

# ELEC0080-1 Energy Networks, Part 1

## Introduction to Sector Coupling

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20/11/2019

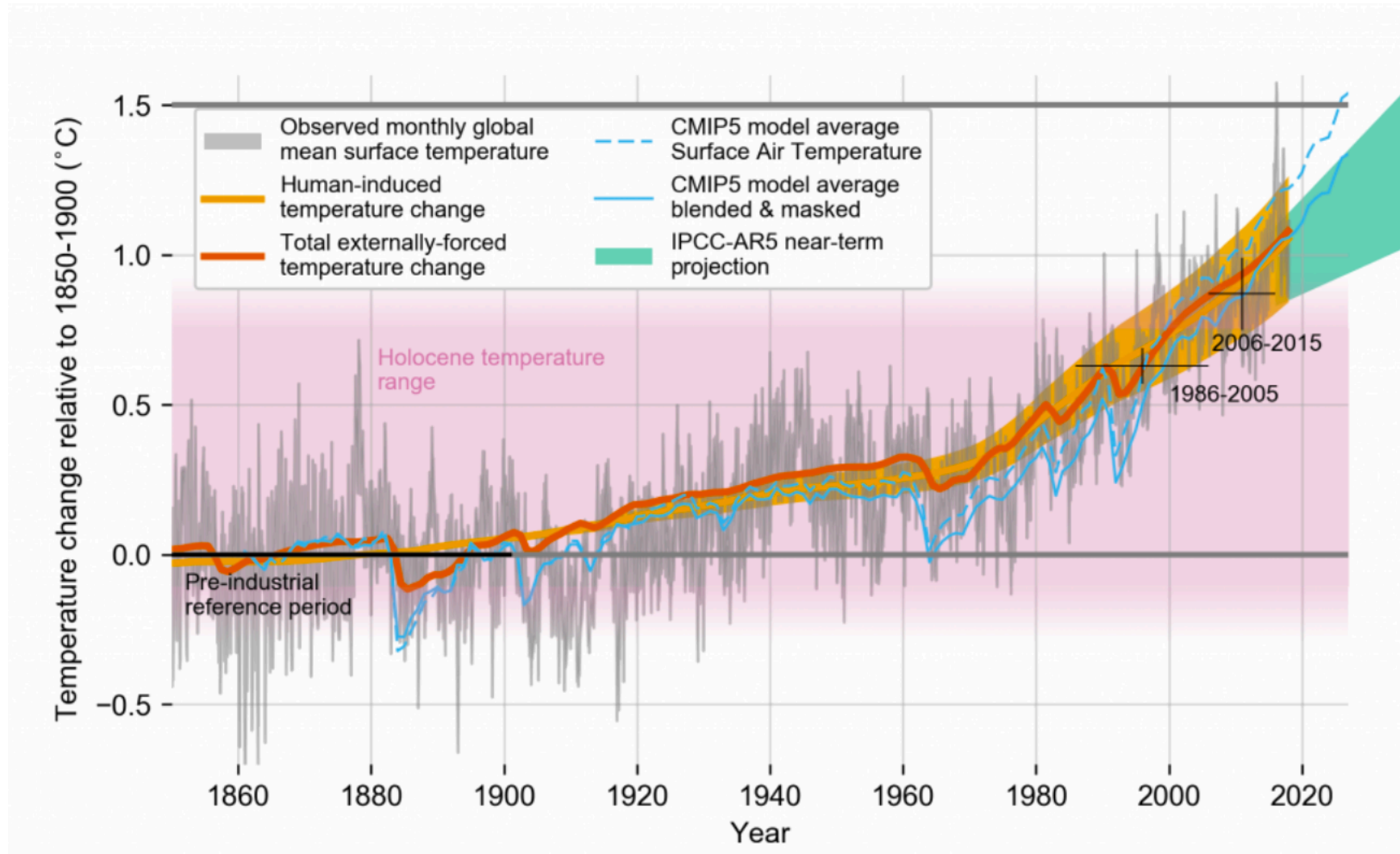
Arlon, Belgium

# Lecture Plan

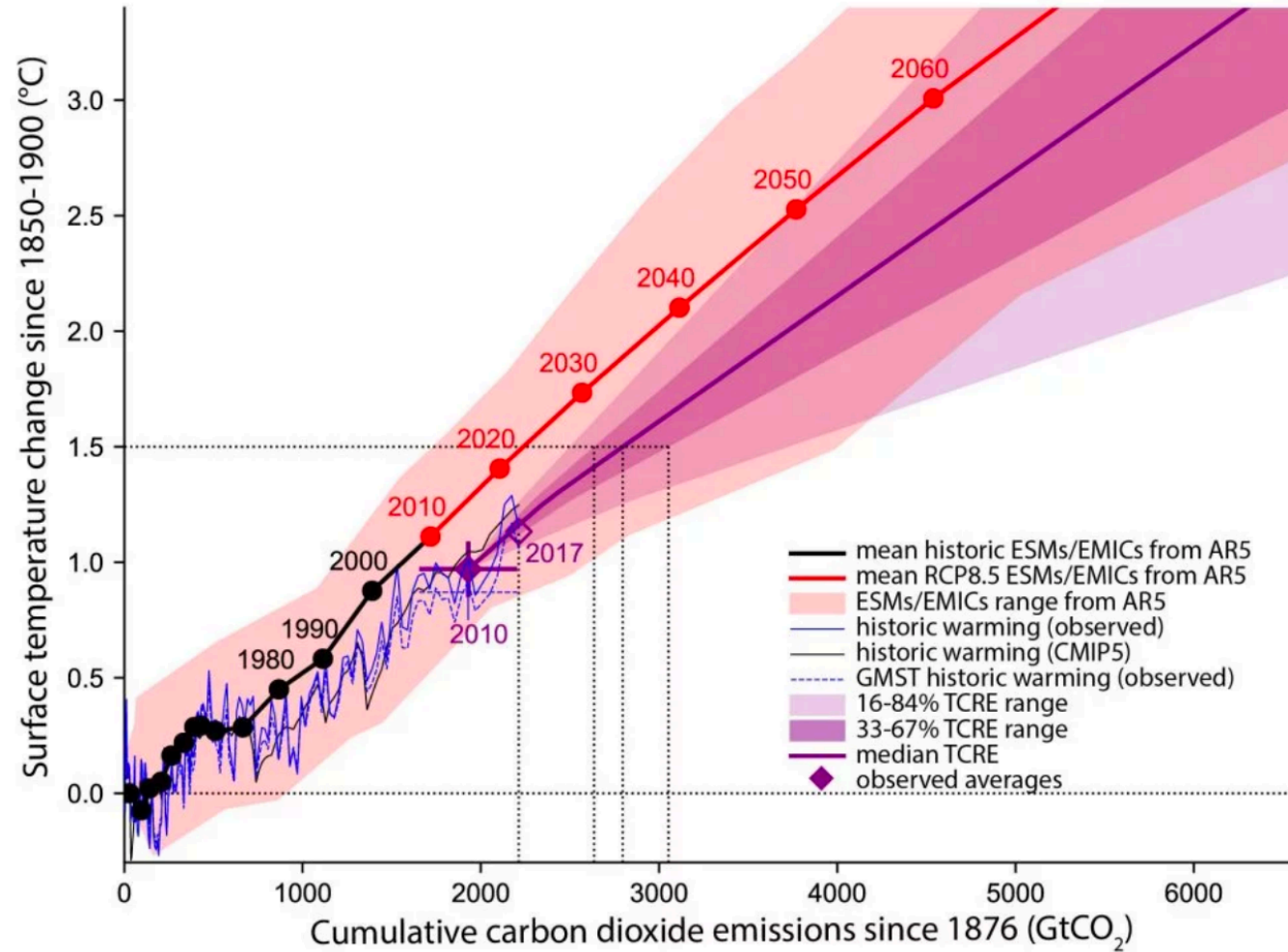
- The rationale behind sector coupling
- Definitions of sector coupling
- Enabling processes and technologies
- Going beyond technologies: energy system integration
- Sector coupling in the Belgian context: a case study
- Summary

# The Rationale behind Sector Coupling

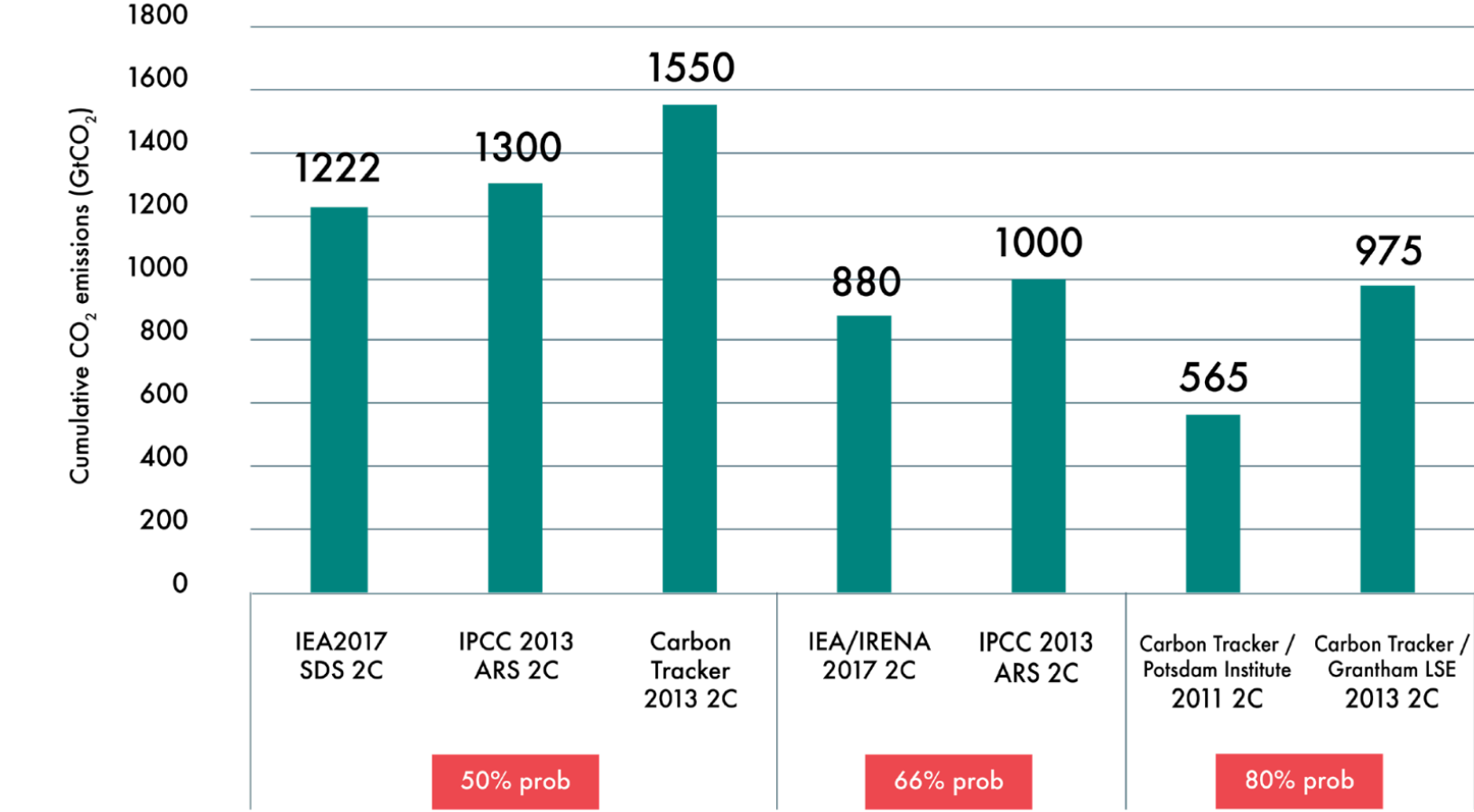
# They see me risin'...



... they hatin'



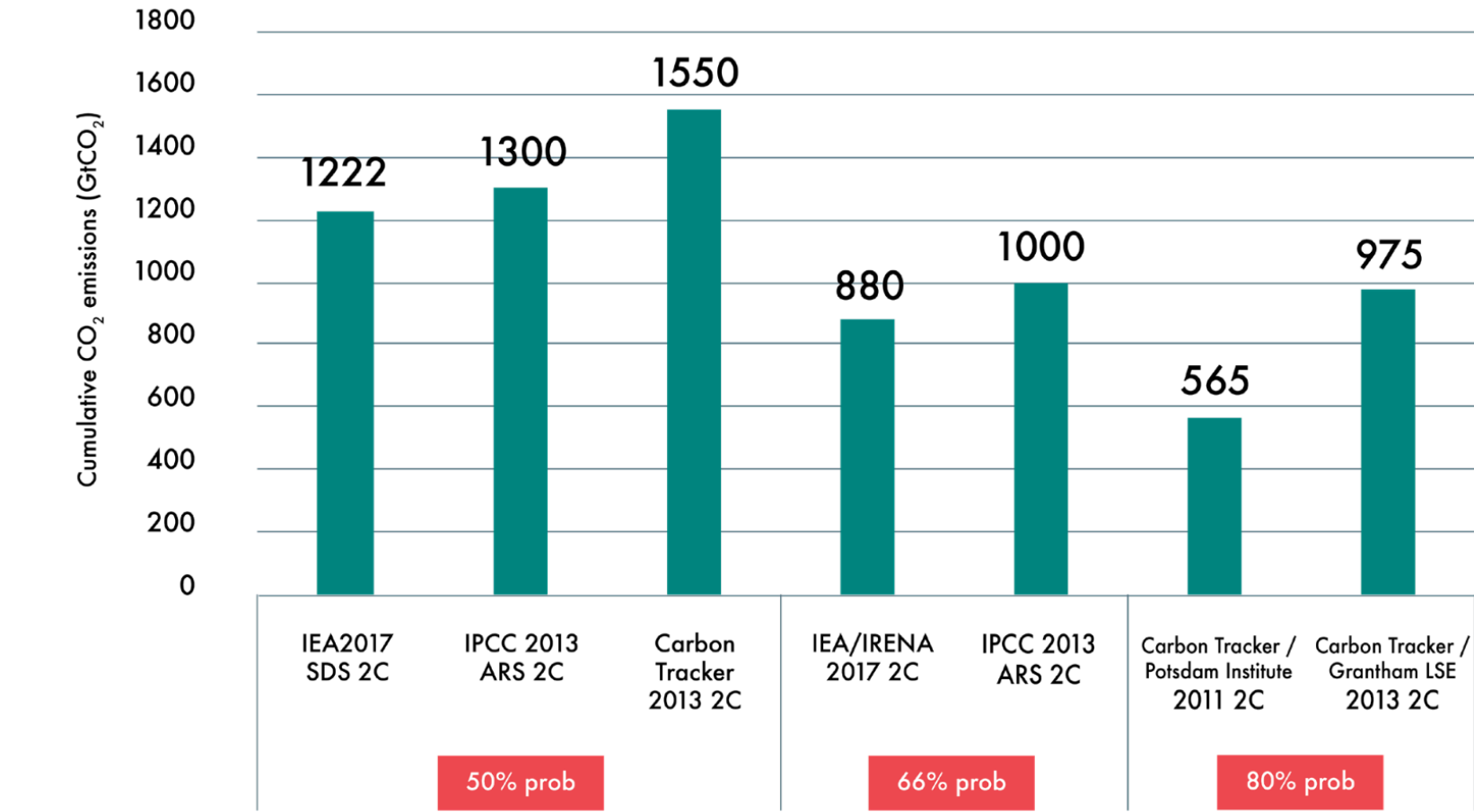
# We're on a (carbon) budget



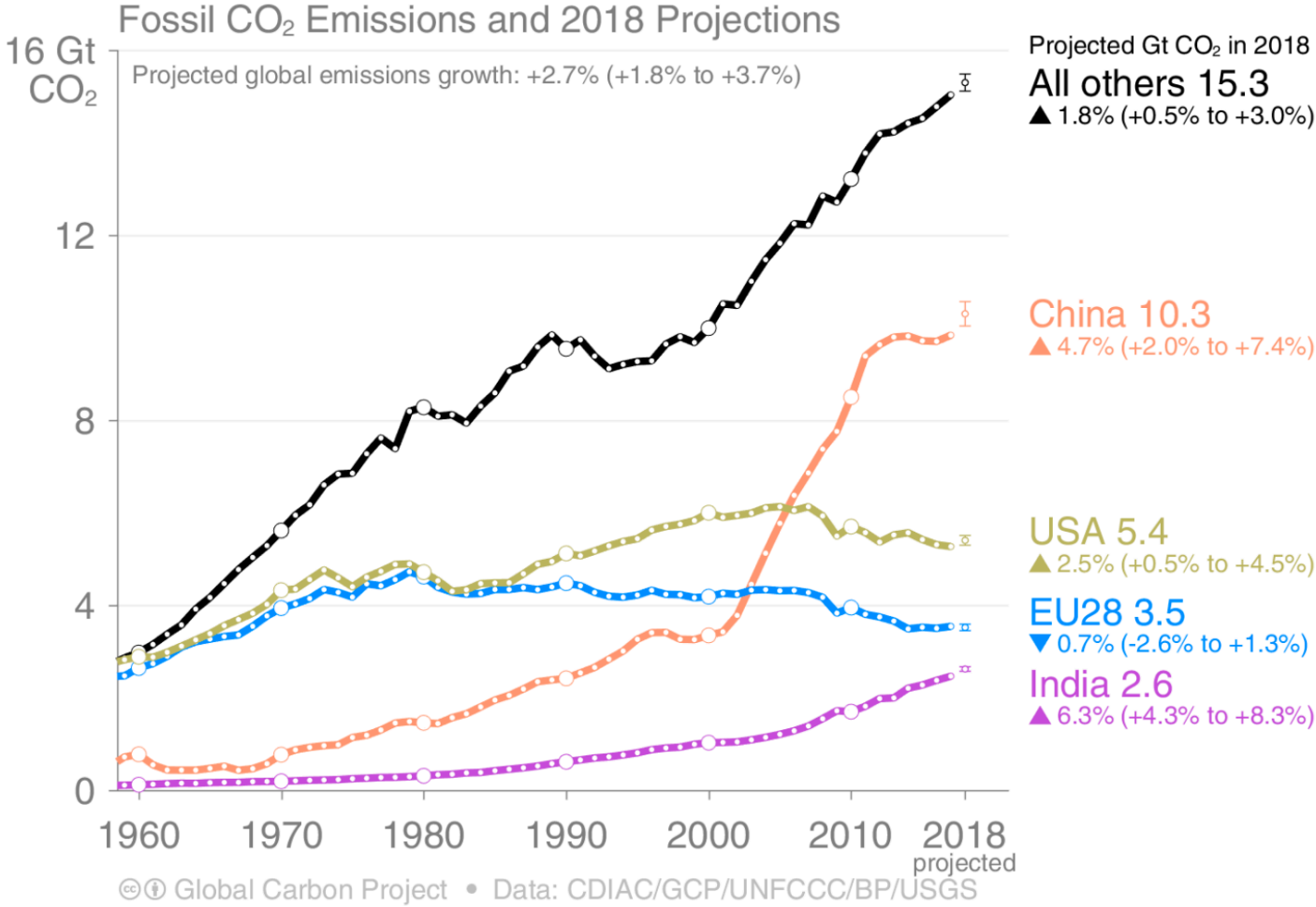
Source: [https://www.europarl.europa.eu/RegData/etudes/STUD/2018/626091/IPOL\\_STU\(2018\)626091\\_EN.pdf](https://www.europarl.europa.eu/RegData/etudes/STUD/2018/626091/IPOL_STU(2018)626091_EN.pdf)

# A tight one, that is

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

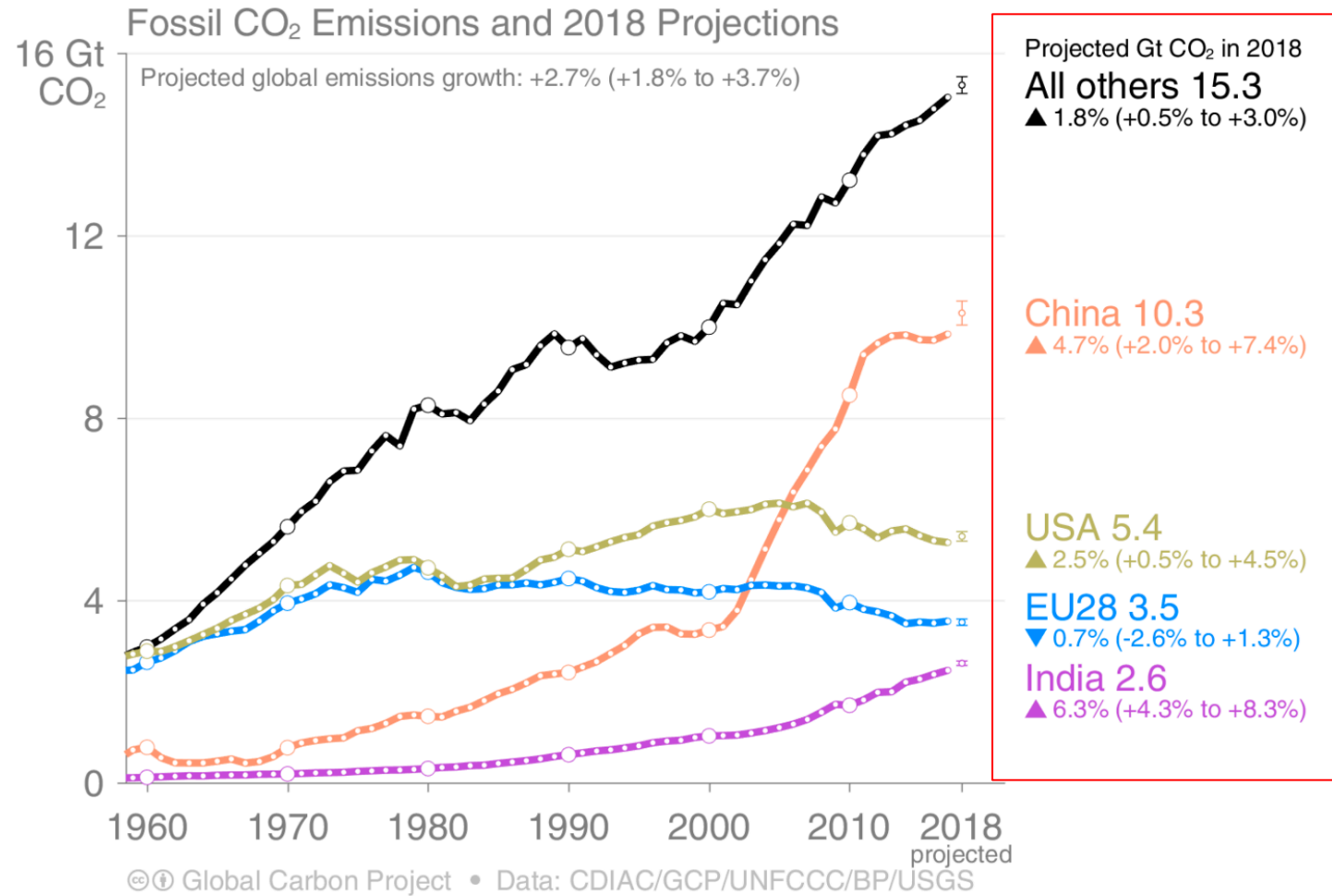


# Where are we at?

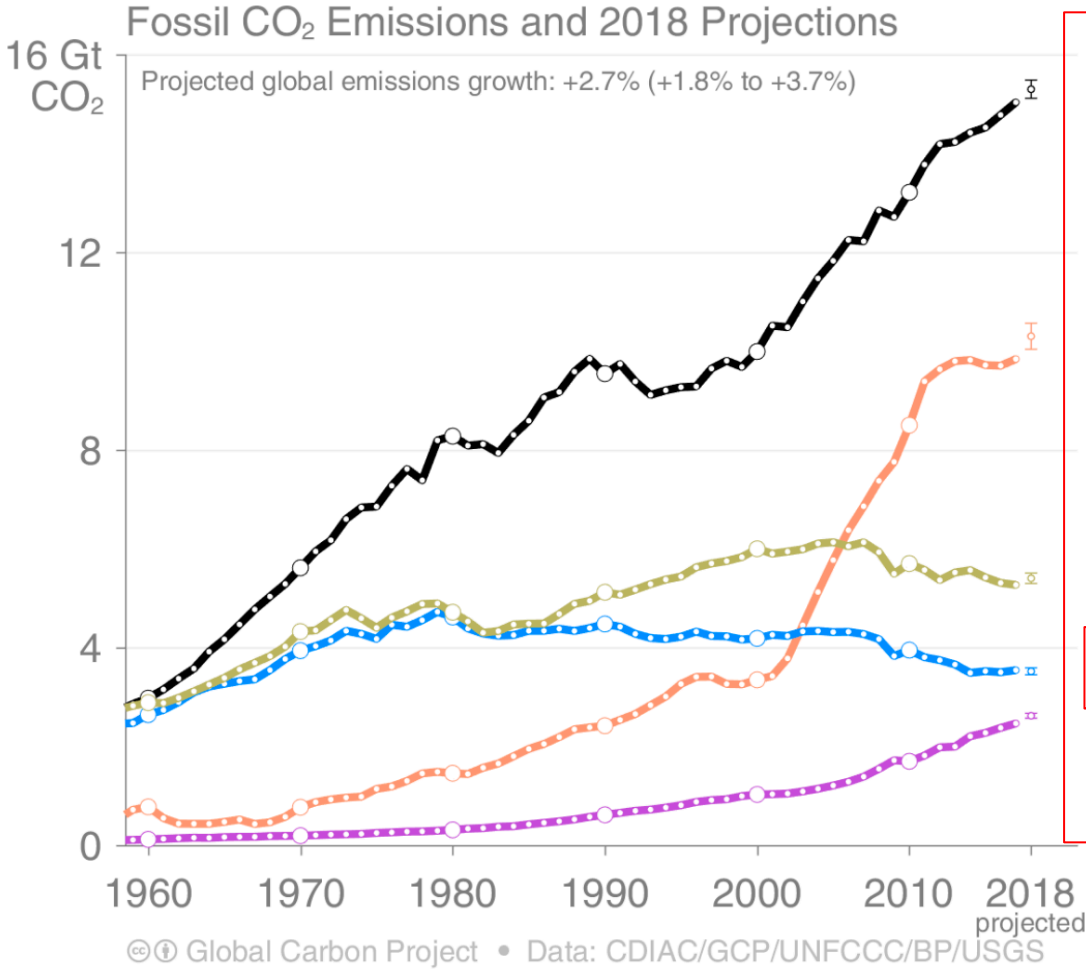




# This ain't looking good



# What about Europe?



Sums to 37.1 Gt

Projected Gt CO<sub>2</sub> in 2018

**All others 15.3**  
▲ 1.8% (+0.5% to +3.0%)

**China 10.3**  
▲ 4.7% (+2.0% to +7.4%)

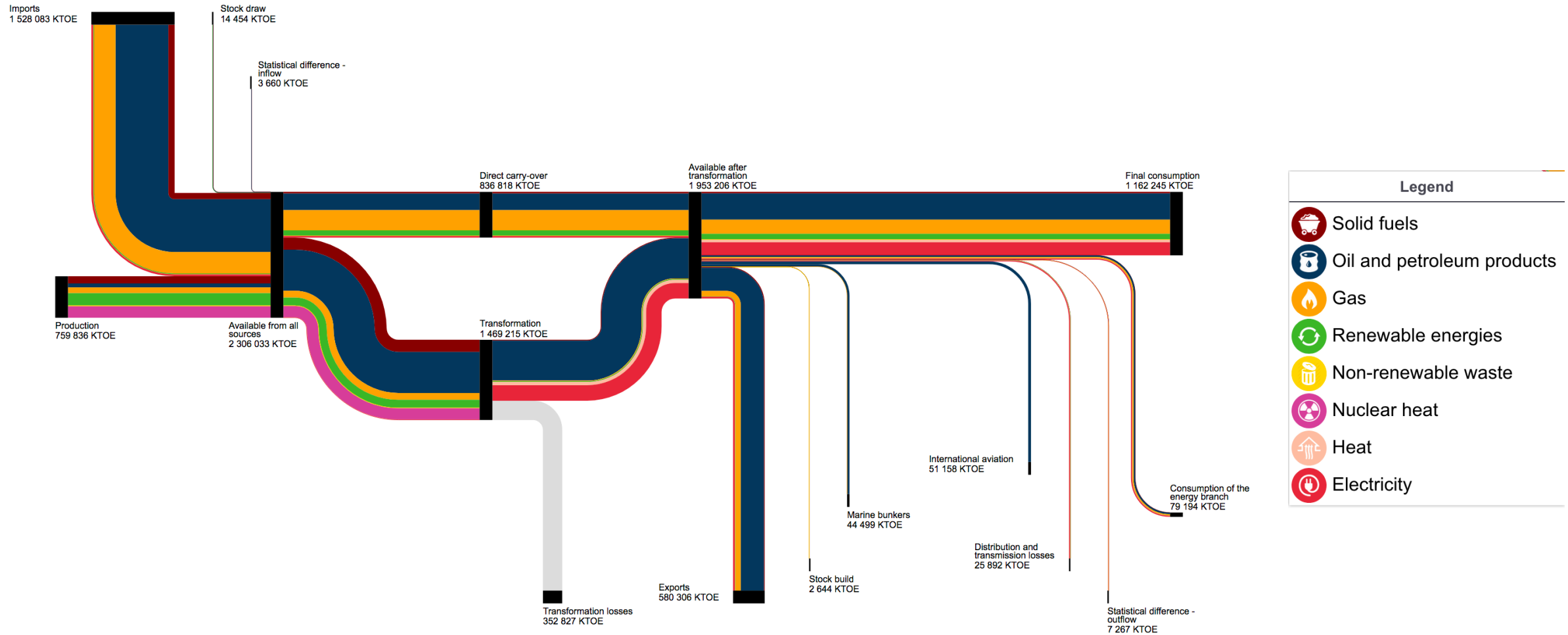
**USA 5.4**  
▲ 2.5% (+0.5% to +4.5%)

**EU28 3.5**  
▼ 0.7% (-2.6% to +1.3%)

**India 2.6**  
▲ 6.3% (+4.3% to +8.3%)

Budget exhausted in roughly 25 years

# The oil and gas binge goes on



# The solution?



# Possibly, but ...

## Full electrification 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 infrastructure, notably to absorb vast volumes of decentralised electricity production.
2. public acceptance of new infrastructure projects has become a show-stopper in several regions.
3. 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 the electricity.
4. besides hydro, which is already saturated or near saturation 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 may 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 resulting interconnected system.

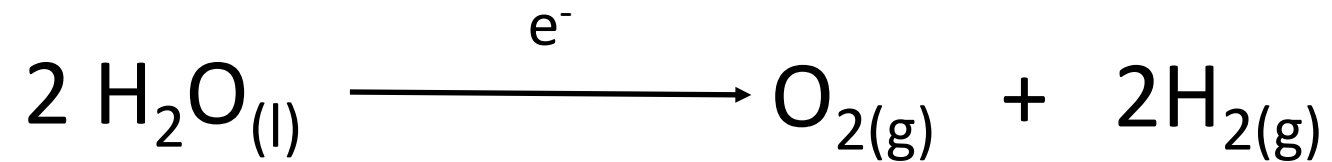
# Enabling Processes and Technologies

# 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



1 kilogram

0.89 kilogram

0.11 kilogram

# Water Electrolysis Technologies

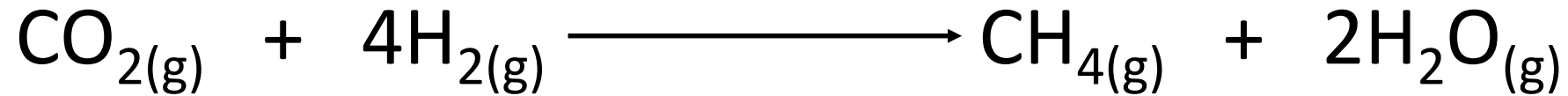
Three main technologies:

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)

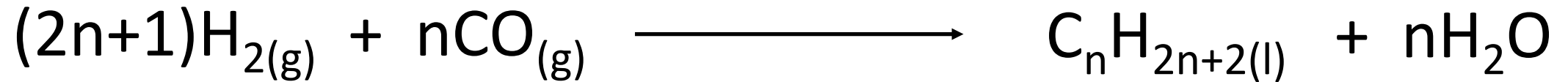
Hydrogenation of carbon dioxide (Sabatier reaction)



Two technologies exist, namely catalytic methanation and biological methanation

# Fischer-Tropsch Synthesis

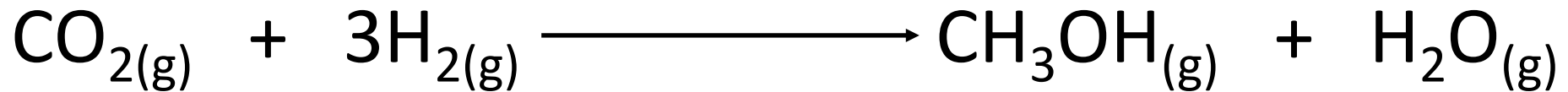
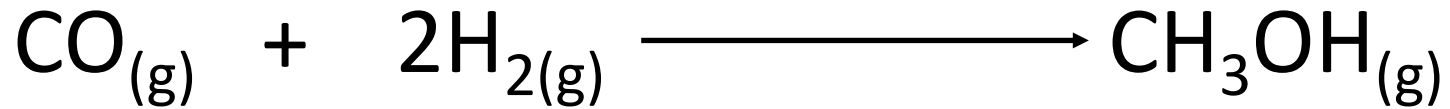
Alkane (hydrocarbon) formation from hydrogen and carbon monoxide



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

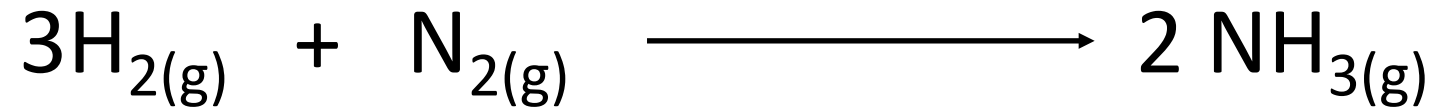
Hydrogenation of carbon monoxide and carbon dioxide (variant of Sabatier reaction)





# Ammonia Synthesis

Combination of hydrogen and nitrogen (Haber-Bosch process)



Other processes include the solid-state ammonia synthesis process.

# 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%.

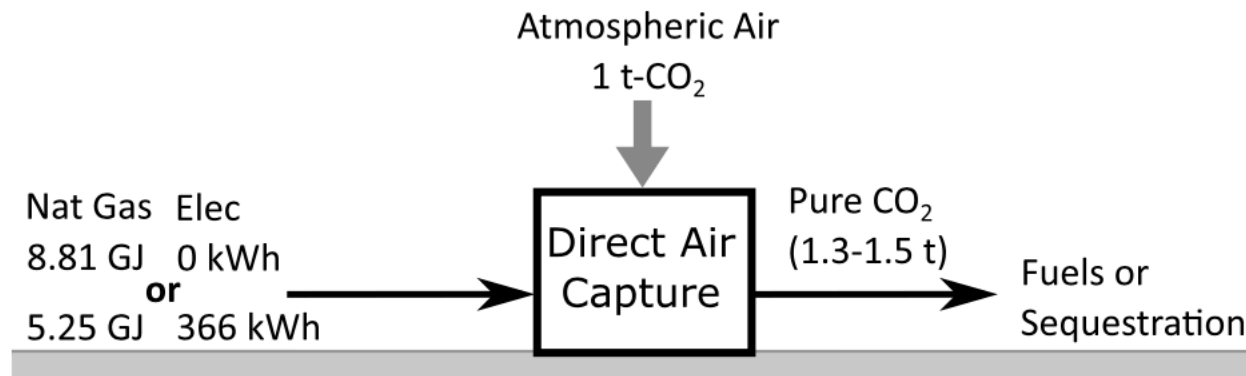
Capture units also lead to extra investment and operational costs, often on the order of that of the electric generator itself

# 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



# 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: wanna heat or light?

**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**

# We're on the right track but not quite there yet

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



Association of gas transmission system operators



Association of electricity transmission system operators





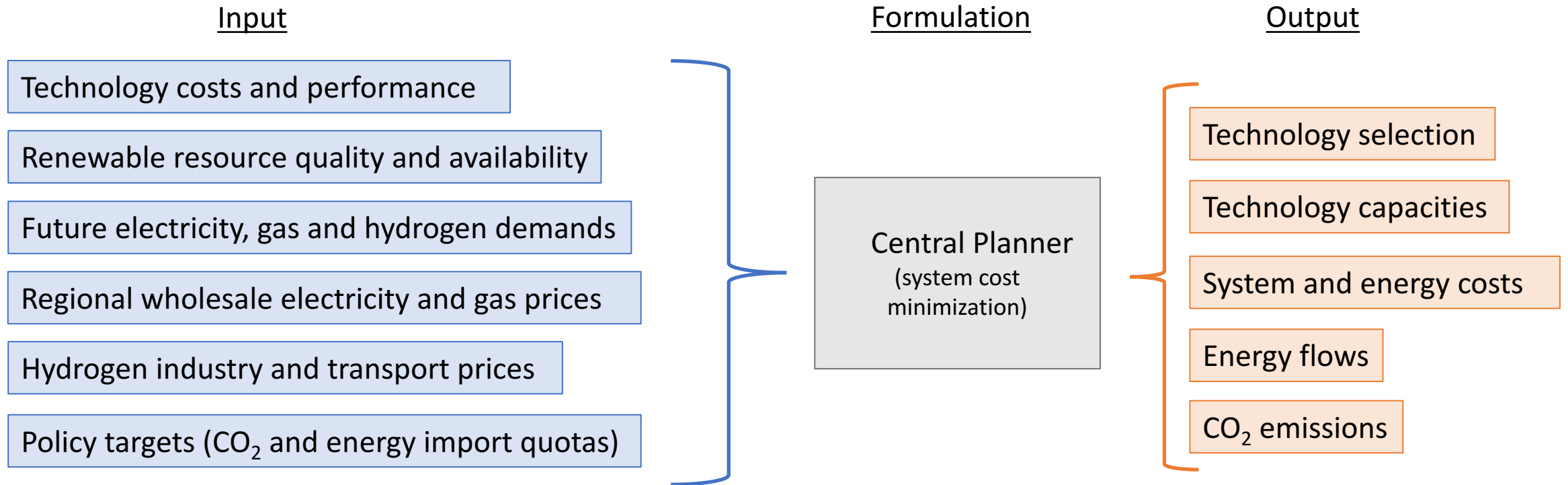
# Sector Coupling in the Belgian Context

# 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

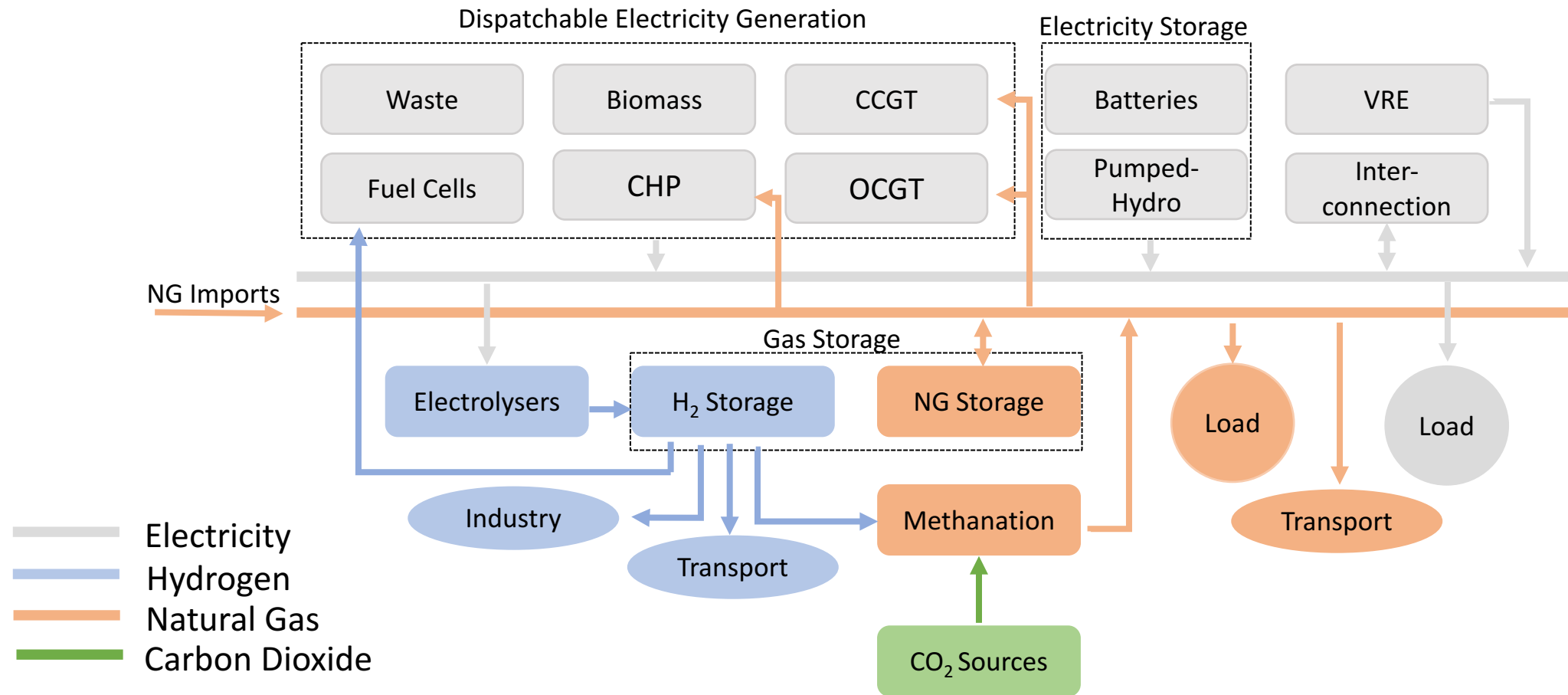
Which generation, conversion and storage technologies should be deployed, and in what quantities, to supply load at minimum cost whilst satisfying technical constraints and pre-specified policy targets?



# 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

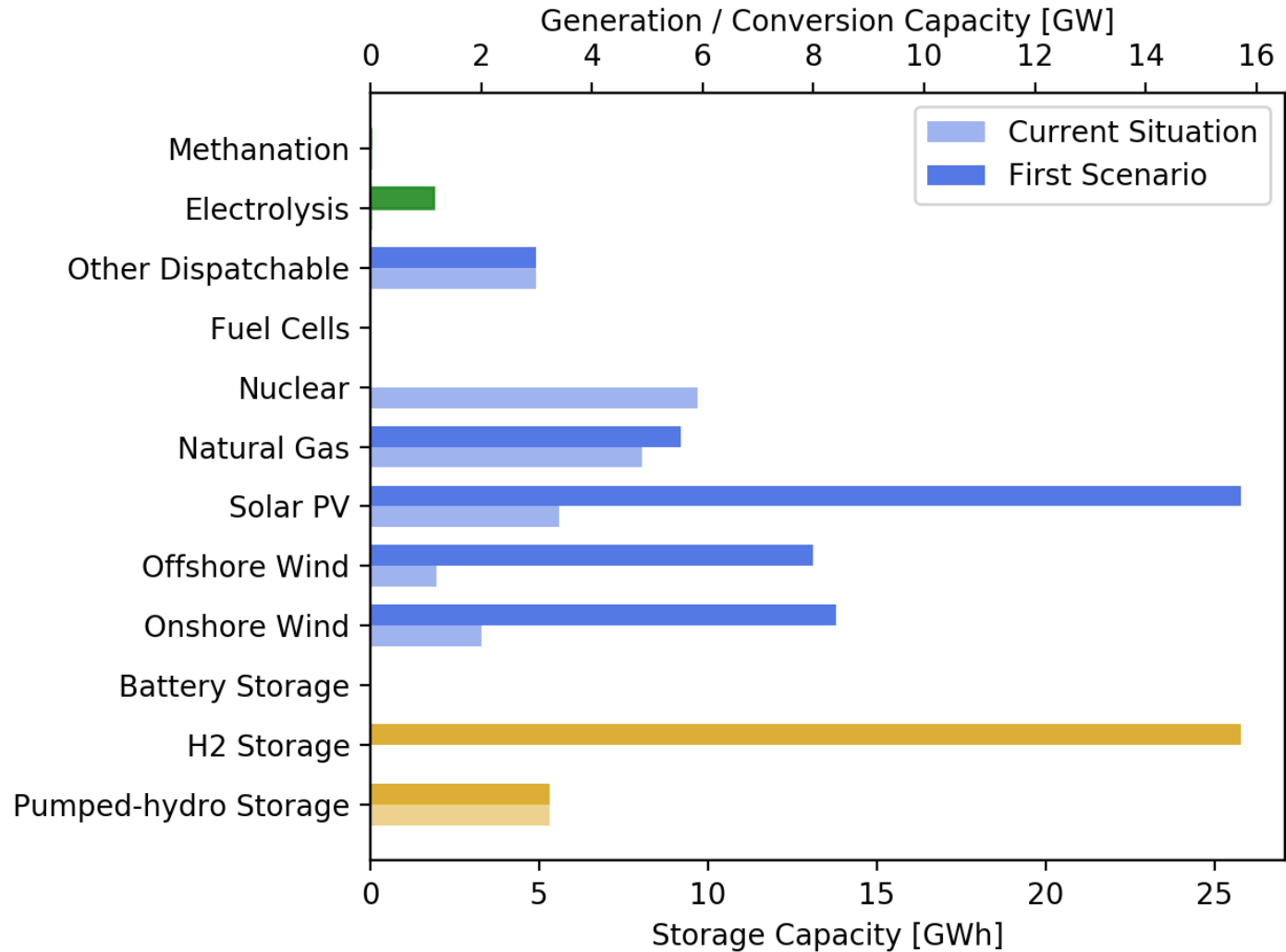
## Constant Carbon Dioxide Emissions and Nuclear Phase-Out

1. 38 Mt annual carbon dioxide emissions budget for electricity and gas systems, defined as difference between CO<sub>2</sub> emitted and absorbed, excluding CO<sub>2</sub> emitted by cars running on CNG.
2. Belgian RES potential of solar PV is 40 GW.
3. CAPEX of 1400 €/kW<sub>e</sub> (electrolysers), 600 €/kW<sub>H<sub>2</sub></sub> (methanation), 1000 €/kW<sub>e</sub> (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<sub>2</sub> 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<sup>1</sup> and Costs

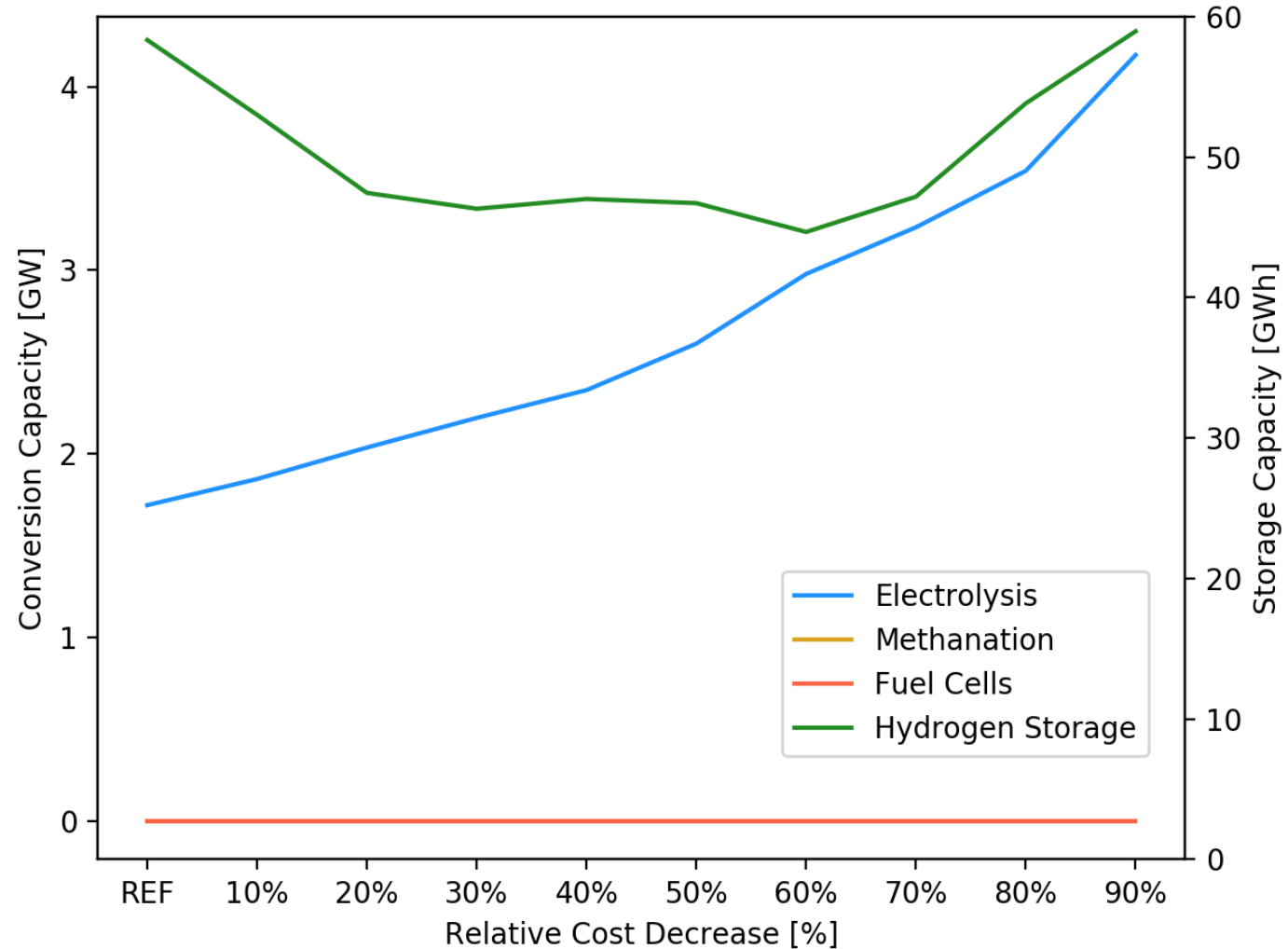
System Cost:  
8.4 B€

Energy Cost:  
36.5 €/MWh



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

# Sensitivity Analysis on Power-to-Gas and Fuel Cell Costs

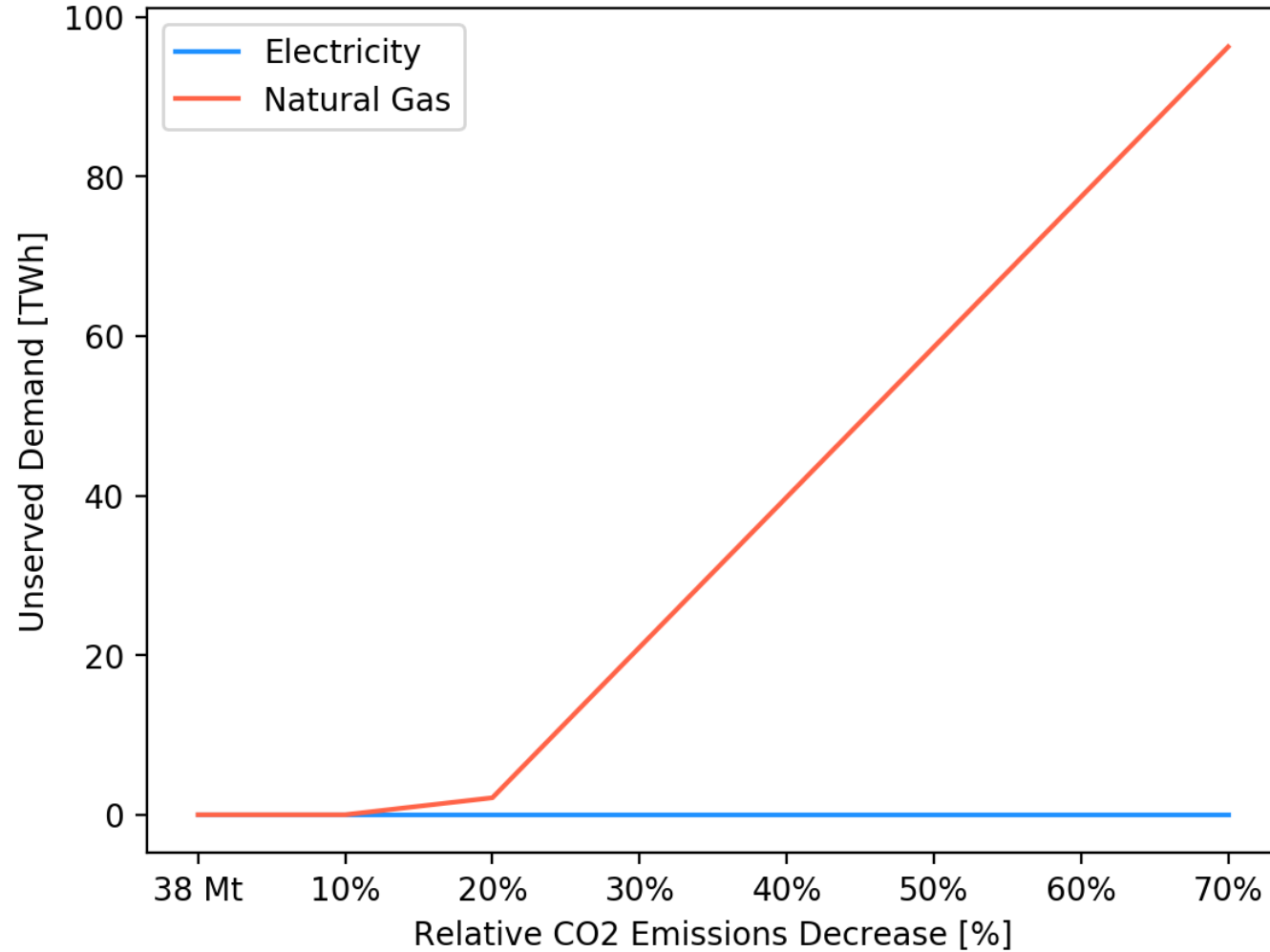




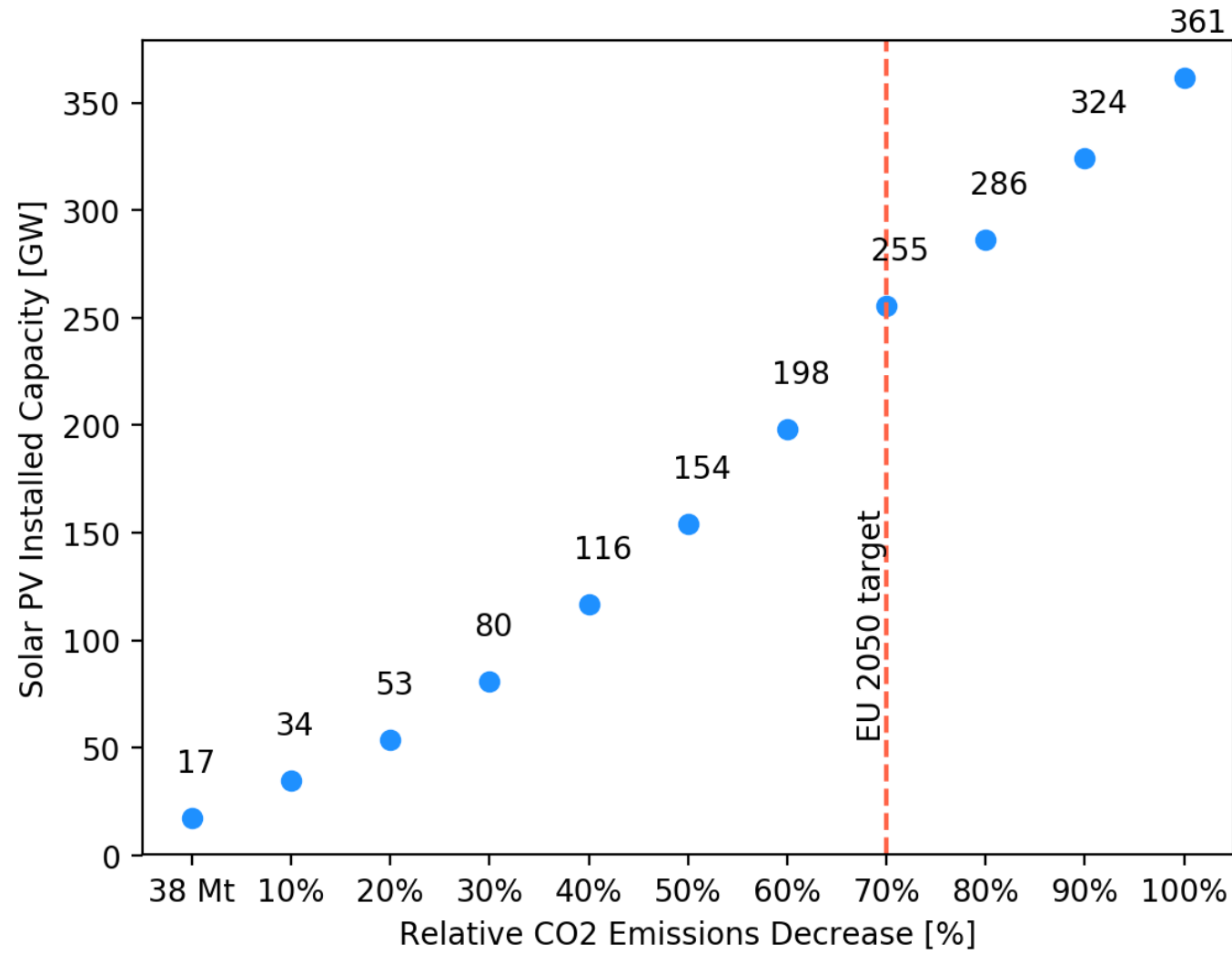
# Energy not Served vs Carbon Budget

Electricity VoLL<sup>2</sup>:  
3000 €/MWh

Gas VoLL:  
500 €/MWh



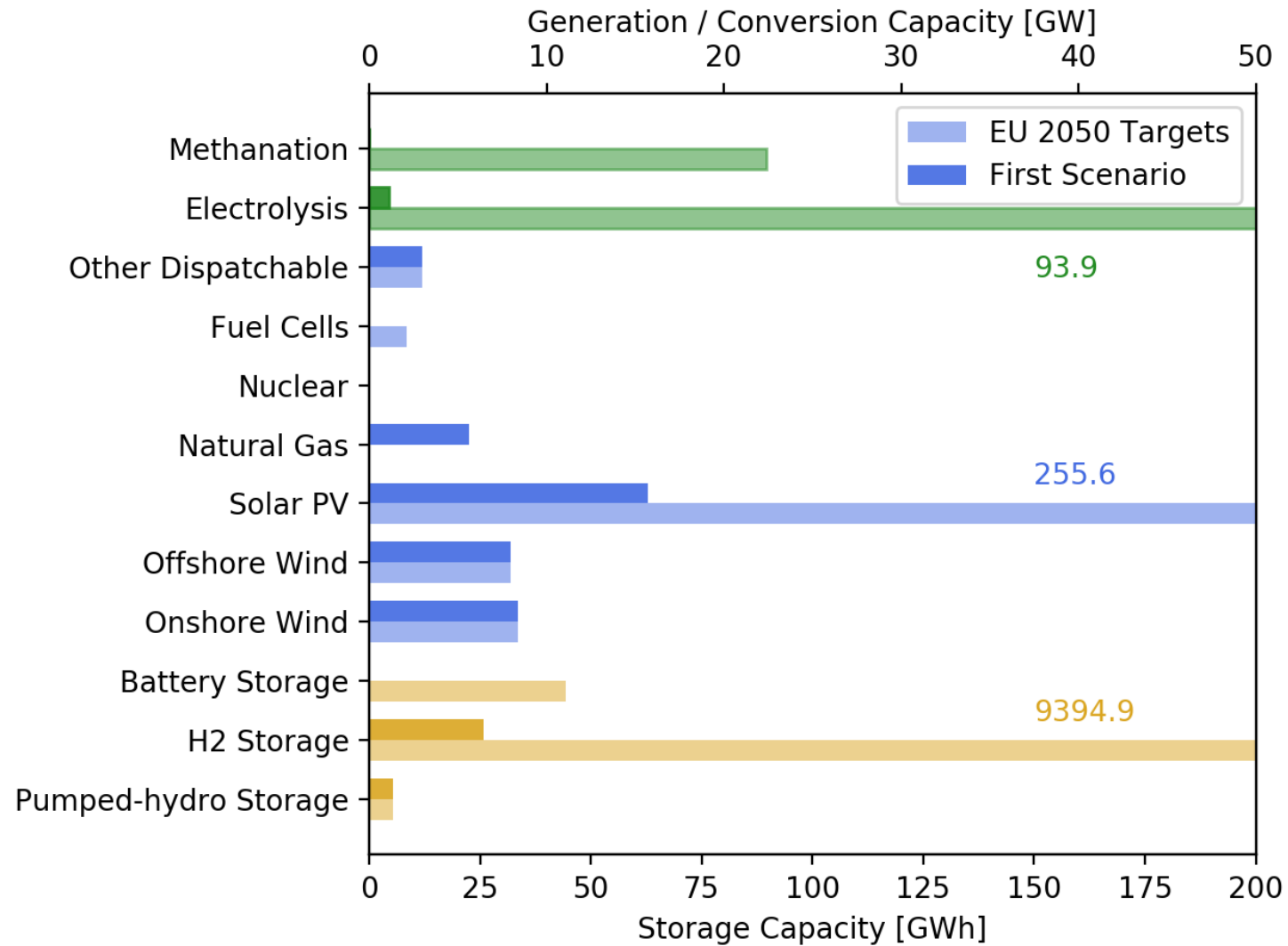
# Solar PV Capacities for Zero Shedding vs Carbon Budget<sup>3</sup>



# System Design for European 2050 Targets

System Cost<sup>4</sup>:  
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<sup>2</sup> of land, whilst 10 MW of wind turbines span 1 km<sup>2</sup>

Solar PV Surface Area

2556 km<sup>2</sup>

Onshore Wind Surface Area

840 km<sup>2</sup>

Offshore Wind Surface Area

800 km<sup>2</sup>

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

Hydrogen Storage Volume

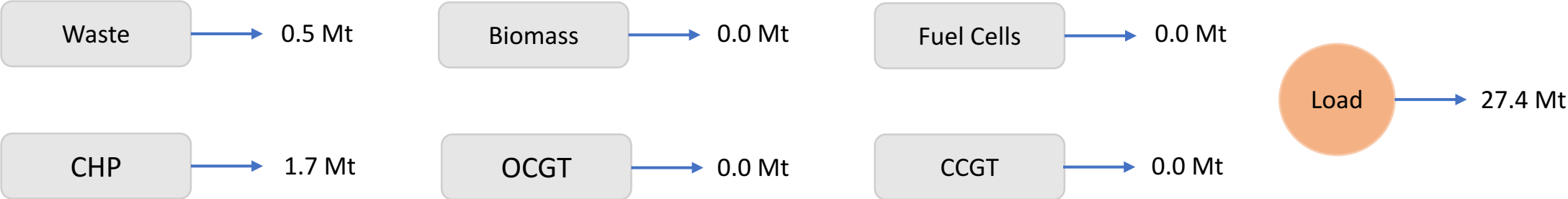
5.7 Mcm

Side Length of Equivalent Cube

178 m

# Carbon Dioxide Budgeting

## Carbon Dioxide Emissions



## Carbon Dioxide Consumption



## Net Carbon Dioxide Budget

$$0.5 + 1.7 + 27.4 - 18.2 = 11.4 \text{ Mt}$$

# 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

34.4 Mcm

Side Length of Equivalent Cube

325 m

The methanation process consumes CO<sub>2</sub>. In total, 92 TWh of synthetic methane are produced, which requires

Mass of Carbon Dioxide Required

18.2 Mt/y

Emissions from cement industry in Belgium

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

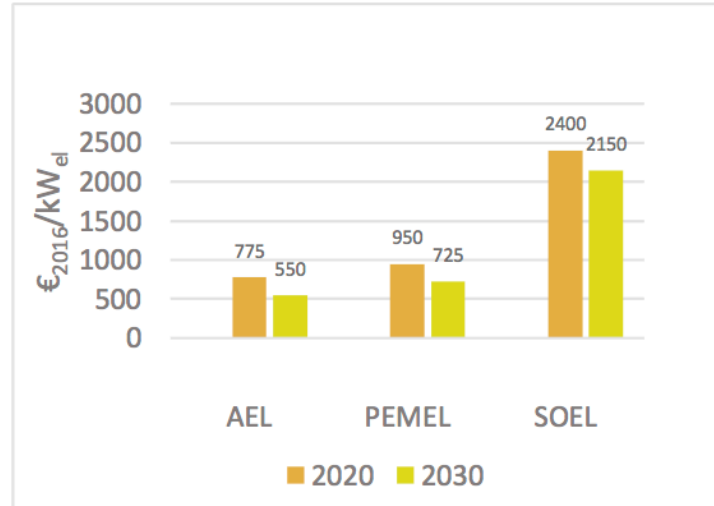
M. Berger et al., “The role of power-to-gas and carbon capture technologies in cross-sector decarbonisation strategies”, to appear in Electric Power Systems Research.

Will be shared shortly, along with 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

<b>AEL</b>	Mature (TRL 9)
<b>PEMEL</b>	Commercial with development potential (TRL 8)
<b>SOEL</b>	Demonstration (TRL 6)

## DEPLOYMENT SCALE

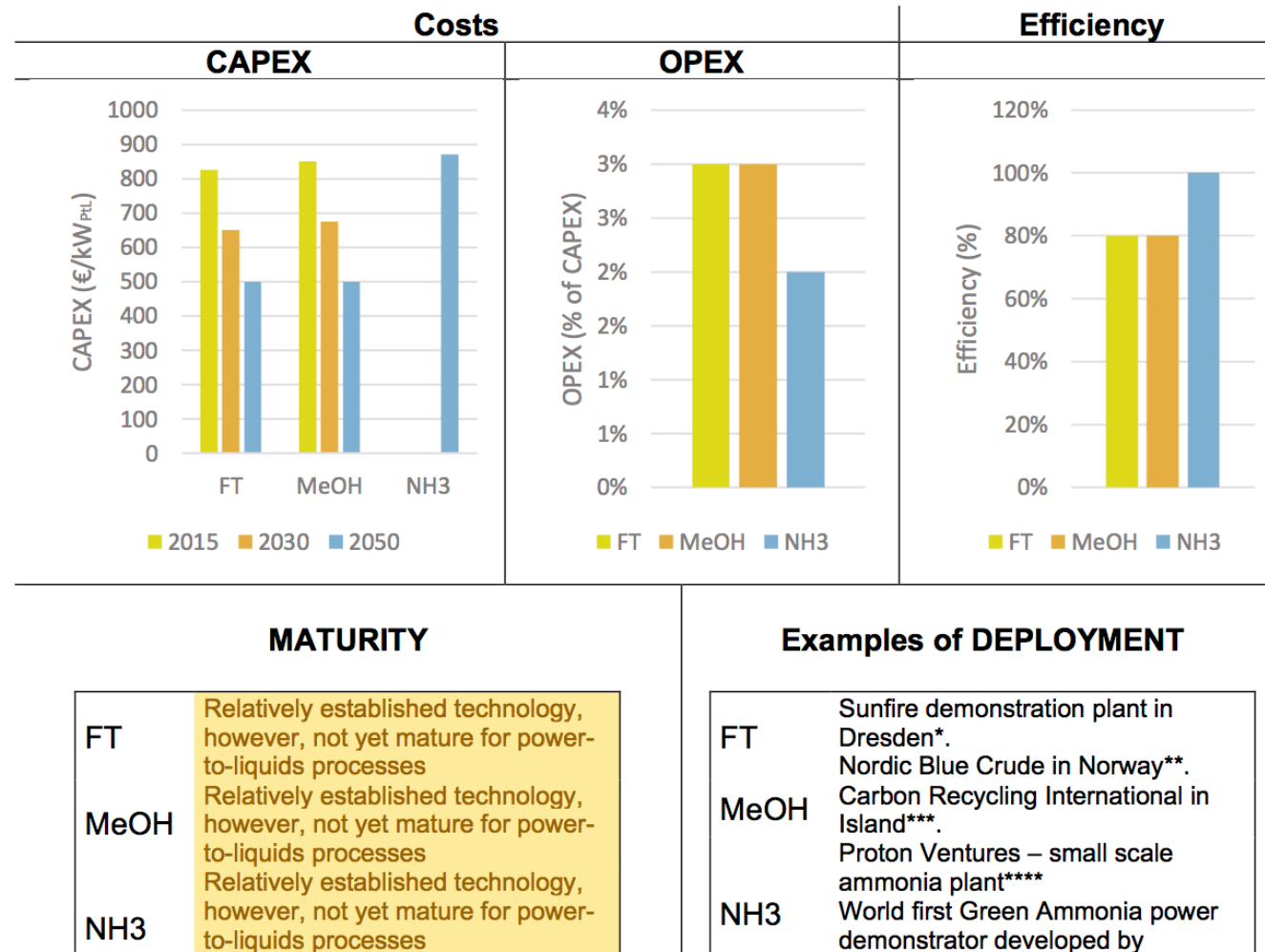
<b>AEL</b>	MW
<b>PEMEL</b>	MW
<b>SOEL</b>	kW

# Power-to-Liquids

FT: Fischer-Tropsch

MeOH: Methanol

NH3: Ammonia



# Further reading and references

ETIP SNET white paper on sector coupling, to appear soon on:

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