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ParisTech's Chair Modeling for sustainable development

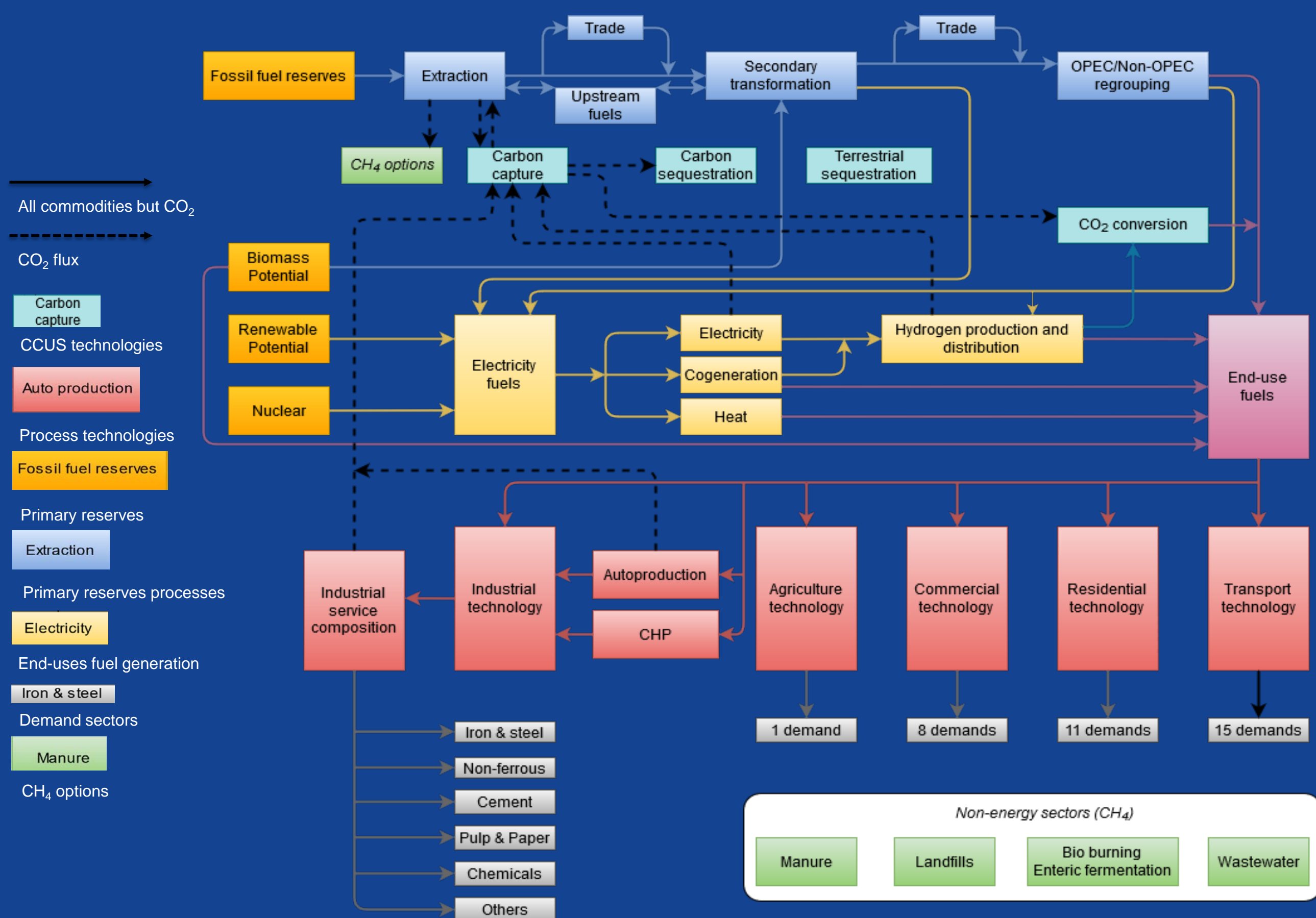
THE ROLE OF CARBON CAPTURE UTILIZATION AND STORAGE IN THE GLOBAL ENERGY TRANSITION: LONG-TERM OPTIMIZATION ON THE INDUSTRY SECTOR



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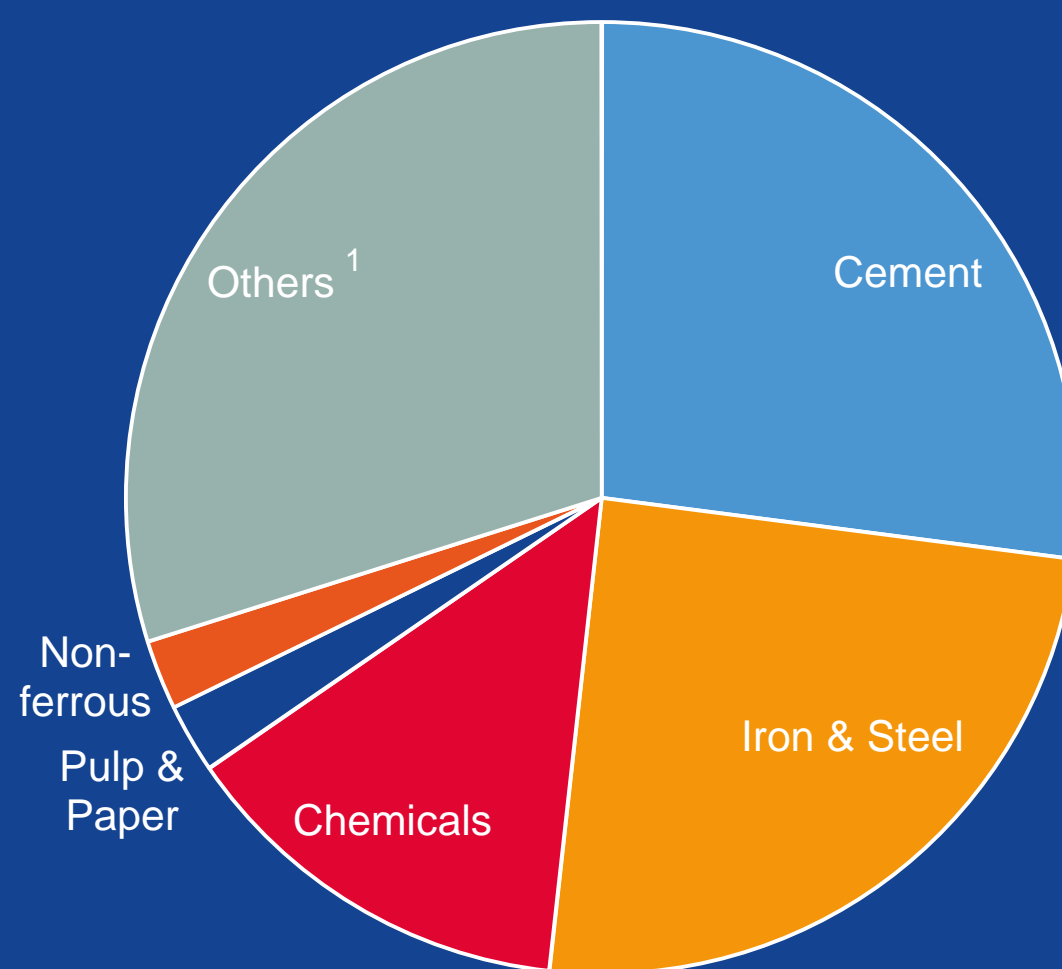
TIAM-FR Model

- French version of the IEA-ETSAP TIMES Integrated Assessment Model
- Bottom-up linear programming model optimizing costs over decades
- Geographically integrated into 15 regions
- Commodities, processes and demand depicted in a Reference Energy System below



CCUS technologies for industry

Industrial CO₂ emissions per sector



8.5 Gt of direct CO₂ emitted in 2017² (IEA)

Key facts about industry

- 23% of global direct CO₂ emissions
- 30% of global GHG emissions (direct and indirect)
- 37% of global final energy use
- High dependence on fossil fuels
- Energy intensive 'hard-to-abate' sector
- CCS can achieve industry decarbonation alongside with green hydrogen, blue hydrogen, and energy efficiency
- CCU can reduce both fossil-based fuels and fossil feedstocks

How CCUS technologies can help reduce industrial CO₂ emissions?

Main assumptions and scenarios

- IEA-ETSAP data (2010)
- 25 years technology life duration
- 1706 GtCO₂ storage capacity
- Business As Usual
- 2100 2°C/1.5°C climate targets
- With and without CCUS

3 key sectors for CCUS options in TIAM-FR

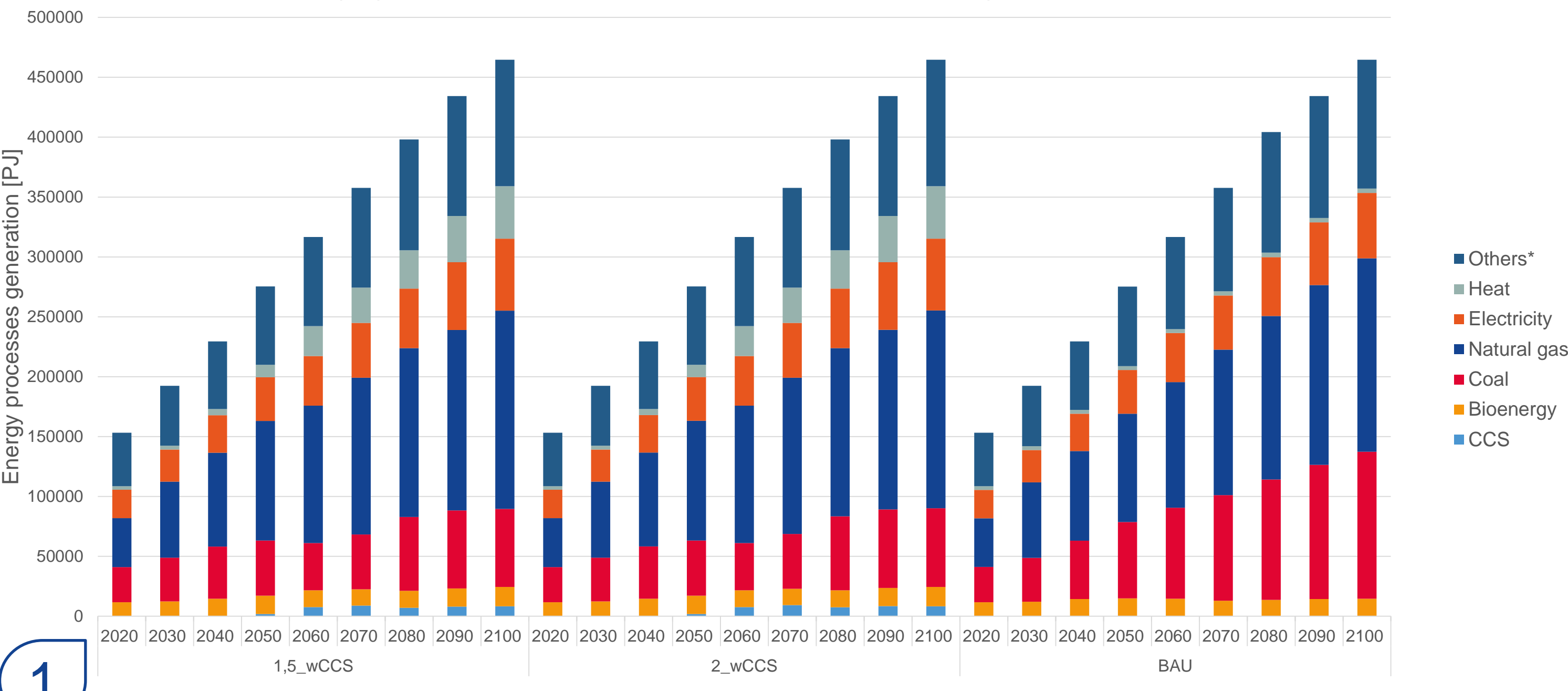
| Power generation | Industrial processes | Fuel generation |
|--|---|--|
| <ul style="list-style-type: none"> • Coal-fired + CCS • CCGT + CCS • Bioenergy + CCS • Co-firing + CCS | <ul style="list-style-type: none"> • Process heat + CCS • Process steam + CCS • Industrial heat + CCS • Industrial electricity + CCS • Co-generation + CCS | <ul style="list-style-type: none"> • Diesel + CCS • Heavy fuels + CCS • Ethanol + CCS • Hydrogen + CCS • CCU for methanol |

¹Including mainly food-processing, textile, mining, manufacturing and construction industries

²Including energy-related and process emissions

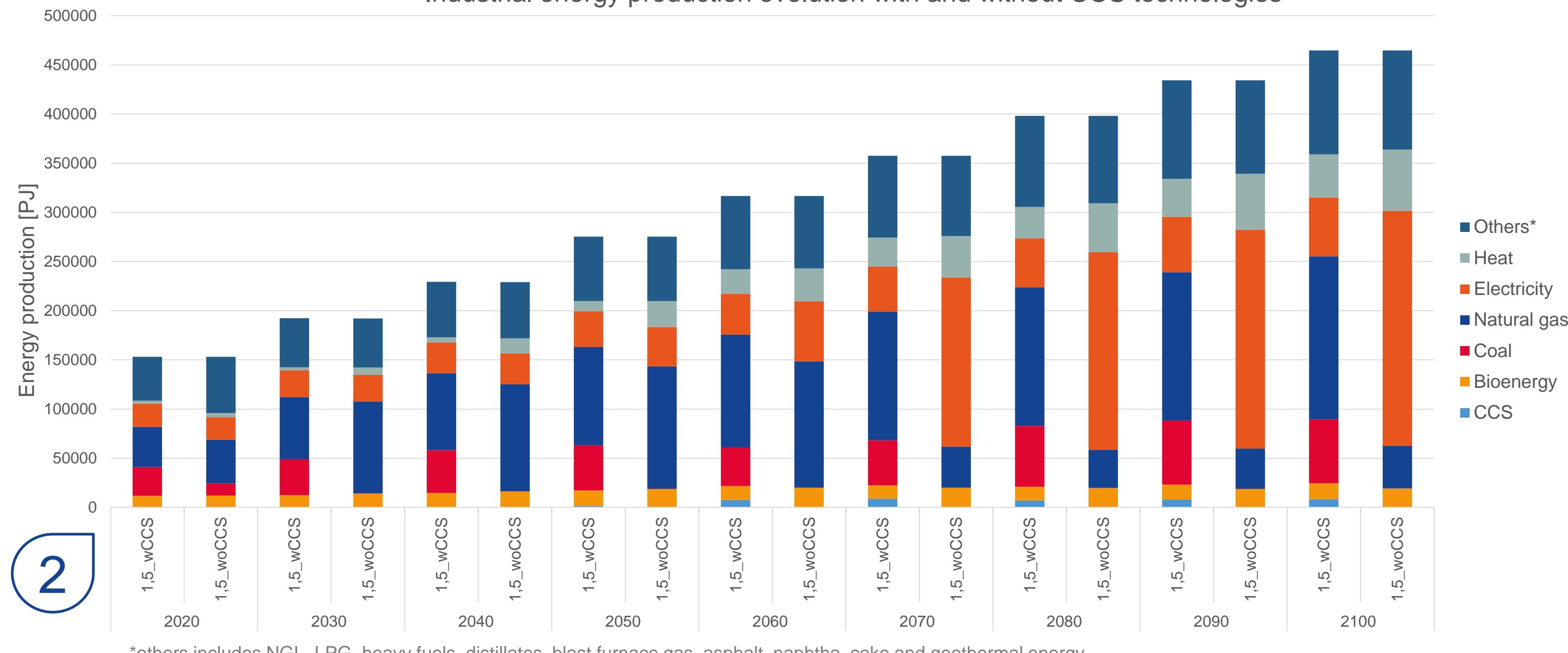
Results for the industry sector by 2100

Industrial energy generation temporal breakdown in mitigation scenarios and BAU scenario



1

Industrial energy production evolution with and without CCS technologies

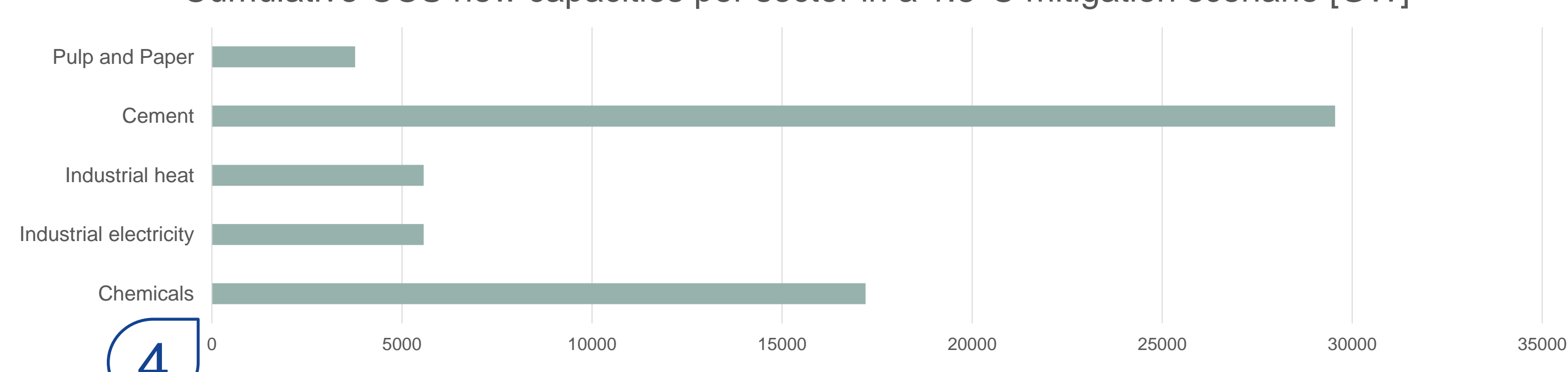


2

| Scenario | Label | Industrial CCS investment [TW] | CO ₂ stored from industrial processes [Gt] | Industrial discounted cost [B€] |
|------------------------------|-----------|--------------------------------|---|---------------------------------|
| Business as usual | BAU | 0.2 | 1 | 10,300,000 |
| 1.5°C mitigation with CCS | 1.5_wCCS | 62 | 142 | 11,100,000 |
| 1.5°C mitigation without CCS | 1.5_woCCS | 0 | 0 | 12,300,000 |
| 2°C mitigation with CCS | 2_wCCS | 61 | 141 | 11,100,000 |

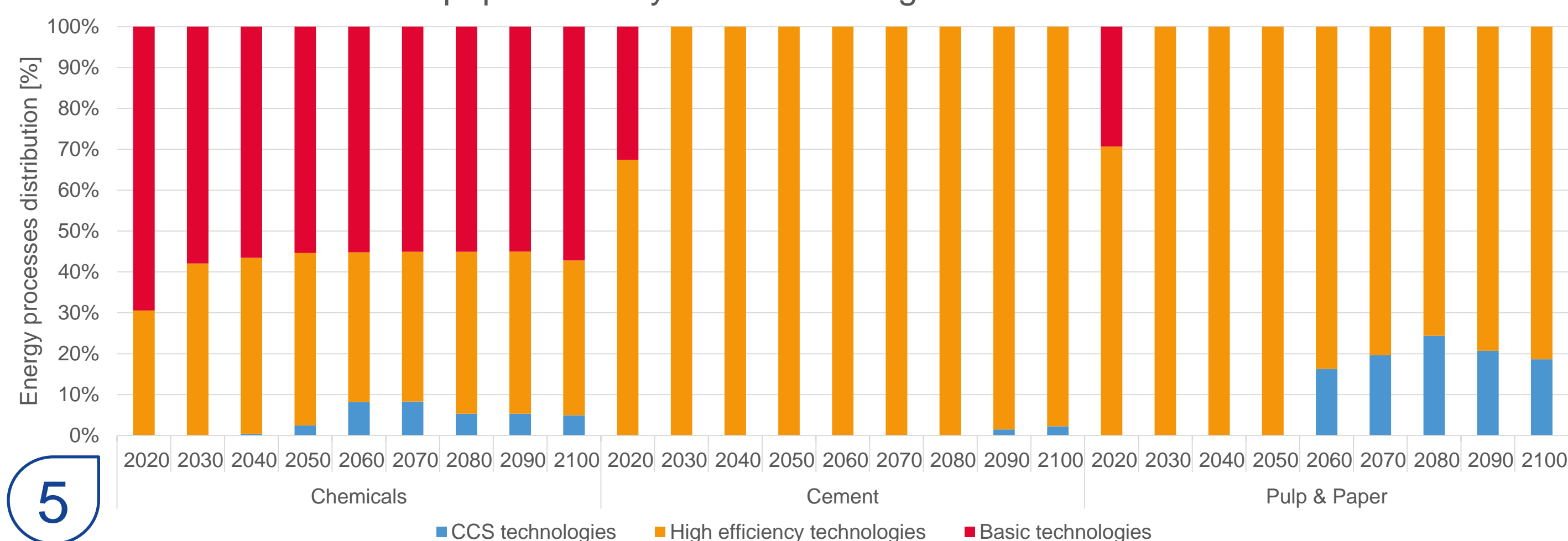
3

Cumulative CCS new capacities per sector in a 1.5°C mitigation scenario [GW]



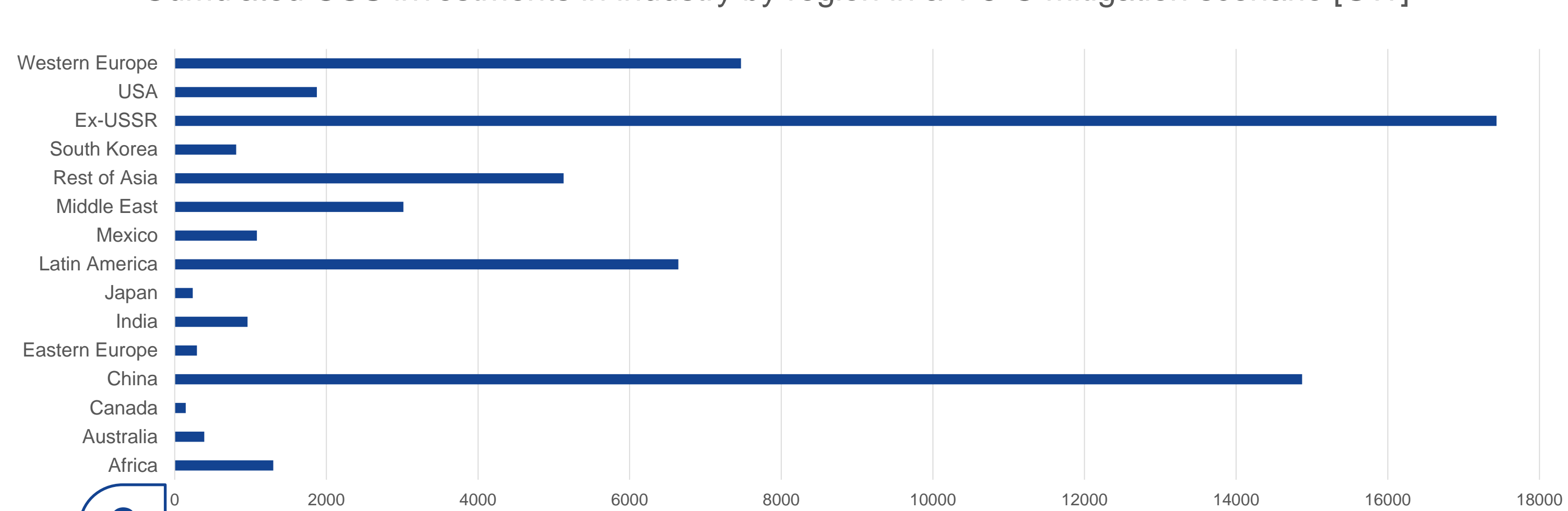
4

Industrial investments temporal breakdown for the chemical, cement and pulp & paper industry in a 1.5°C mitigation scenario



5

Cumulated CCS investments in industry by region in a 1.5°C mitigation scenario [GW]



6

Key findings

- 1 Minor disruptions in industrial processes between the BAU scenario and the mitigation scenarios, in where the use of coal is slightly replaced by heat importation.
- 2 Not relying on CCUS technologies will require the electrification of industry. Thus, the carbon content of electricity is dramatically reduced as of 2070.
- 3 Not relying on CCS will be more expensive.
- 4 The model choices to invest in CCS mainly for the cement and chemical industries in the second half of the 21st century.
- 5 New technologies with better energy efficiencies are preferred against CCS technologies to reduce industrial emissions. Hydrogen is not chosen as an option.
- 6 China, ex-USSR, Latin America and Western Europe are the regions that invest the most in CCS technologies.

Key issues and way further

- Cost actualization
- CCU implementation
- Sensitivity analysis
- Other mitigation pathways consideration
- Comparison with MIT top-down model
- Results feasibility assessment