TNO 2023 R10586-1

Energy assessment for CCUS options EU Cement sector

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TNO | Amsterdam

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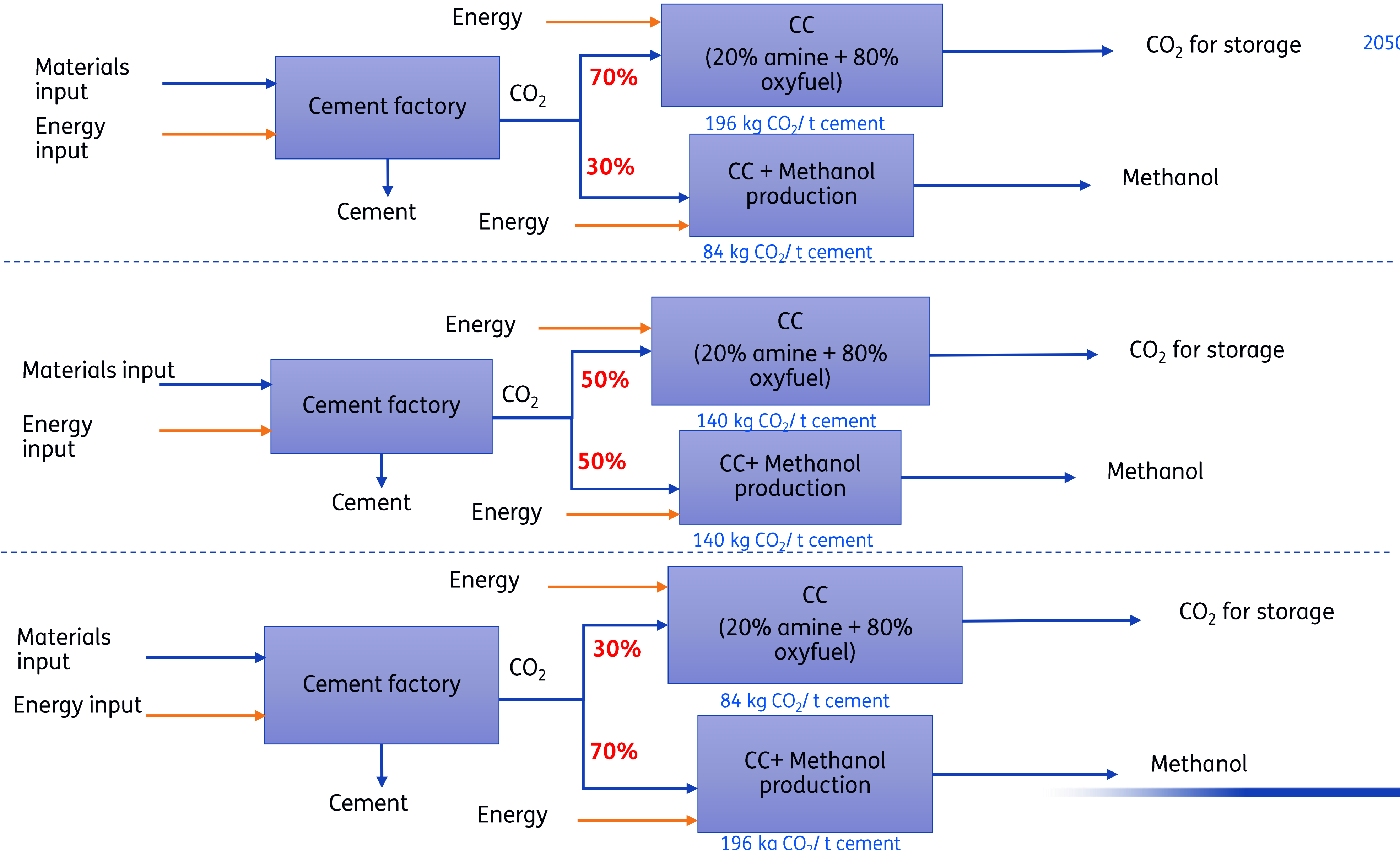
1. Scenarios for the assessment

Abatement targets for CCUS

- **2030: 28 kg CO_2/t cement (10% of 2050 target)**
- **2050: 280 kg CO_2/t cement (based on roadmap)**

2050 mitigation targets



Materials input
Energy input
Cement factory
Cement
CO_2
70%
30%
Energy
CC (20% amine + 80% oxyfuel)
196 kg CO_2/ t cement
CO_2 for storage
Energy
CC + Methanol production
84 kg CO_2/ t cement
Methanol

Case High CCS

Materials input
Energy input
Cement factory
Cement
CO_2
50%
50%
Energy
CC (20% amine + 80% oxyfuel)
140 kg CO_2/ t cement
CO_2 for storage
Energy
CC+ Methanol production
140 kg CO_2/ t cement
Methanol

Case Half CCS/CCU

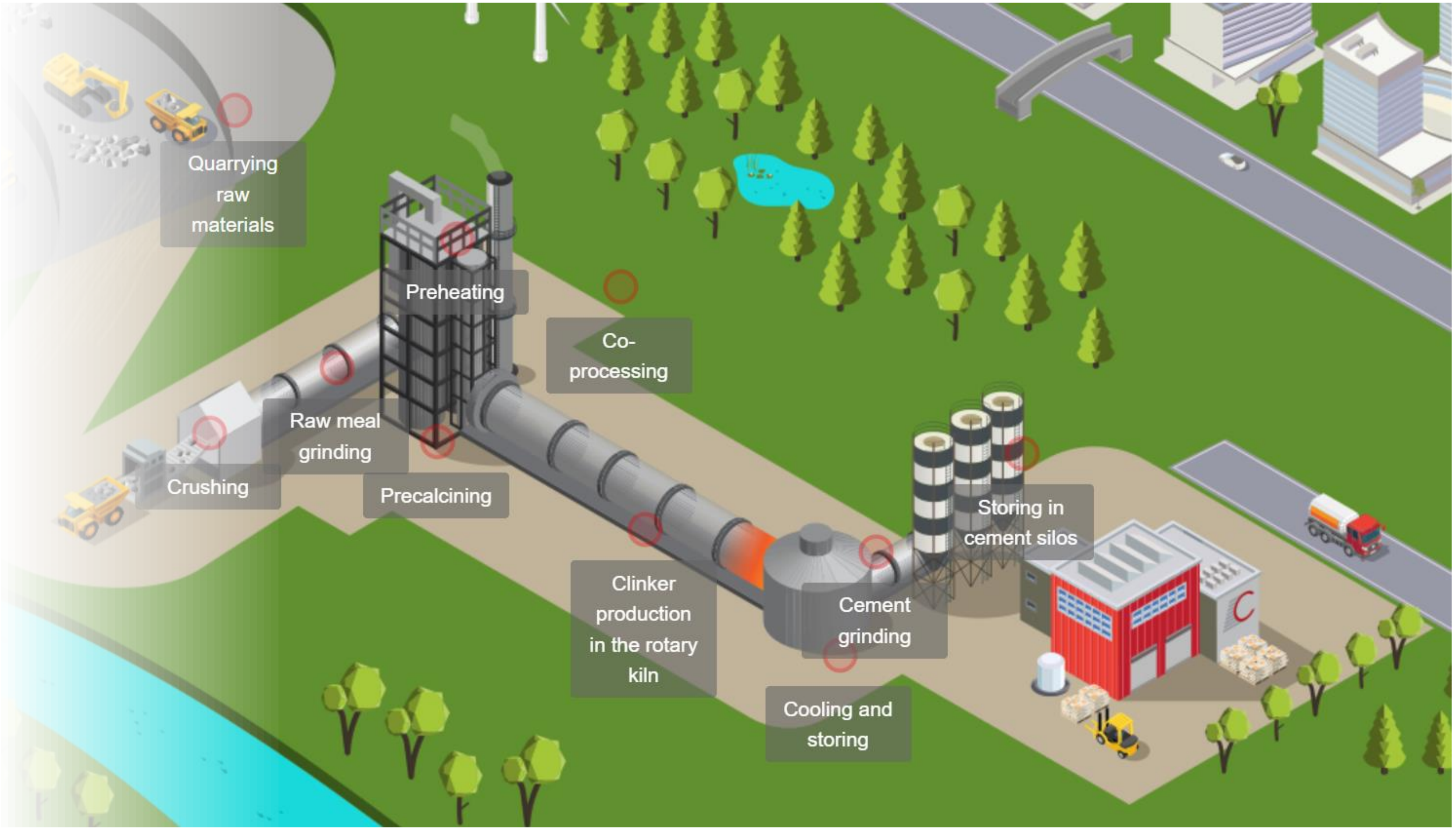
Materials input
Energy input
Cement factory
Cement
CO_2
30%
70%
Energy
CC (20% amine + 80% oxyfuel)
84 kg CO_2/ t cement
CO_2 for storage
Energy
CC+ Methanol production
196 kg CO_2/ t cement
Methanol

Case High CCU

2. Baseline for cement sector

The cement production can be grouped in 5 main process:

- Quarrying and Crushing:
  - Quarrying raw materials and initial crushing
- Grinding & Blending
  - Raw Meal grinding and blending
- Kiln & Clinker production
  - Preheating, pre-calcining and co processing and clinker production
- Cement Milling and grinding
- Storage and Dispatch



Source: [1]

2. Baseline for cement sector – Energy intensity

Main considerations

- Based on the Cembureau roadmap and GNR data collection, the overall **thermal energy demand** of the global cement sector is expected to reduce 10% by 2030 and 29% by 2050
- The **electricity demand** is expected to reduce around 10% by 2030 and 27% by 2050 (excluding electricity required for emission reduction technologies such as CCUS)
- **Clinker to cement ratio** is expected to reduce from 0.77 to 0.65 (16% less)
- The energy breakdown per process step is based on Cembureau's Roadmap calculations (excel shared) for a typical cement plant
- The electricity demand is expected to be **fully renewable** by 2050.

Table 1- Baseline specifications for a typical cement plant

Clinker thermal intensity (Clinker)	2020	2030	2050
Fossil fuels (GJ/t clinker)	1.92	1.38	0.31
Alternative fossil & mixed (GJ/t clinker)	0.85	1.24	1.41
Biomass (GJ/t clinker)	0.57	0.83	1.40
Clinker Content (t clin/t cem)	77%	74.0%	65.0%

Source: [2] [3]

Energy intensity (Cement)	2020	2030	2050
Thermal (GJ/ton cement)	3.1	2.8	2.2
Electricity (GJ/ton cement)	0.43	0.39	0.31
Total (GJ/ton cement)	3.5	3.2	2.5

Source: [2] [3]

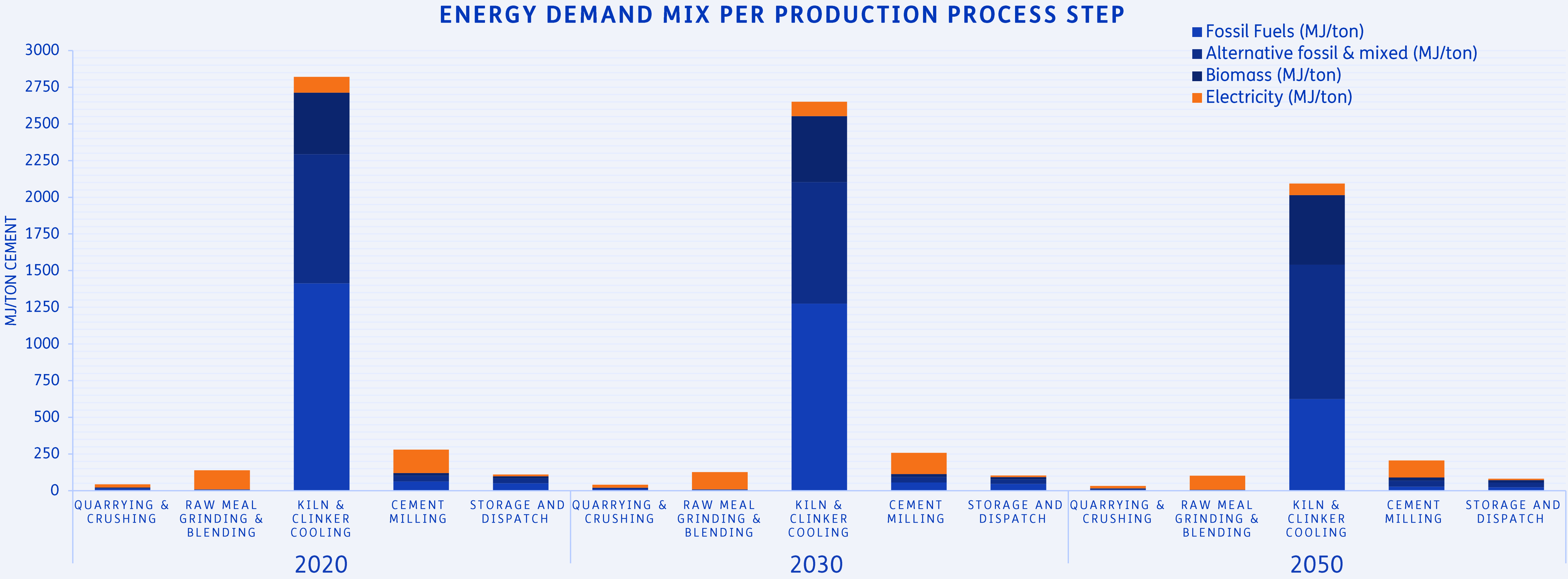
Production Stage	%Electrical Energy	%Thermal energy
Quarrying & Crushing	5%	0.8%
Raw Meal Grinding & Blending	30%	0.3%
Kiln & Clinker Cooling	25%	91.5%
Cement Milling	37%	4.1%
Storage and Dispatch	3%	3.3%

Source: [2]

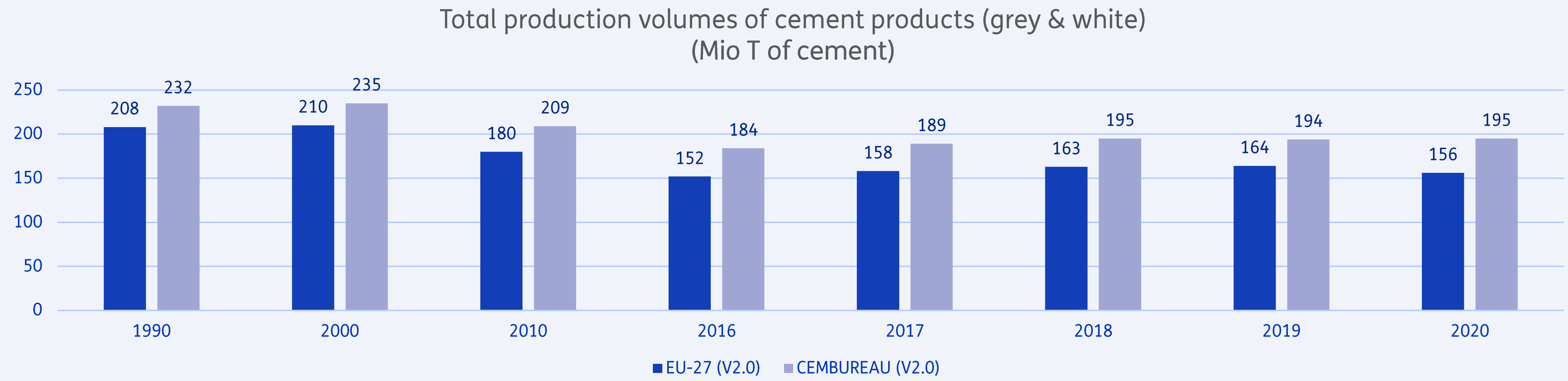
2. Baseline for cement sector – Energy intensity

Main considerations

- The same energy distribution per production process step is kept for 2030 and 2050.
- The energy carriers indicated by Cembureau Roadmap for 2030 and 2050 are considered.



2. Baseline for cement sector – Production capacity



SOURCE: [4]

TOTAL PRODUCTION VOLUME FROM CEMBUREAU MEMBERS

195 mi

TONS OF CEMENT IN 2020

Same production volume value was assumed for **2030** and **2050**

3. Technologies database

Post-Combustion CCS with alkanolamine

- End-of-the-pipe technique with CO_2 absorption (commonly with MEA) and purification
- Mature technology (TRL 8-9)
- 95% CO_2 capture rate
- Because the maximum capture rate was considered, the maximum values of the ranges for energy consumption were taken into account for the scenarios calculations
- The capture efficiency is kept the same for both 2030 and 2050, however, the clinker factor 0.74 for 2030 and 0.65 for 2050. For this reason, the technology characteristics per tonne cement is different for each year
- Thermal energy demand in table 2 was not translated to electricity demand

Table 2- Specifications for post combustion capture system with MEA

Post-Combustion with MEA			
Inputs	**2030**	**2050**	**unit**
Thermal Energy	2,590	2,275	MJ/t cem
Electricity	278	244	MJ/t cem
Steam import	1.8	1.6	MJ/t cem
Electricity for e-boiler*	1.9	1.7	MJ/t cem
Outputs			**unit**
Direct CO_2 Emissions	0.04	0.04	t CO2/t cem
CO_2 Captured	0.81	0.71	t CO2/t cem

Source: [5]

*E-boiler efficiency considered to be 99% (source 8)

3. Technologies database

Oxyfuel CCS

- Pure oxygen is obtained via ASU unit;
- In the ECRA database, the electric consumption due to ASU unit is **not** included in the overall electricity consumption. **Additional 100 kWh/t cli** is considered in the calculations to account for the ASU (reference provided by Cembureau during the review process).
- Oxyfuel implemented by recirculation of flue gases (Pure oxyfuel suitable only for new kiln installations)
- 95% CO_2 capture rate
- Because the maximum capture rate was considered, the maximum values of the ranges for energy consumption were taken into account for the scenarios calculations.
- The capturing efficiency is kept the same for both 2030 and 2050 and, similarly to the MEA technology, the clinker factor for 2030 and 2050 is different, which impacts the input and output values for this technology as well
- Thermal energy in table 3 was not translated to electricity demand

Table 3- Specifications for oxyfuel capture system

CCS Oxyfuel			
Inputs	**2030**	**2050**	**unit**
Thermal Energy	333	292	MJ/t cem
Electricity	866	761	MJ/t cem
Oxygen	200	176	Nm3/t cem
Outputs			**unit**
Direct CO_2 Emissions	0.03	0.03	t CO2/t cem
CO_2 Captured	0.62	0.54	t CO2/t cem

Source: [5]

3. Technology database

CO_2 Transport via Pipeline

- Only pipeline transport was included in the scenarios
- Main source is SDE++ endadvies, which considers the electricity consumption value for CO_2 compression from 1 to 25 bar
- Different sources consider a similar electricity consumption level for compression up to 100 bar, which would be suitable for long distance transportation, no dependency to the transport distance
- Electricity consumption value can vary depending on the compressor efficiency, however, experts from TNO mention that the consumption would be in the range between 95-130kWh/t CO_2
- The amount of CO_2 captured per tonne of cement changes due to the different clinker factor for 2030 and 2050, this also impacts the energy consumed for transport

Table 4- Specifications for CO_2 transport via pipeline for storage

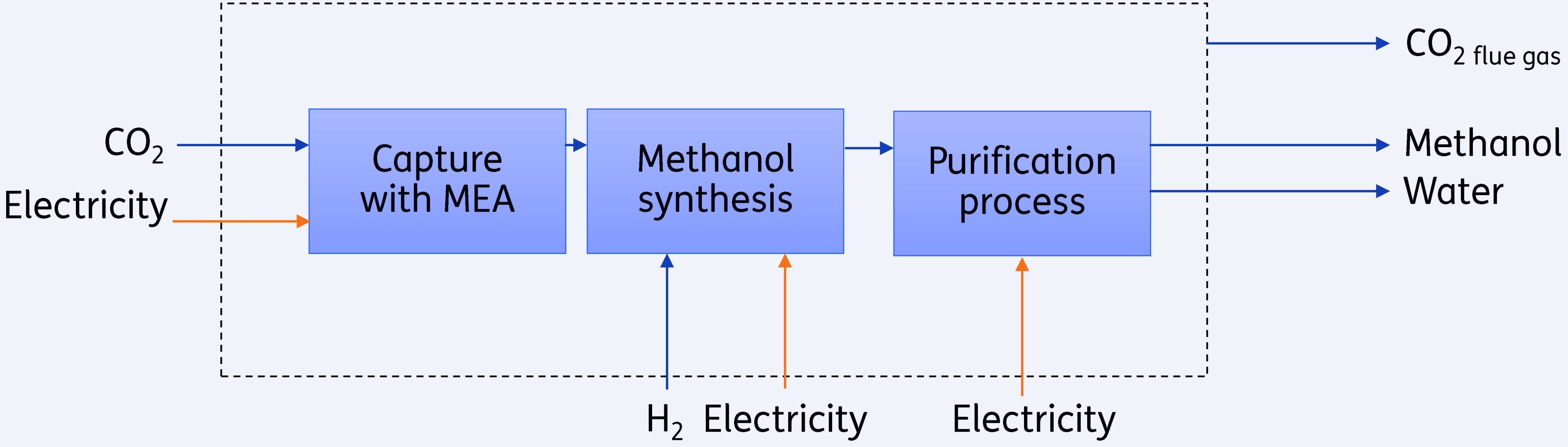
CO_2 transport Inputs	From literature	Unit	Value considered 2030	Value considered 2050	Unit
Electricity for compression	125.00	kWh/t CO2 captured	365	320	MJ/t cem

Source: [6]

3. Technology database

Methanol production via CO_2 and hydrogen – carbon capture

- The methanol synthesis process requires a stream with high concentration of CO_2 (above 90%vol.), however, the stream delivered by the cement factory most likely would have low concentration of CO_2. For this reason, a capture system with MEA was included in the CCU system.
- The data used for the capture system is the same as presented by Table 2, which is based on the ECRA papers.



3. Technology database

Methanol production via CO_2 and hydrogen

- In the methanol synthesis step, the catalytic conversion of CO2 and hydrogen to methanol and water occurs.
- The conversion efficiency is improved by recycling unreacted gases back to the reactor, however, a purge stream is needed.
- Any CO present in the purge is converted to CO2 via an oxidize, releasing a flue gas stream rich in CO2.
- The crude methanol is purified by leading it through a fractionation column (connected to a heat exchanger) and a stripper unit.
- The process heat from the synthesis reactor generates steam, which is partly used in the purification process (fractionation and gas stripping). Some electricity is required to run the plant, e.g. to drive the compressors for gas compression.
- The process runs at a typical temperature of 200-250 °C and at 30-80 bar and is a net electricity consumer and a heat producer (due to the exothermic nature of the reaction.
- The extra heat produced via the methanol synthesis is considered to be used by the MEA capture system.

Table 5- Specifications for CO_2 use for methanol synthesis

Methanol synthesis		
Inputs	**2030/2050**	**unit**
CO_2 (high concentration)	1.4	t/t MeOH
Hydrogen	0.2	t/t MeOH
Electricity	1005	MJ/t MeOH
Outputs		**unit**
Methanol	1	t/t MeOH
Water	0.6	t/t MeOH
Heat	1809	MJ/t MeOH
CO_2 (flue gas)	0.20	t/t MeOH
CO_2 Captured	**1.21**	**t/t MeOH**

Source: [7]

3. Technology database

Methanol production via CO_2 and hydrogen – hydrogen supply

- It is considered that only green hydrogen is used in the methanol production system
- This hydrogen is assumed to be produced via alkaline electrolysis connected to a wind farm
- The power consumption considered is 51 kWh/kg hydrogen for both 2030 and 2050
- Considering the hydrogen needed for 1 tonne of methanol production, the total electricity demand increases from 1.5 GJ/t methanol to 39 GJ/t methanol (0.4 GWh/ t methanol to 10.8 GWh/t methanol)

Table 6- Specifications for green hydrogen production

Green hydrogen production		
Inputs	**2030/2050**	**unit**
Water	14.5	t/t hydrogen
Electricity	183.6	GJ/t hydrogen
Outputs		**unit**
Hydrogen	1	t/t hydrogen

Source: [8]

3. Technology database

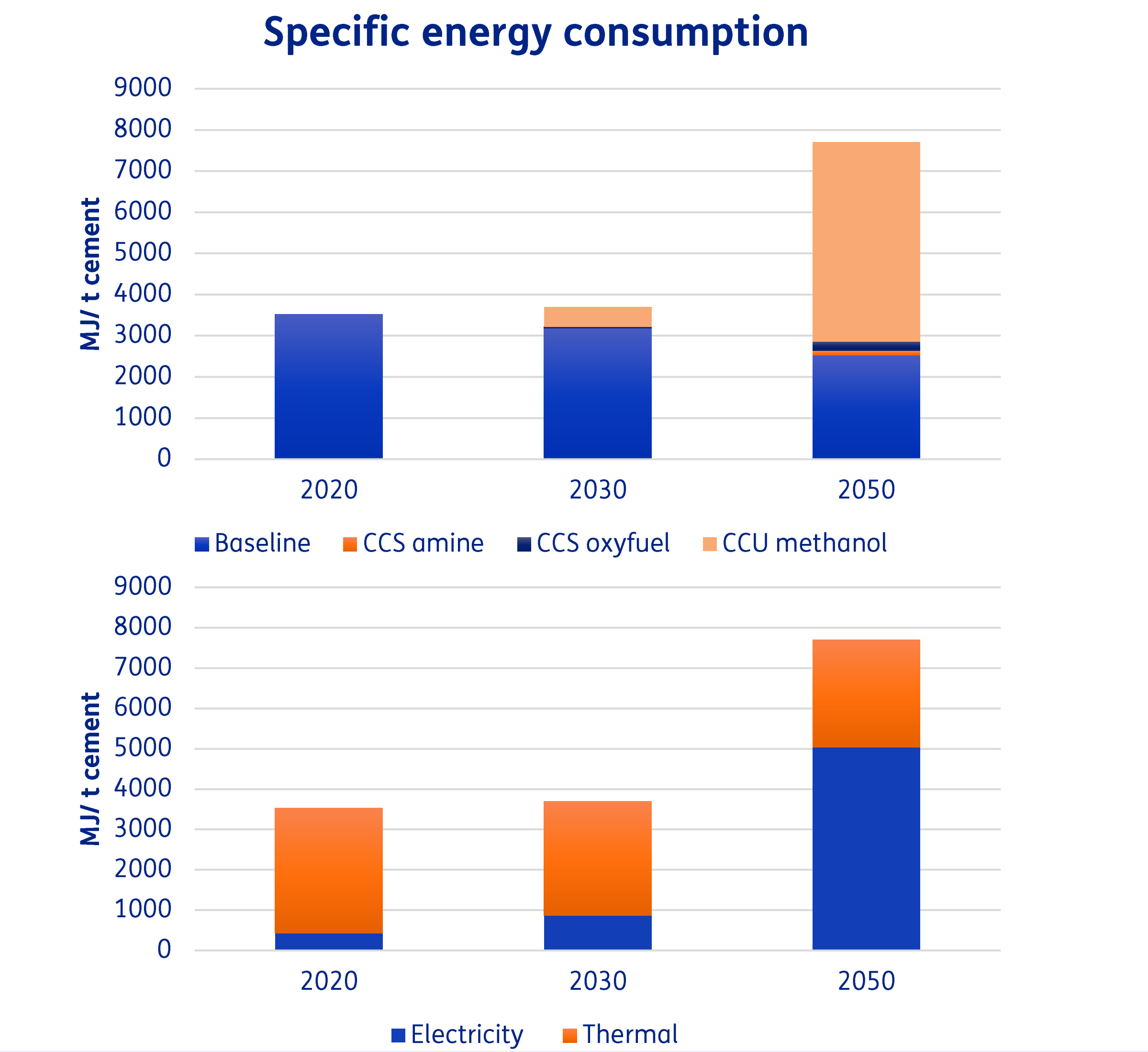
Methanol production via CO_2 and hydrogen – overall mass and energy balance

Table 7- Specifications for carbon capture + methanol synthesis + green hydrogen production

Inputs	2030/2050	unit
CO_2 (low concentration)	1.48	t/t methanol
Hydrogen	0.20	t/t methanol
Electricity	39,007	MJ/t methanol
Steam import [e-boiler electricity input]	3.2 [3.3]	MJ/t methanol
Water	2.36	t/t methanol
Heat	2,684	MJ/t methanol
Outputs		**unit**
Methanol	1	t/t methanol
CO_2 (flue gas)	0.28	t/t methanol
CO_2 mitigated	**1.21**	**t/t methanol**

- Green hydrogen production is responsible for more than 96% of total electricity input in the system
- The CO_2 mitigated is calculated subtracting the direct CO_2 emissions (flue gases) from the total input of CO_2.

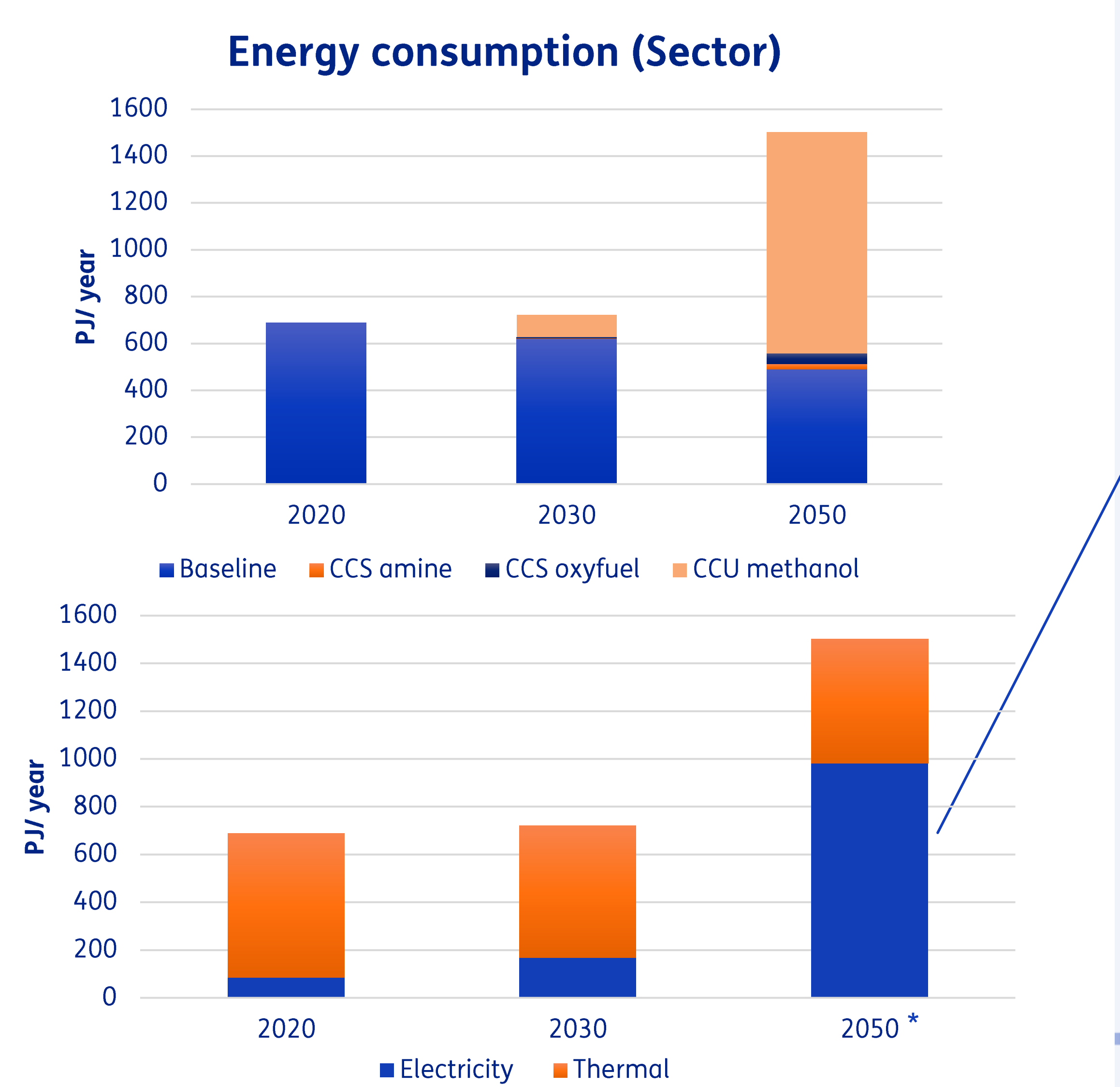
4. Scenarios results – 50% CCS/CCU case



- In 2030, the total specific energy consumption (electricity + thermal) increases 5%, when compared to the baseline for 2020
- **For 2050, the total specific energy demand is 119% higher than the baseline for 2020**
- In 2050, **CCU methanol represents 93% of the total additional energy needed** for CCUS technologies implementation
- The electricity consumption increases from 0.4 GJ/t cement (2020) to around 5 GJ/t cement in 2050. **The electrolysis alone represents 87% of the electricity demand**
- By 2050, is considered that the electricity supply will be fully renewable. Therefore, the **availability** and **costs** per MJ may vary in different future scenarios.

4. Scenarios results – 50% CCS/CCU case

Total sector



2020 vs 2050

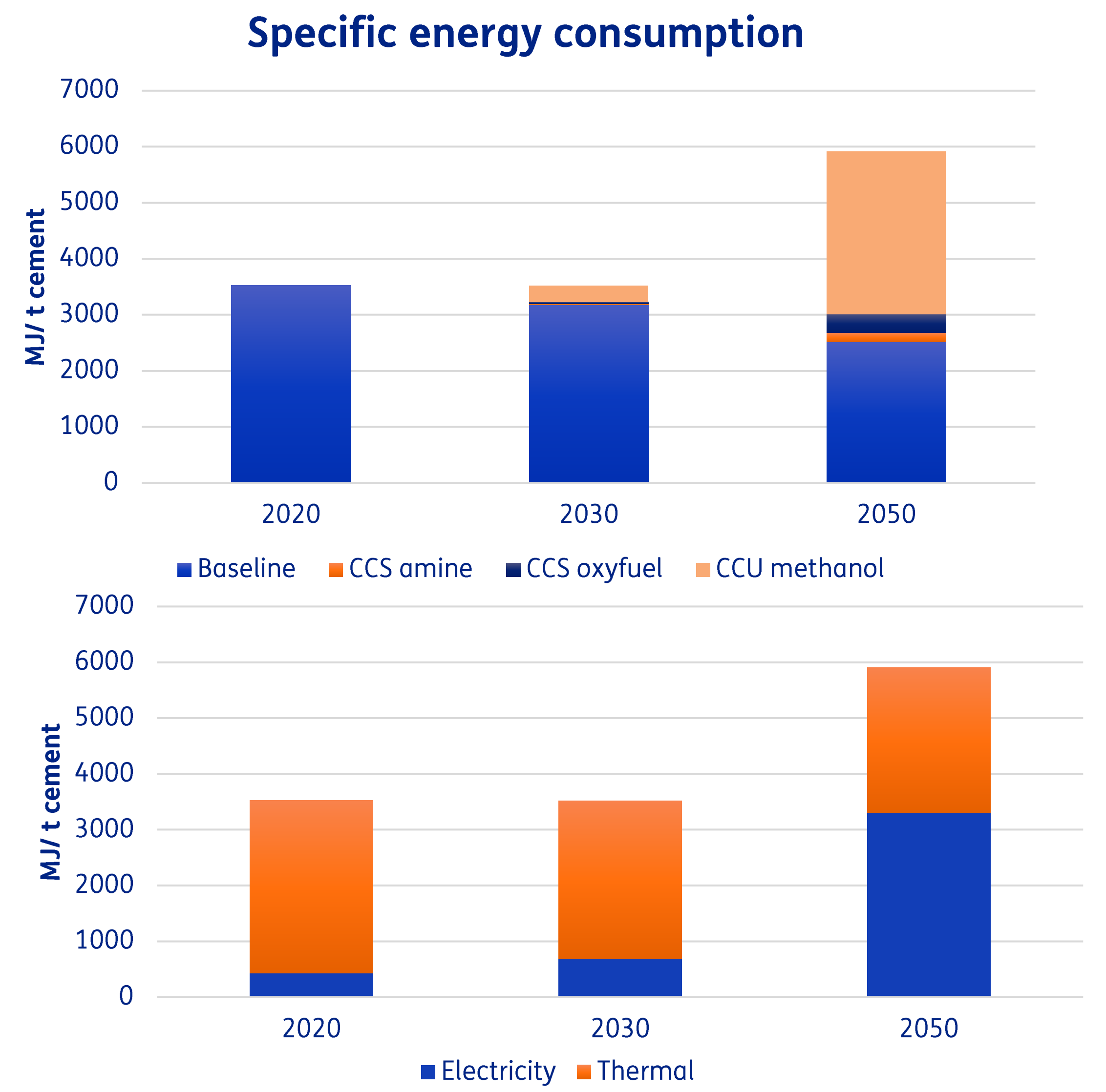
Electricity demand increases from 84 PJ/yr to 982 PJ/yr

Thermal demand reduces from 603 PJ/yr to 521 PJ/yr

* By 2050, is considered that the electricity supply will be fully renewable. Therefore, the **availability** and **costs** per PJ may vary in different future scenarios.

*PJ = 1x10^{15} J

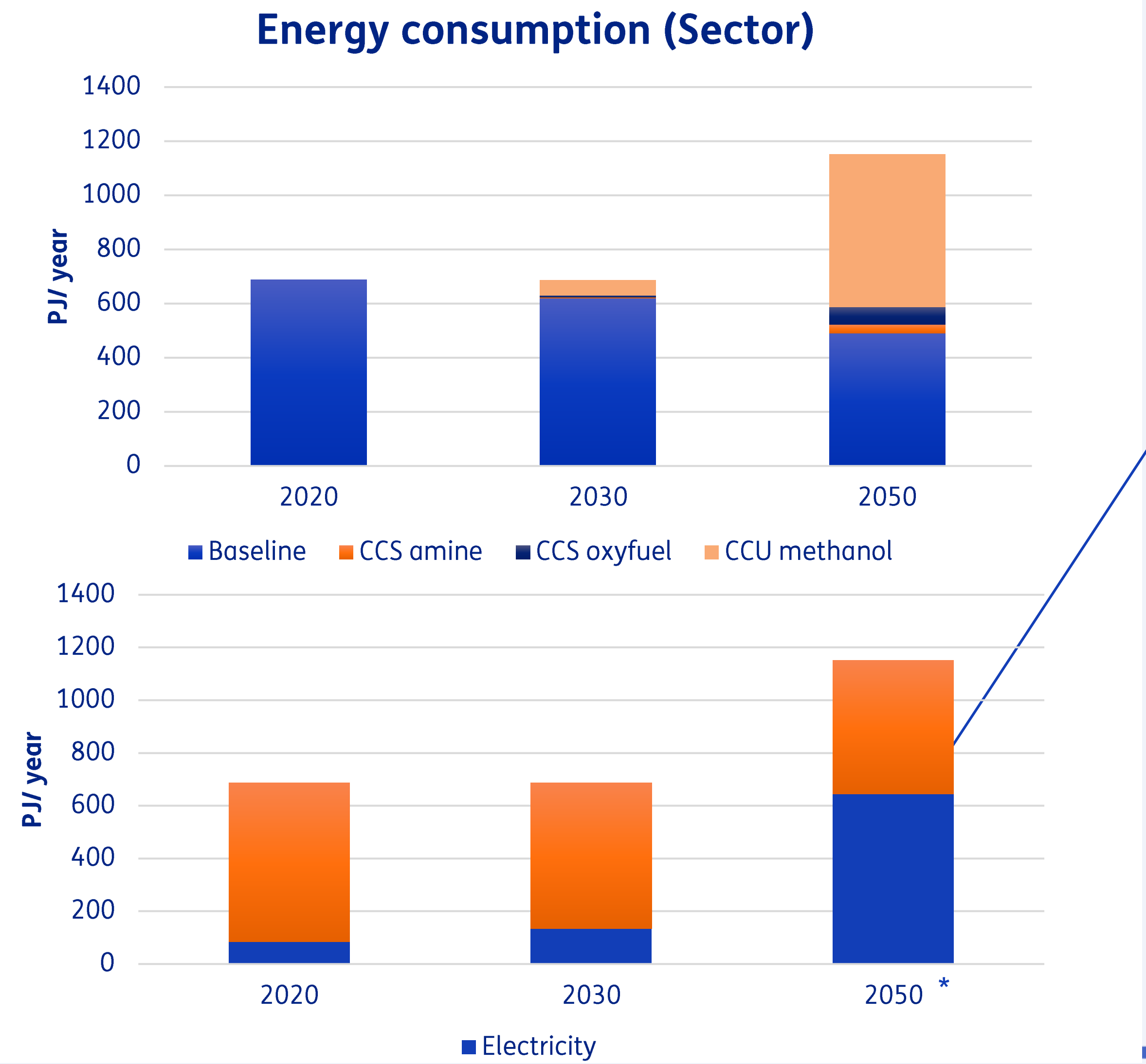
4. Scenarios results – 70% CCS 30% CCU case


Specific energy consumption

- **In 2030, the total specific energy consumption reduces 0.2%**, when compared to the baseline for 2020. This reduction is mainly due to the fact that the cement process becomes more efficient in 2030 and the CCU process is less relevant than CCS in this scenario
- **For 2050, the total specific energy demand is 68% higher than the baseline for 2020**
- In 2050, CCU methanol represents 86% of the total additional energy needed for CCUS technologies implementation
- Among the CCS technologies, oxyfuel represents 66% of the energy consumption
- The electricity consumption increases from 0.4 GJ/t cement (2020) to around 3.3 GJ/t cement in 2050. **The electrolysis alone represents 79% of the electricity demand**

4. Scenarios results – 70% CCS 30% CCU case

Total sector



2020 vs 2050

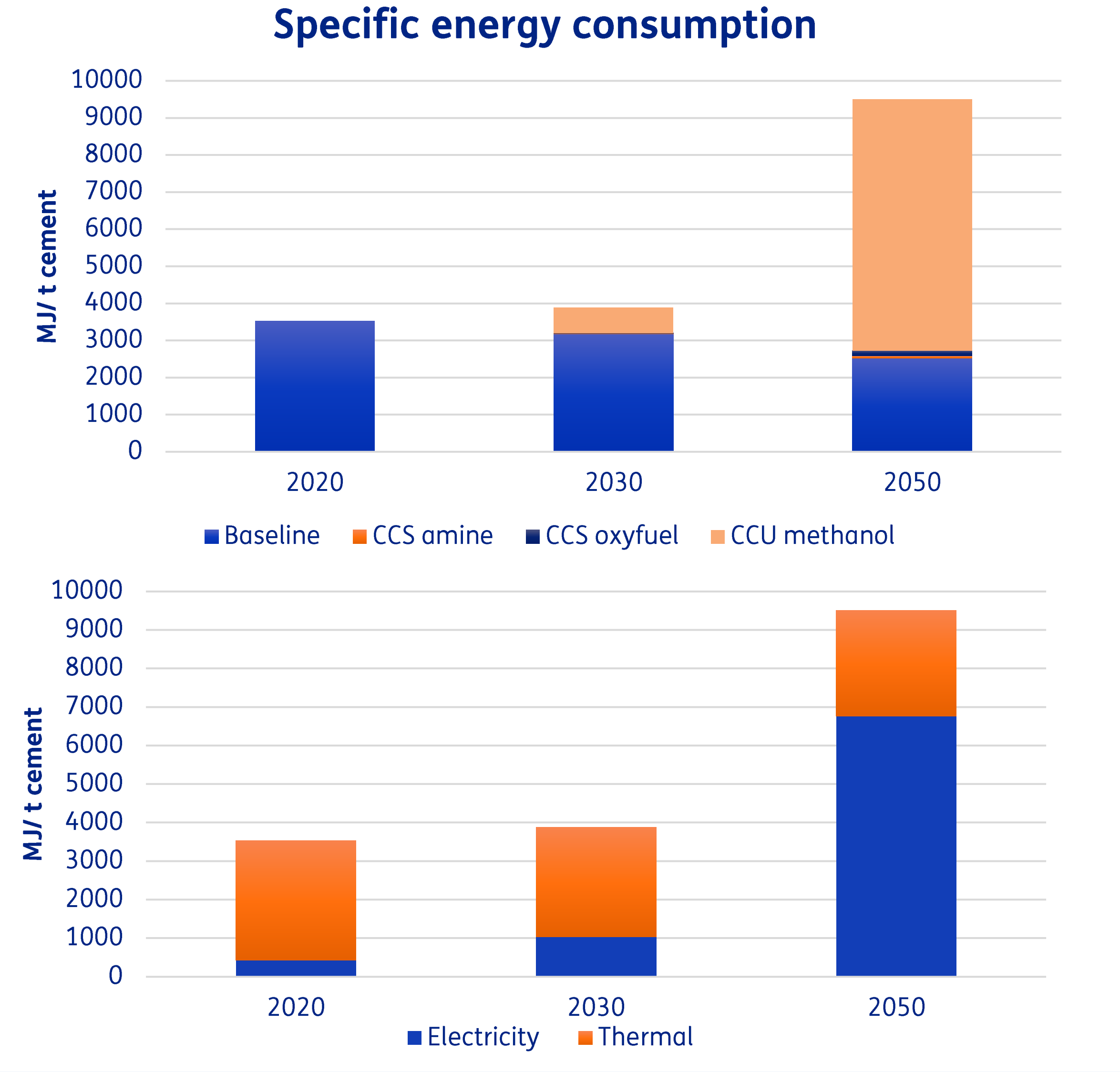
Electricity demand increases from 84 PJ/yr to 643 PJ/yr

Thermal demand reduces from 603 PJ/yr to 509 PJ/yr

* By 2050, is considered that the electricity supply will be fully renewable. Therefore, the **availability** and **costs** per PJ may vary in different future scenarios.

*PJ = 1×10^{15} J

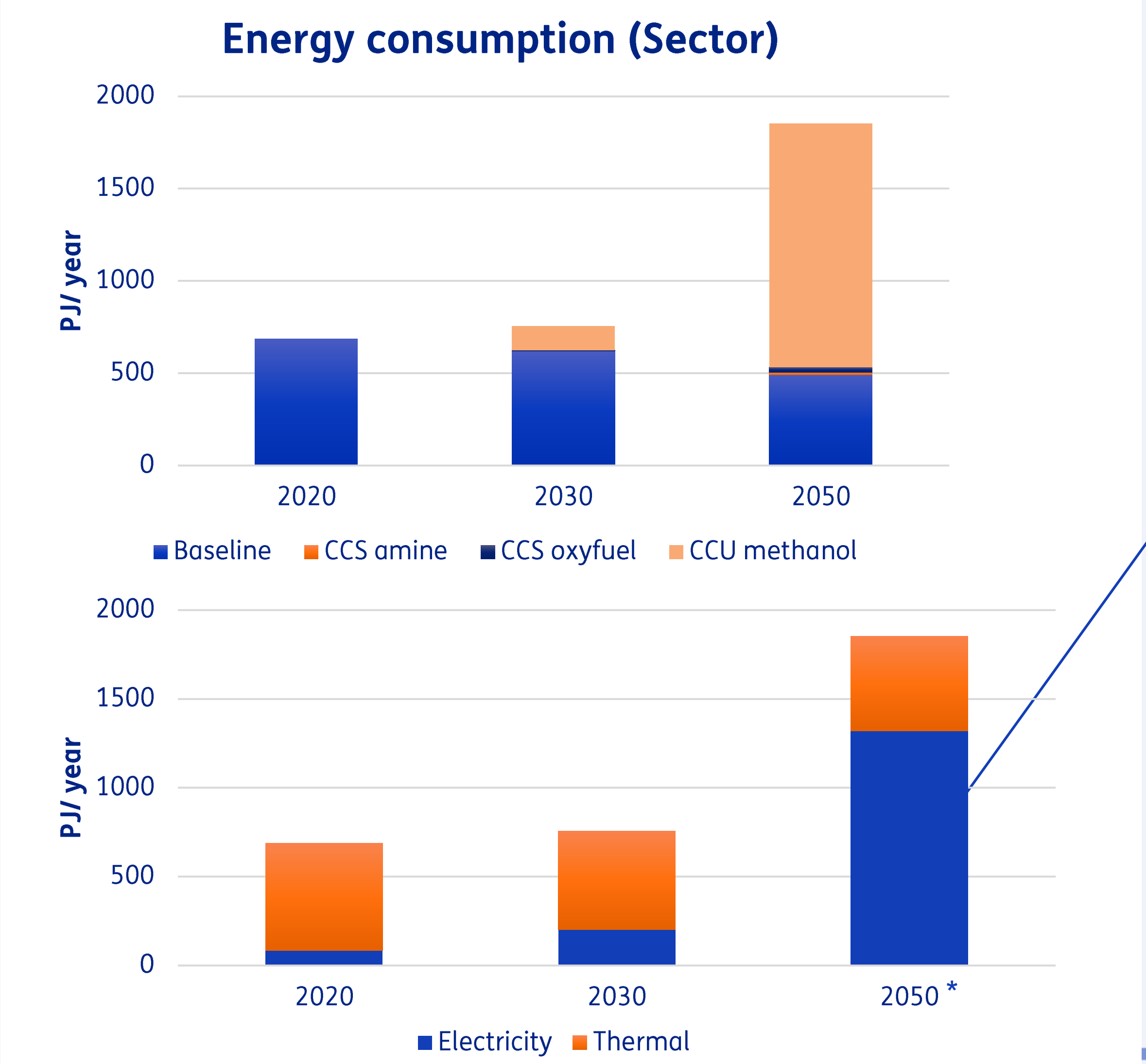
4. Scenarios results – 30% CCS 70% CCU case



- In 2030, the total specific energy consumption increases 10%, when compared to the baseline for 2020.
- **For 2050, the total specific energy is almost 3 times the baseline for 2020 (170% higher than the baseline)**
- In 2050, **CCU methanol represents 97% of the total additional energy needed for CCUS** technologies implementation
- The electricity consumption increases from 0.4 GJ/t cement (2020) to around 6.8 GJ/t cement in 2050. **The electrolysis alone represents 90% of the electricity demand**

4. Scenarios results – 30% CCS 70% CCU case

Total sector



2020 vs 2050

Electricity demand increases from 84 PJ/yr to 1320 PJ/yr

Thermal demand reduces from 603 PJ/yr to 533 PJ/yr

* By 2050, is considered that the electricity supply will be fully renewable. Therefore, the **availability** and **costs** per PJ may vary in different future scenarios.

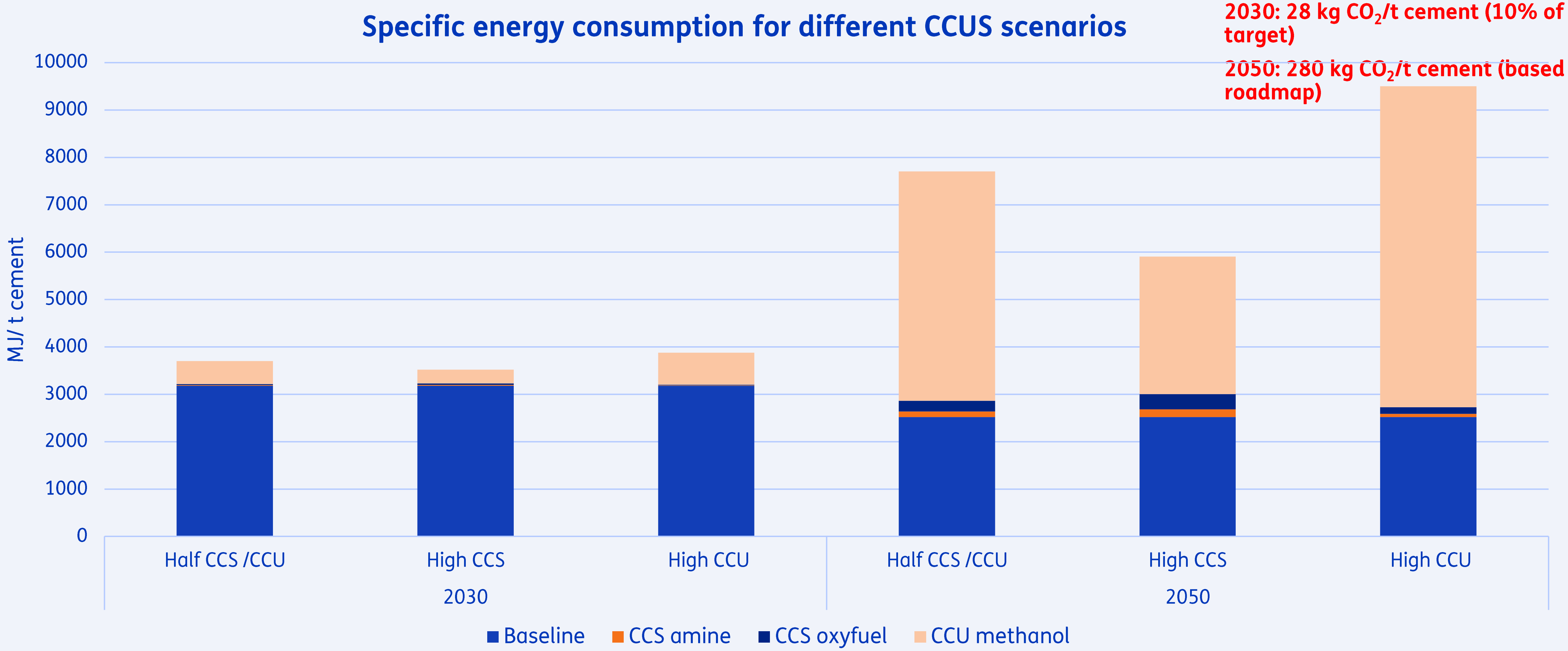
***PJ = 1x10^{15} J**

4. Scenarios results – specific energy comparison

Abatement targets for CCUS

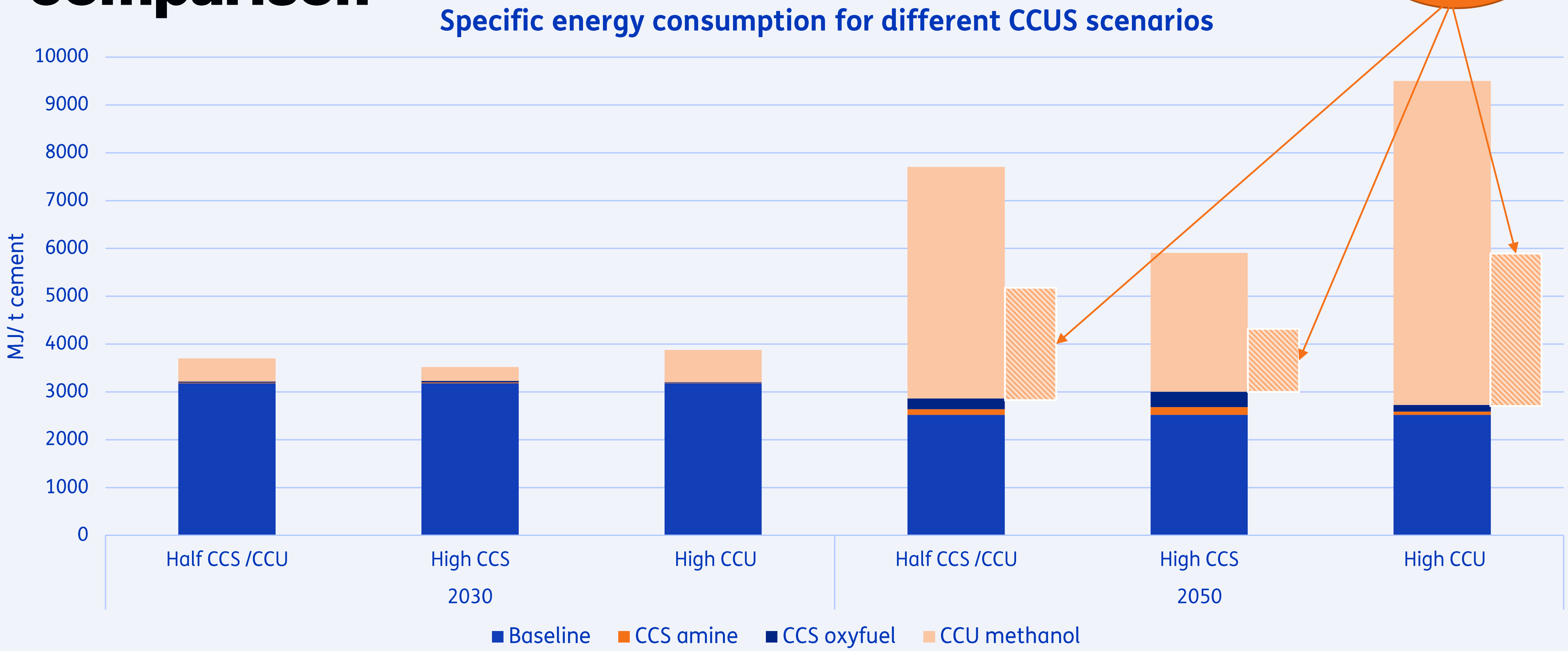
2030: 28 kg CO_2/t cement (10% of 2050 target)

2050: 280 kg CO_2/t cement (based on roadmap)

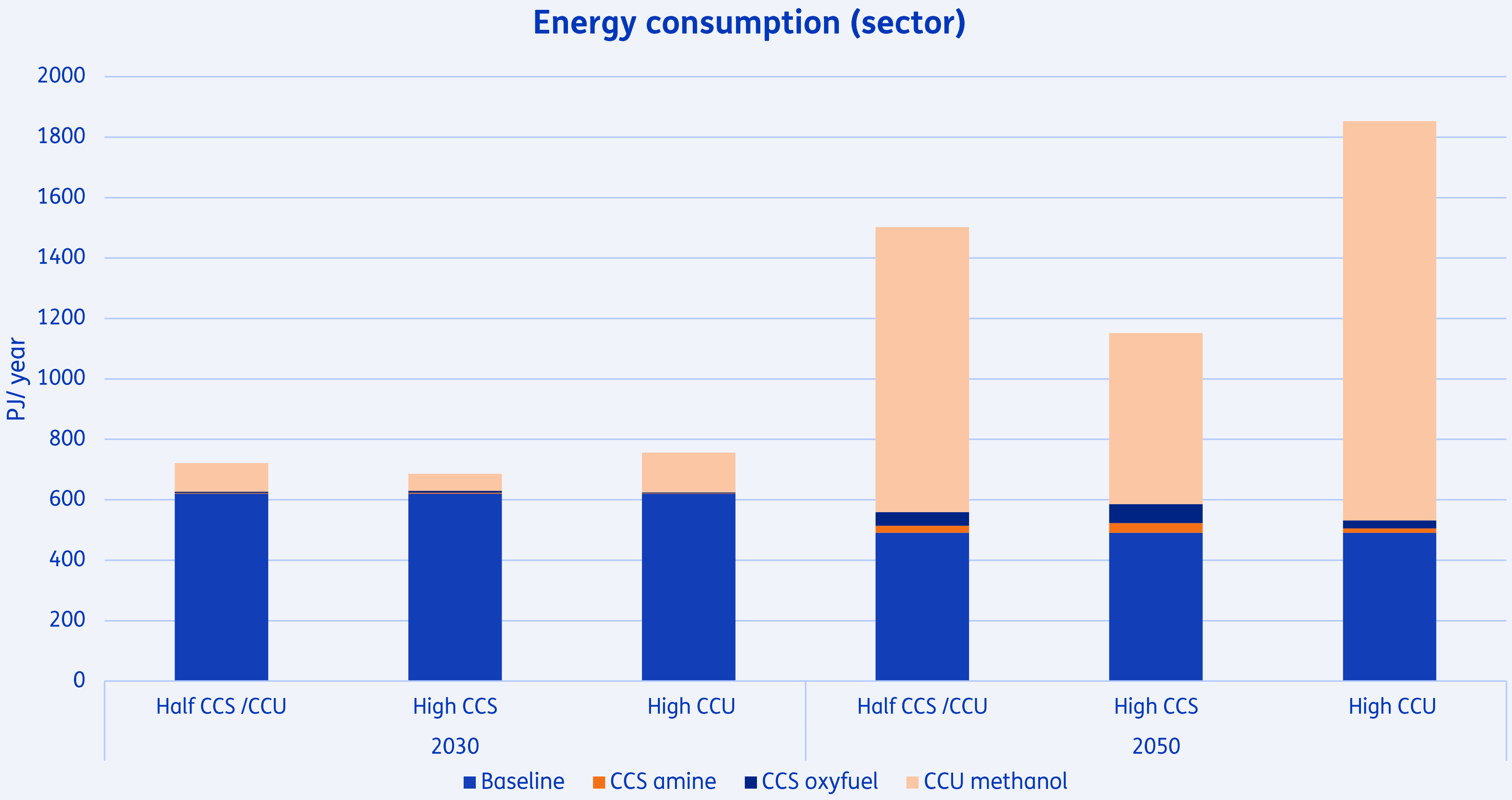


4. Scenarios results – specific energy comparison

48% of the energy consumed for CCU is embedded in methanol



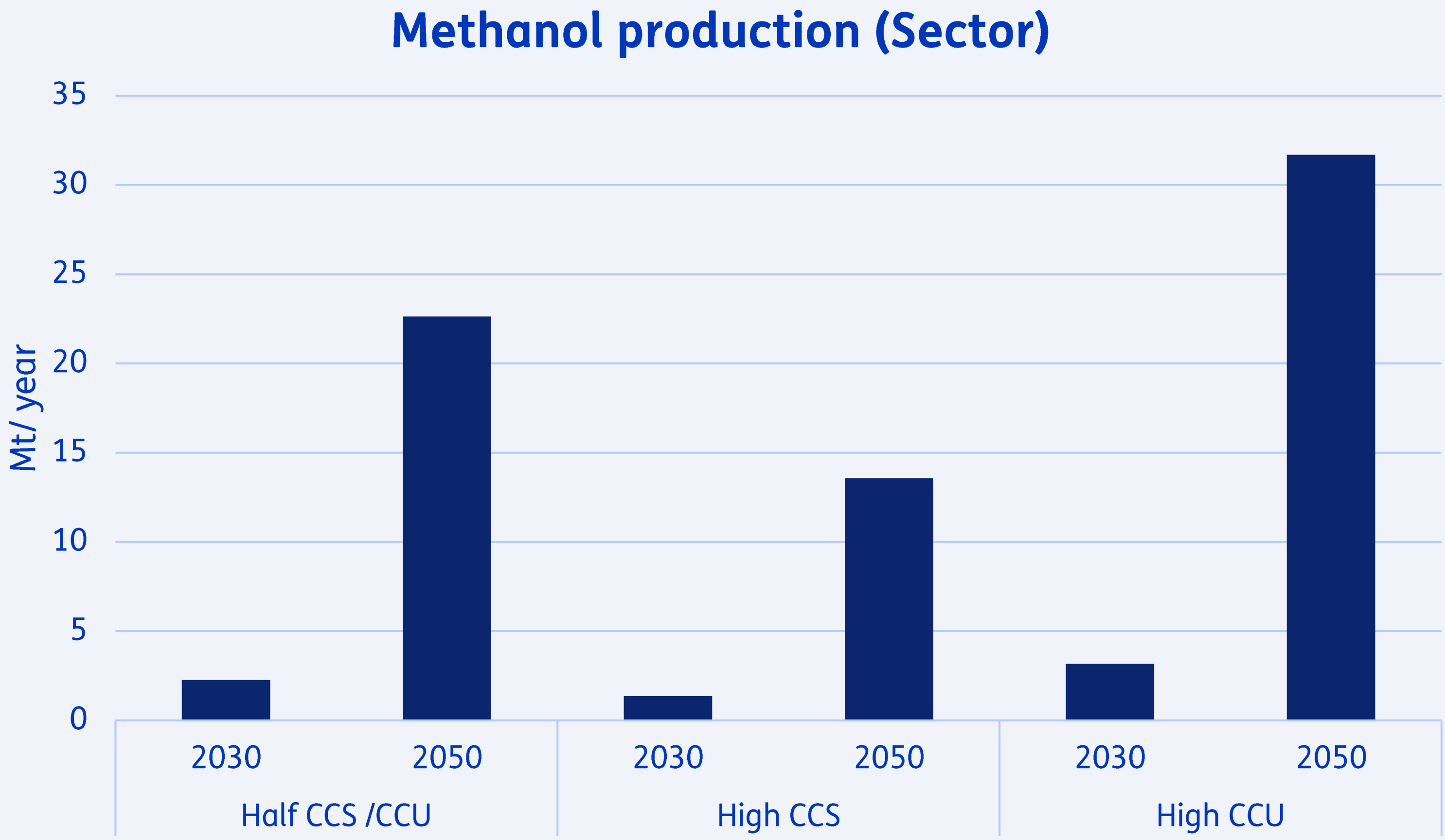
4. Scenarios results – total energy comparison



Total energy demand varies from 686 to 1853 PJ/year

(191-515 TWh/year)

4. Scenarios results – total methanol produced



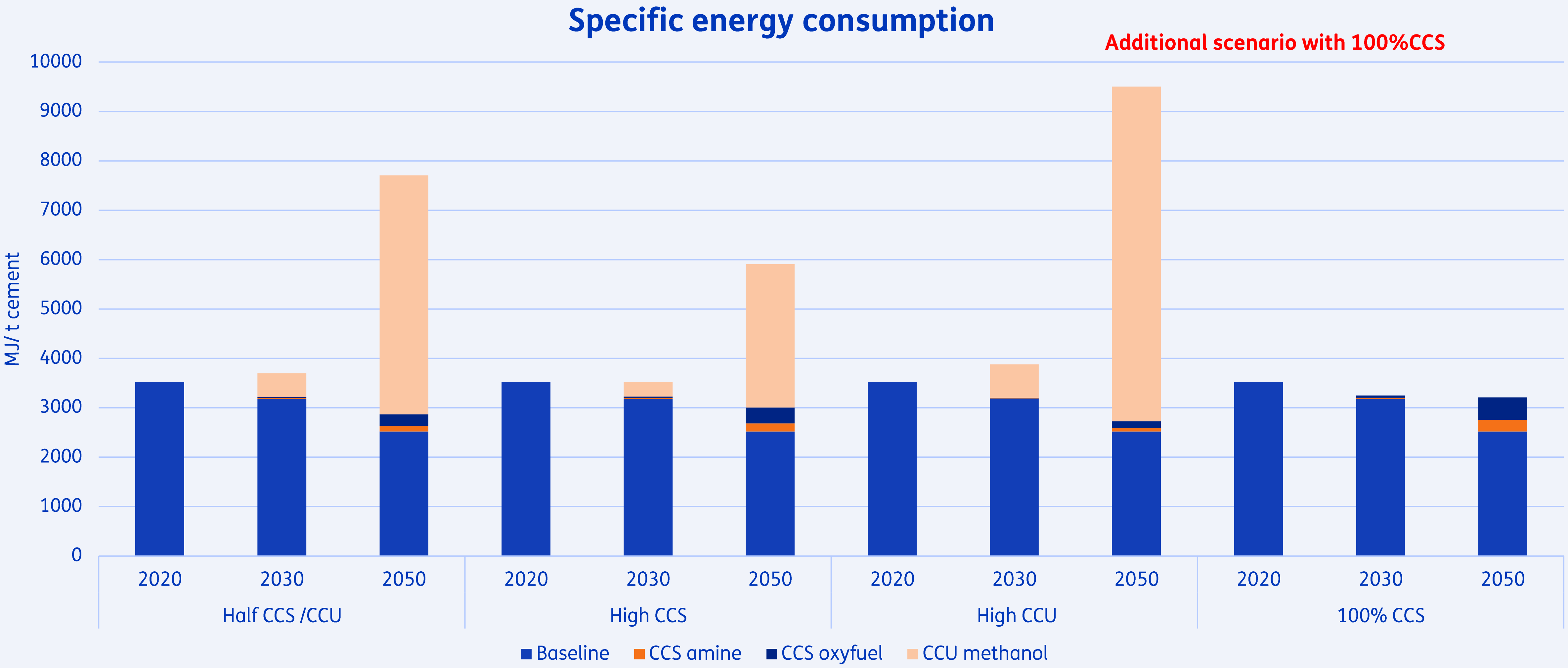
The total methanol production potential via CCU in 2050 is

14-32

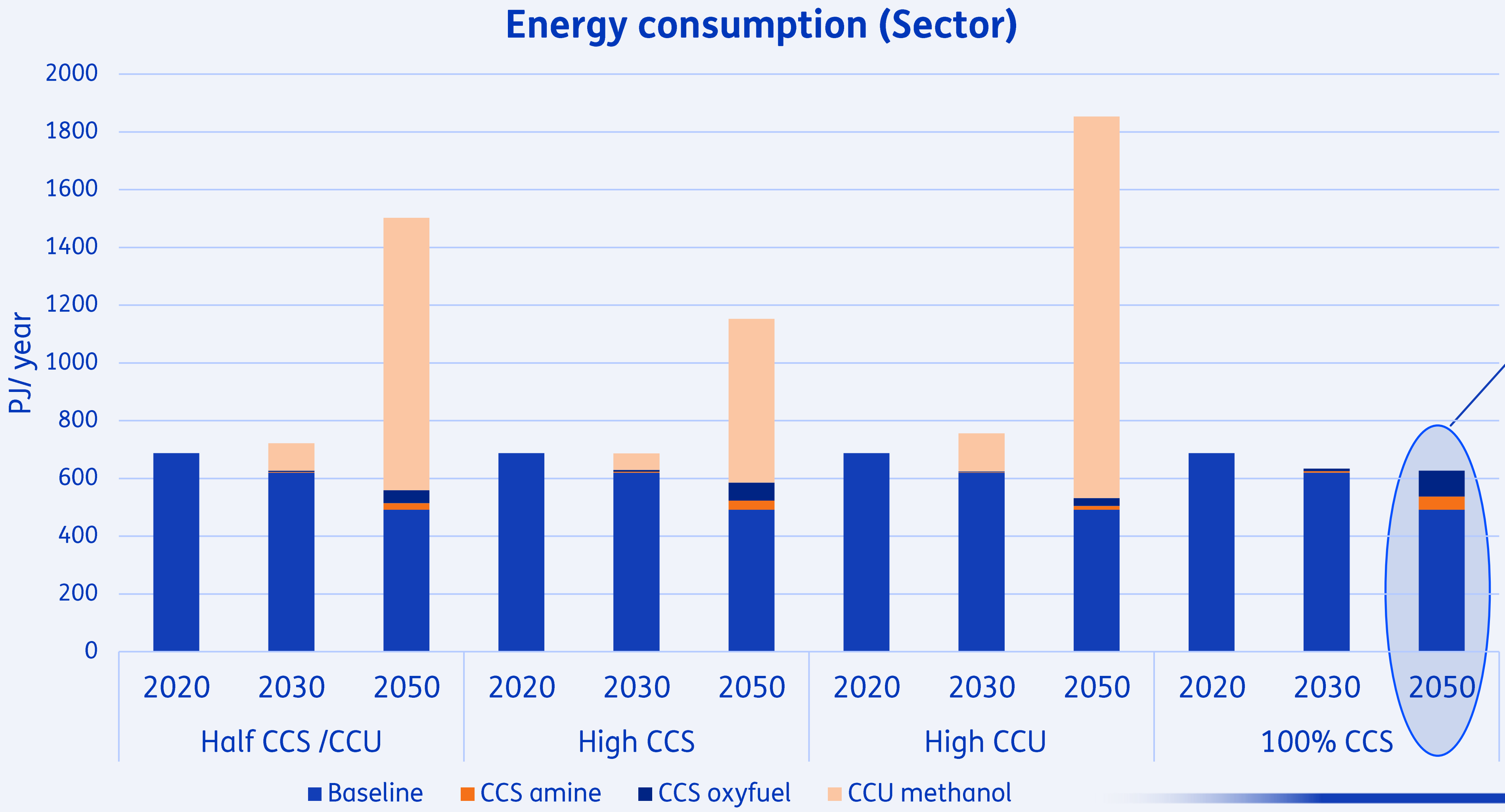
Mt/year

*For reference, the global methanol production in 2021 was 106 Mt

4. Scenarios results – specific energy comparison



4. Scenarios results – total energy comparison



Total energy demand

627 PJ/year

(174 TWh/year)

9% lower than the baseline in 2020

5. Conclusion and discussion

- The energy intensity of the cement production process is expected to decrease 30% by 2050 due to the decrease of the clinker ratio and due to the higher electric efficiency
- However, the CCU and CCS technologies that are needed to reach the emission targets will increase considerably the total demand of energy of the sector for almost all scenarios studied:
- **2030**
  - **+ 5%** for the 50% CCS/CCU case
  - **- 0.2%** for the high CCS case
  - **+ 10%** for the high CCU case
- **2050**
  - **+ 119%** for the 50% CCS/CCU case
  - **+ 68%** for the high CCS case
  - **+ 170%** for the high CCU case
- Electrolysis for green hydrogen production is the process that impacts the most the total electricity consumption of the system, representing 79-90% of the total consumption for the 2050 scenarios
- Although the CCU process impacts significantly on the system's energy demand, methanol is a marketable product and it is expected to become more relevant in the coming years

6. Next steps

- **Support CEMBUREAU with development of Carbon Roadmap**, which could be based on the following pillars:
  - Technology developments (Leilac process, Oxyfuel, Post-Combustion Amine based, etc.)
  - CCS (incl. on-going projects and timings)
  - Clinker substitution
  - Overall recycling
  - CCU (dependent on cost).

- . **Support CEMBUREAU with a deeper dive of CCUS assessment for the European Cement industry through:**
  - Consider energy efficiency improvements on the CCS and CCU technologies towards 2050.
  - Evaluation of direct and indirect emissions of each alternative route.
  - If the production of methanol is considered, the O_2 co-produced from the electrolytic production of H2 can be used in the Oxyfuel process, lowering Capex and energy consumption of the ASU. This optimization could be a future study.

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This report is an update from a version from March 2023, based on feed-back received from Virtual WGA "Climate Change & Energy“ on April 27.

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* Source is a technical regulation written in Dutch. The Netherlands Environmental Assessment Agency (PBL) issues advice on basic technical, costs, and energy related parameters to facilitate financial-economic evaluations for diverse technologies. This memorandum contains the draft advice with regard to CO$_2$ capture and storage (CCS).

Thank you

Appendix A

CCS data based on tonne of clinker

Post-Combustion with MEA (per tonne of clinker)		
Inputs	**2030/2050**	**unit**
Thermal Energy	3500	MJ/t clinker
Electricity	376	MJ/t clinker
Steam import	2.5	MJ/t clinker
Electricity for e-boiler	2.6	MJ/t clinker
Outputs		**unit**
Direct CO_2 Emissions	0.06	t CO2/t clinker
CO_2 Captured	1.1	t CO2/t clinker

Source: [5]

CCS Oxyfuel		
Inputs	**2030/2050**	**unit**
Thermal Energy	450	MJ/t clinker
Electricity	1170	MJ/t clinker
Oxygen	270	Nm3/t clinker
Outputs		**unit**
Direct CO_2 Emissions	0.04	t CO2/t cem
CO_2 Captured	0.83	t CO2/t cem

Source: [5]