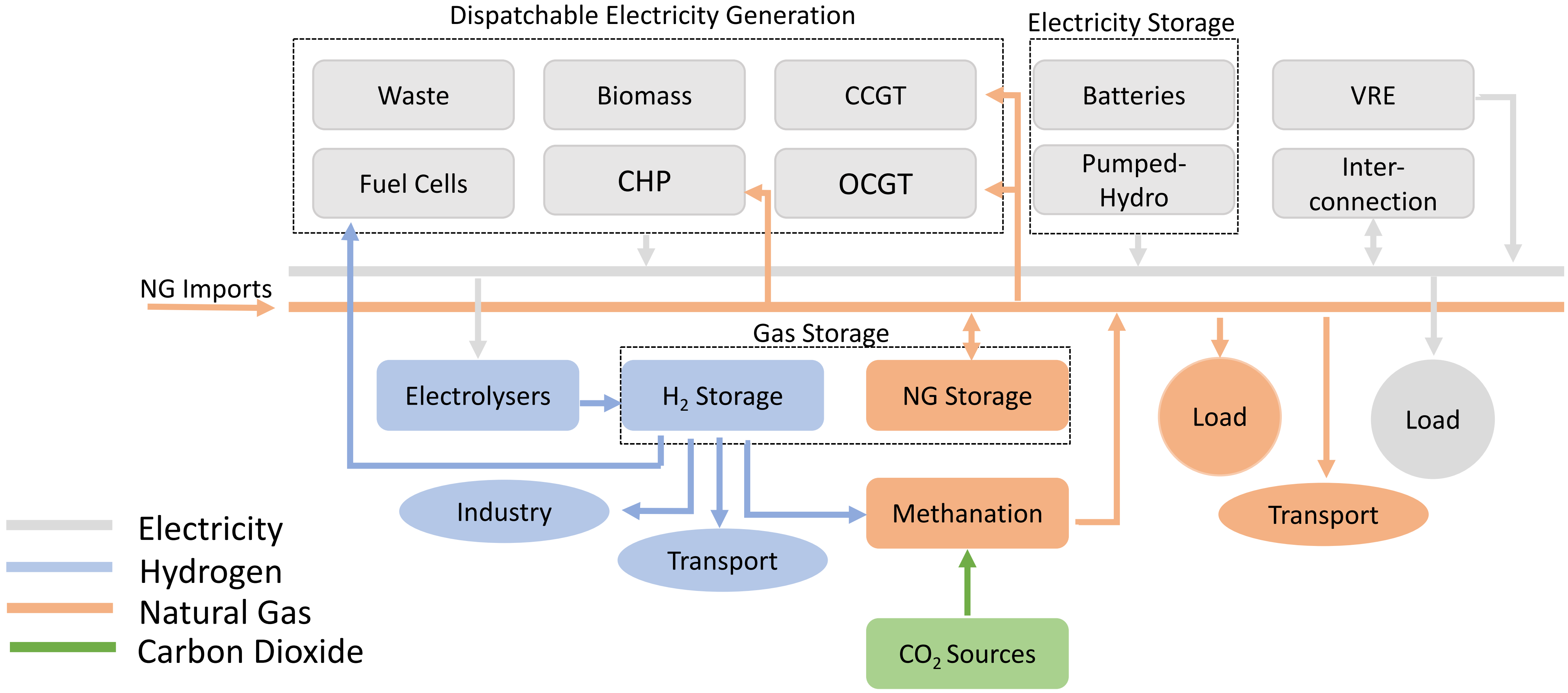
Output

- Technology selection
- Technology capacities
- System and energy costs
- Energy flows
- CO_2 emissions

Model Assumptions

- Joint electricity and gas system planning, plants are aggregated by technology.
- No congestion in networks, electricity, gas and hydrogen demands are spatially-aggregated.
- Multi-year investment horizon with hourly resolution, “overnight” technology deployment.
- Perfect foresight and perfect competition.

System Configuration



First Scenario

Constant Carbon Dioxide Emissions and Nuclear Phase-Out

1. 38 Mt annual carbon dioxide emissions budget for electricity and gas systems, defined as difference between CO_2 emitted and absorbed, excluding CO_2 emitted by cars running on CNG.
2. Belgian RES potential of solar PV is 40 GW.
3. CAPEX of 1400 €/kW_e (electrolysers), 600 €/kW_{H2} (methanation), 1000 €/kW_e (fuel cells).
4. RES potential of onshore and offshore wind is 8.4 GW and 8 GW, respectively.
5. Peak electrical load of 13.5 GW and annual electricity consumption of 86.4 TWh.
6. Peak gas load of 40.1 GW and annual (non-power) gas consumption of 135.7 TWh.
7. Hydrogen/CNG transportation market of 250k/500k cars (approx. 2.7/5.4 TWh) and industry hydrogen demand of 1 GWh/h.
8. Import capacity of 6.5 GW, no more than 10% of annual electricity consumption can be imported.
9. Mean electricity and natural gas import costs of 36.9 €/MWh and 11.8 €/MWh, respectively.
10. Capacities of 1.3 GW/5.3 GWh of pumped-hydro storage and (in/out) 3.5/7 GW/8 TWh of natural gas storage.
11. Carbon tax of 80 €/t of CO_2 for emissions from power generation and none for other emissions.
12. Zero initial capacity for RES and gas-fired power plants. 0.3 GW, 0.9 GW and 1.8 GW of waste, biomass and combined heat and power plants, respectively.
13. CAPEX of 1100 €/kW and 2500 €/kW (on/offshore wind), 1000 €/kW (solar PV), 200 €/kWh (batteries), 5 €/kWh (hydrogen storage).
14. Value of lost load of 3000 €/MWh and 500 €/MWh for electricity and gas demands, respectively.
15. Price of hydrogen for industry and transportation of 0.15 €/kWh and 0.3 €/kWh, and CNG price of 0.2 €/kWh.

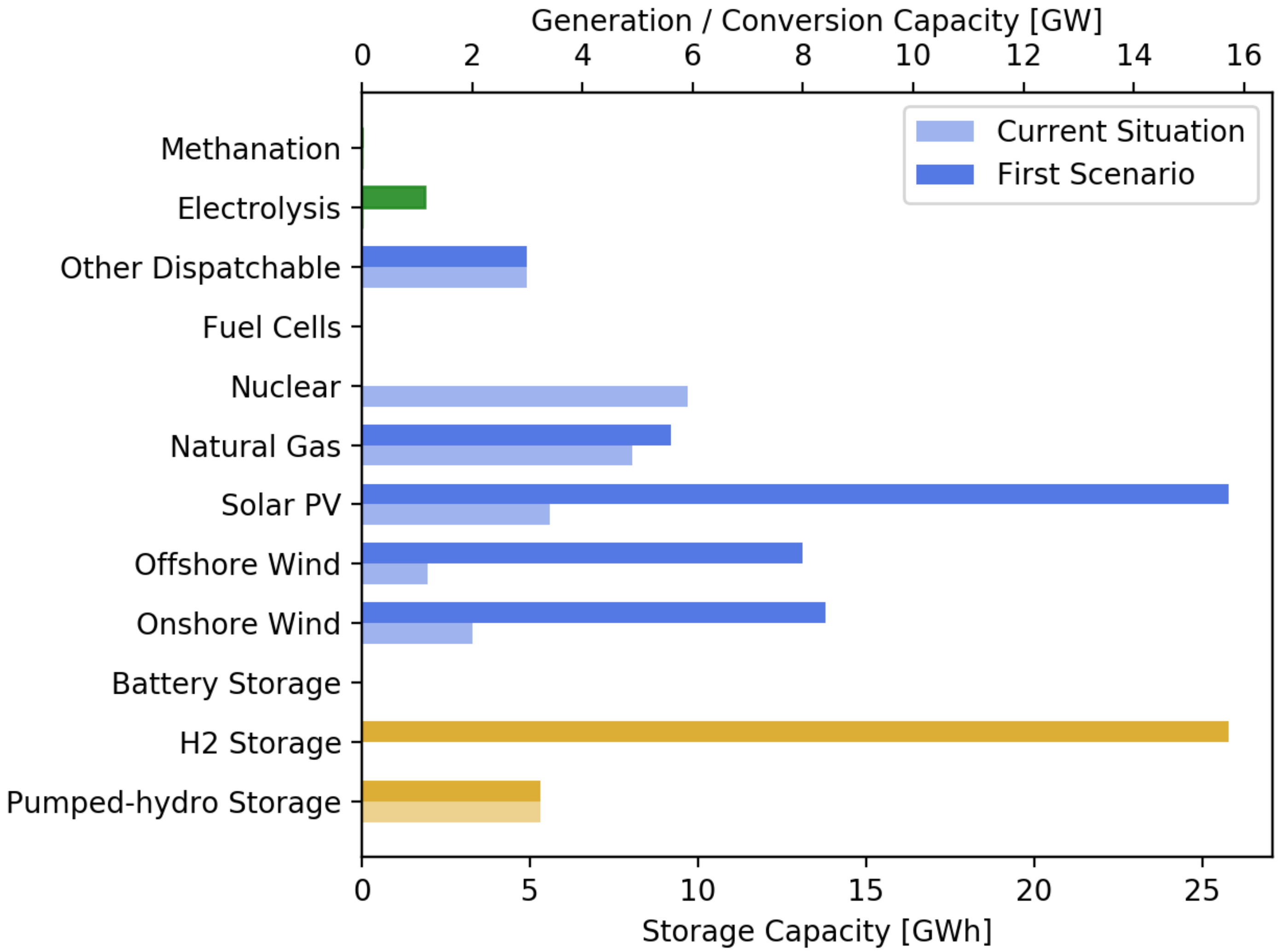
Installed Technologies, Capacities[1] and Costs

System Cost:

8.4 B€

Energy Cost:

36.5 €/MWh

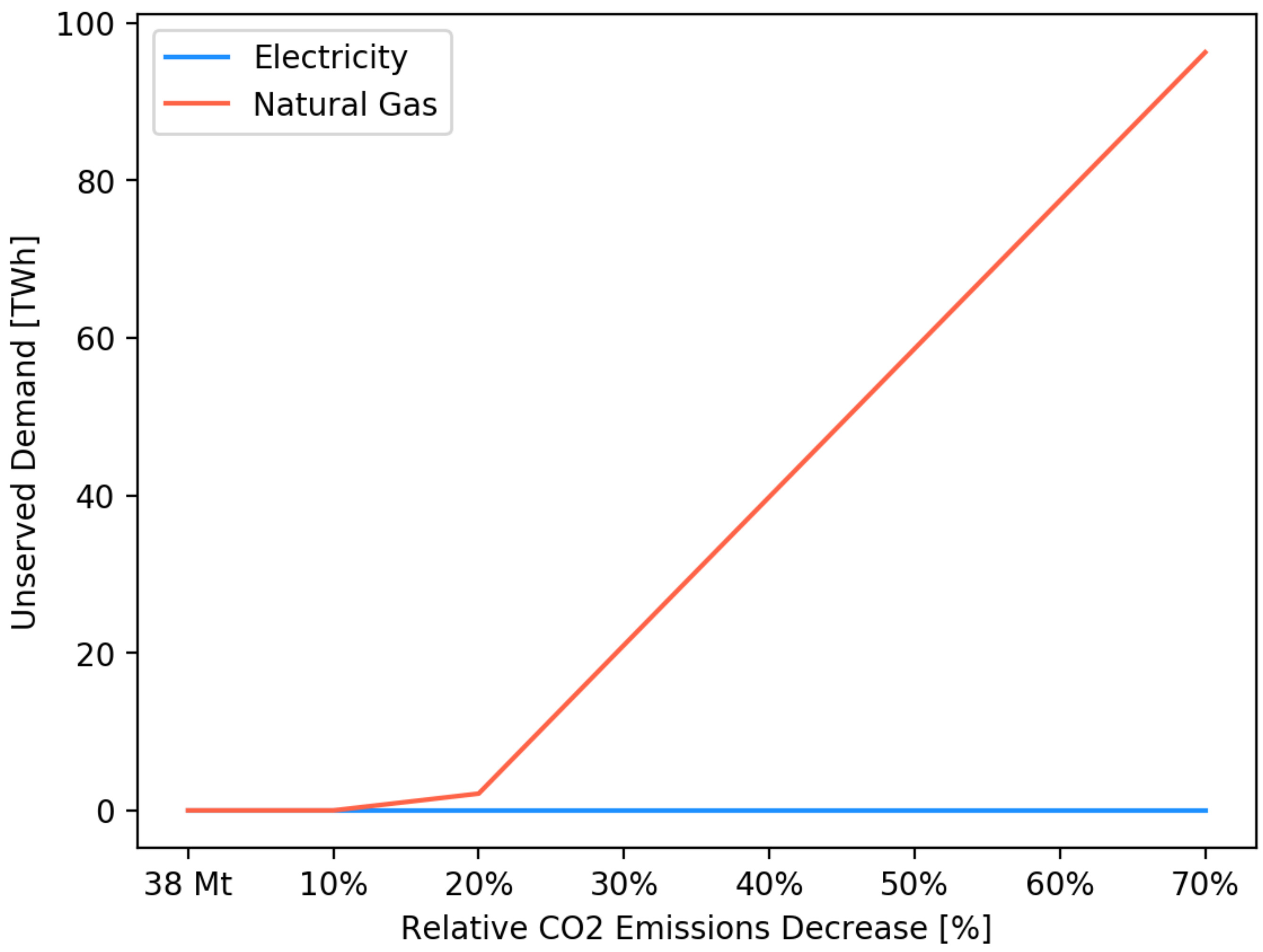


1: Ratio between energy and power capacity of batteries is equal to 2.

Energy not Served vs Carbon Budget

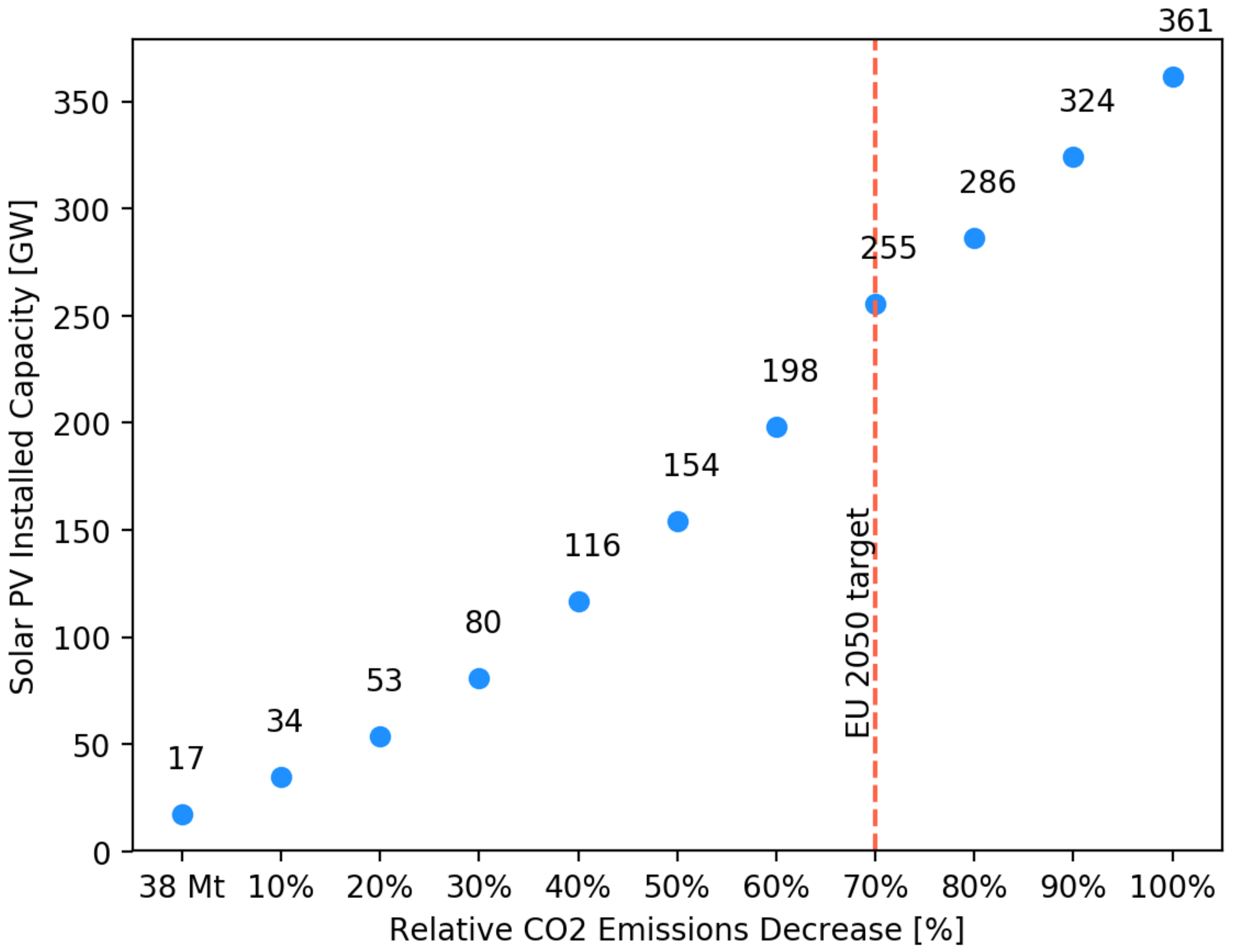
Electricity VoLL[2]:
3000 €/MWh

Gas VoLL:
500 €/MWh



2: Value of Lost Load (VoLL).

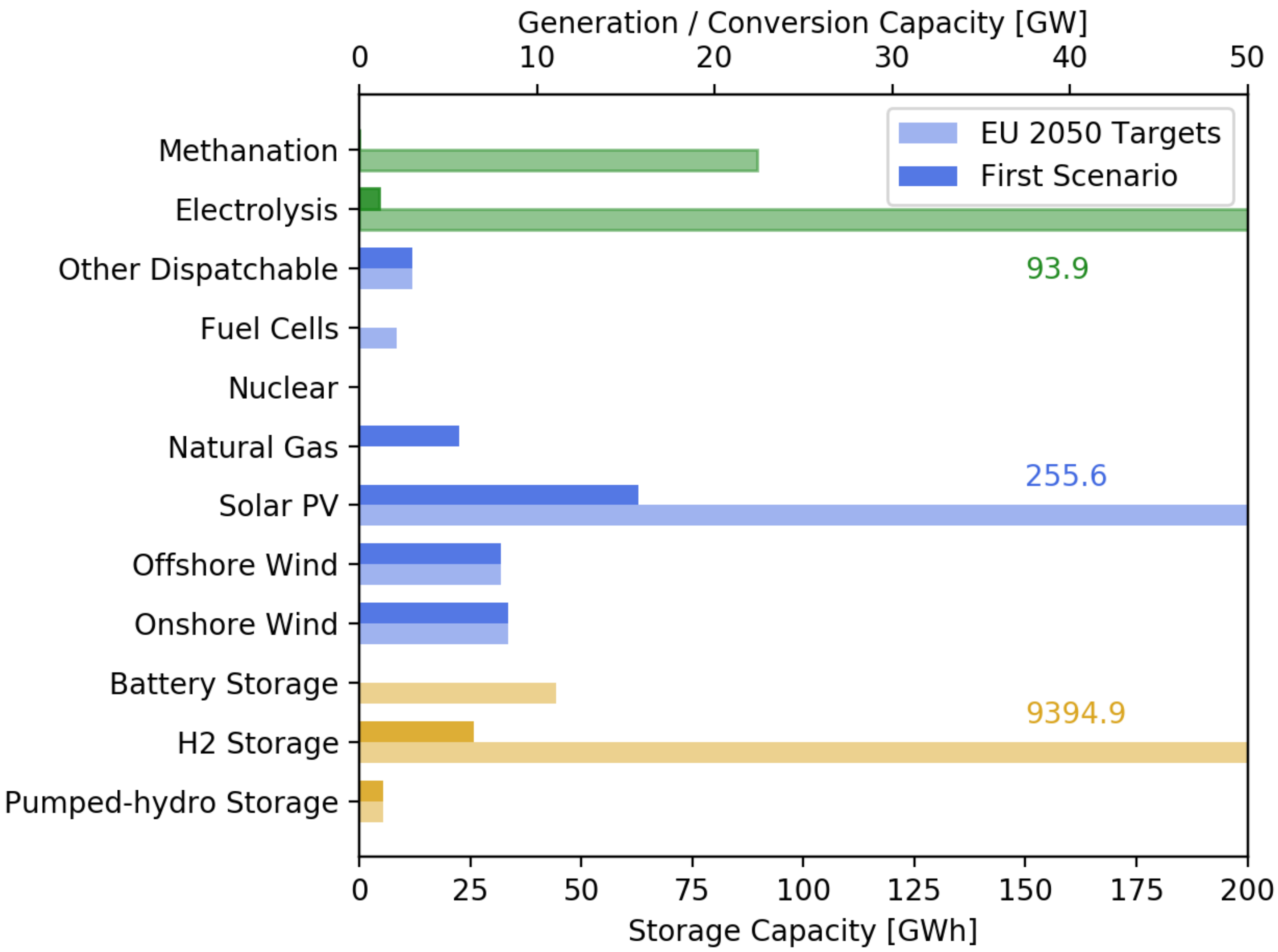
Solar PV Capacities for Zero Shedding vs Carbon Budget[3]



3: Load shedding not allowed, imposed as hard constraint.

System Design for European 2050 Targets

System Cost[4]:
43.1 B€



Energy Cost:
186 €/MWh

4: Power-to-gas and fuel cell costs are half those from first scenario.

Land Area and Storage Volume Requirements

Assuming that 100 MW of solar PV require 1 km^2 of land, whilst 10 MW of wind turbines span 1 km^2

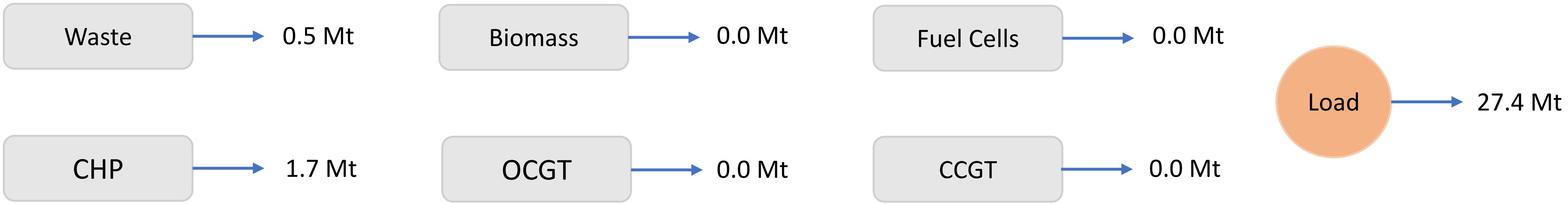
Solar PV Surface Area	Onshore Wind Surface Area	Offshore Wind Surface Area
2556 km^2	840 km^2	800 km^2

Assuming (gaseous) hydrogen compressed at 700 bar has an energy density of 1657 kWh/m^3,

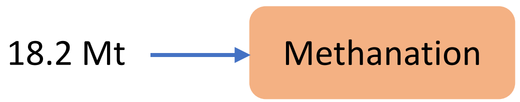
Hydrogen Storage Volume	Side Length of Equivalent Cube
5.7 Mcm	178 m

Carbon Dioxide Budgeting

Carbon Dioxide Emissions



Carbon Dioxide Consumption



Net Carbon Dioxide Budget

0.5 + 1.7 + 27.4 – 18.2 = 11.4 Mt

Carbon Dioxide and Water Needs for Power-to-Gas

The electrolysis process requires water. In total, 127 TWh of hydrogen are produced, which corresponds to

Water Volume for Hydrogen Production	Side Length of Equivalent Cube
34.4 Mcm	325 m

The methanation process consumes CO_2. In total, 92 TWh of synthetic methane are produced, which requires

Mass of Carbon Dioxide Required	Emissions from cement industry in Belgium
18.2 Mt/y	3 Mt/y

Summary

Summary

- The sector coupling concept emerged largely in response to concerns that a full electrification pathway would not be possible or prohibitively expensive.

- A variety of processes and technologies are fundamental enablers of sector coupling. The key process is water electrolysis, which produces hydrogen from an electric current. All processes down the power-to-gas/liquids chain require hydrogen as feedstock. Carbon capture technologies also play key role by providing carbon dioxide used as feedstock.

- For sector coupling to be effective, properly integrating various energy subsystems is crucial. This involves developing coordination mechanisms between system operators to support planning and operation procedures, and establishing regulatory frameworks conducive to these activities.

Reading for Next Session

A recent paper on sector coupling in Belgium

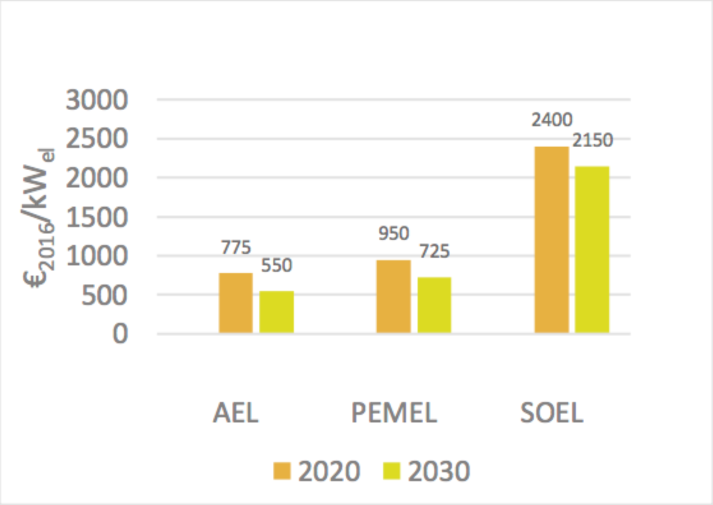
M. Berger et al., “The role of power-to-gas and carbon capture technologies in cross-sector decarbonisation strategies”, Electric Power Systems Research, 2020.

On the site of M Ernst along with the questions.

Additional Techno-Economic Data

Water Electrolysis Technologies

COST



EFFICIENCY

	AEL	PEMEL	SOEL
Stack	63-71 %	60-68 %	98%
System	46-60 %	50-60%	< 84.6%

MATURITY

AEL	Mature (TRL 9)
PEMEL	Commercial with development potential (TRL 8)
SOEL	Demonstration (TRL 6)

DEPLOYMENT SCALE

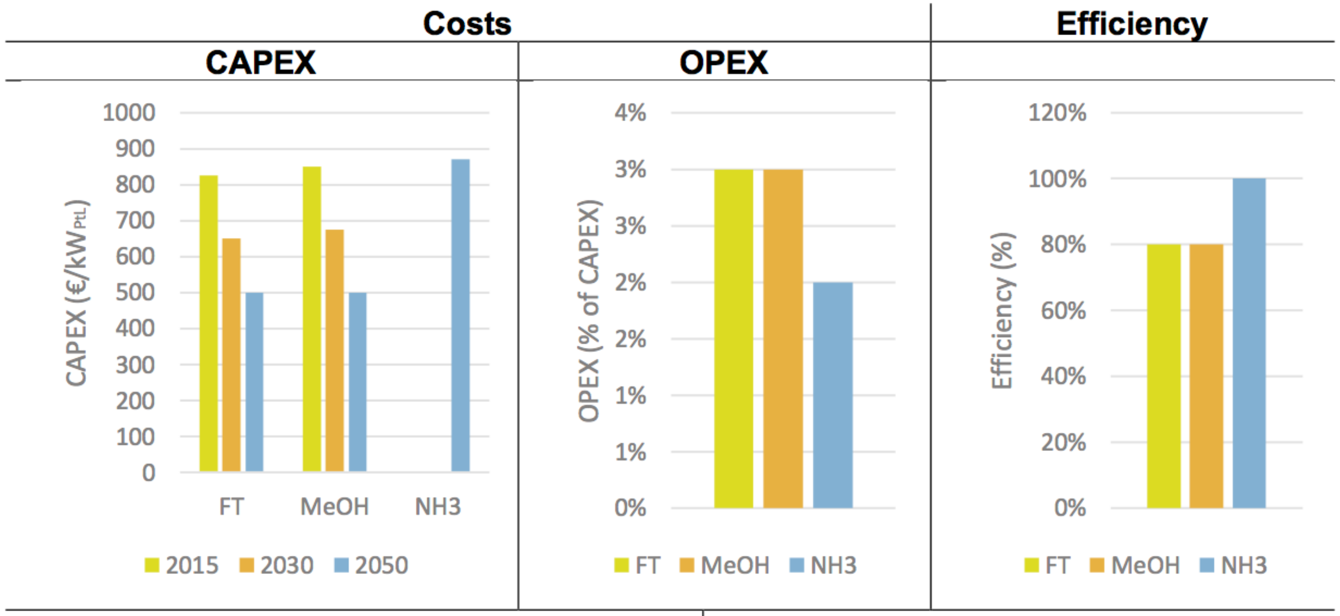
AEL	MW
PEMEL	MW
SOEL	kW

Power-to-Liquids

FT: Fischer-Tropsch

MeOH: Methanol

NH3: Ammonia



MATURITY

FT	Relatively established technology, however, not yet mature for power-to-liquids processes
MeOH	Relatively established technology, however, not yet mature for power-to-liquids processes
NH3	Relatively established technology, however, not yet mature for power-to-liquids processes

Examples of DEPLOYMENT

FT	Sunfire demonstration plant in Dresden*. Nordic Blue Crude in Norway**.
MeOH	Carbon Recycling International in Island***.
NH3	Proton Ventures – small scale ammonia plant**** World first Green Ammonia power demonstrator developed by

Further reading and references

ETIP SNET white paper on sector coupling:

https://www.etip-snet.eu/publications/etip-publications/