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Carbon Capture and Utilisation as a Contribution to National Climate Change Mitigation Goals: Japan Case Study

IEA GREENHOUSE GAS R&D PROGRAMME

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IEA Greenhouse Gas R&D Programme

Carbon Capture and Utilisation as a Contribution to National Climate Change Mitigation Goals: Japan Case Study

Final Report

Carbon Counts Company (UK) Ltd

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Final Report

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Cover photo: Algal fuel testing laboratory, Florida, USA (Paul Zakkour)

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Acronyms and Abbreviations

APCr	Air pollution control residues
CCE	Circular carbon economy
CCS	Carbon capture and storage
CCU	Carbon capture and utilisation
CEAP	Circular Economy Action Plan (EU)
DAC	Direct air capture
EC	European Commission
EtJ	Ethanol-to-Jet
EtOH	Ethanol
ETS	Emissions trading system
EU	European Union
GEMCCU	Greenhouse Gas Emissions Model for CCU
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
IPPU	Industrial Process and Product Use
IRS	Inland Revenue Service (U.S.)
LCA	Life cycle assessment
LTS	Long term strategy
MeOH	Methanol
MSW	Municipal solid waste
NDC	Nationally determined contribution
OECD	Organisation for Economic Cooperation and Development
R&D	Research and development
RD&D	Research, development and demonstration
TEA	Techno-economic assessment
VCS	Voluntary Carbon Standard
WtE	Waste-to-energy

MJ	Megajoule
GJ	Gigajoule
PJ	Petajoule
t	Tonnes (metric)
kt	Kilotonnes
Mt	Megatonnes

Summary

This report builds upon previous studies on the topic of carbon capture and utilisation (CCU) published by the IEA Greenhouse Gas R&D Programme (IEAGHG 2018a, IEAGHG 2018b, IEAGHG 2018c, IEAGHG 2019). First, an update on recent CCU policy developments is set out. Second, previous research and analysis is assembled into a model – the Greenhouse Gas Emissions Model for CCU (GEMCCU) – to examine the emission reduction potential of CCU on an integrated basis. GEMCCU is used to assess the potential of a portfolio of CCU technologies to contribute towards Japan's climate change mitigation goals in 2030 and 2050.

Recent Policy Developments

The research finds that interest in CCU around the world continues apace, building upon the momentum identified in previous studies (IEA GHG, 2018a). Developments include:

- OECD countries are increasingly highlighting the important role that CCU could play within their national decarbonisation strategies.
- The United States, European Union and Japan could provide RD&D funding for CCU in excess of US$700 million over the next 10 years.
- Evaluations of the climate change mitigation potential of CCU in the literature suggest that CO_2 utilisation rates in the order of 100 to 1,100 $MtCO_2$ by 2050 could be achieved under scenarios of comprehensive and sustained climate action.

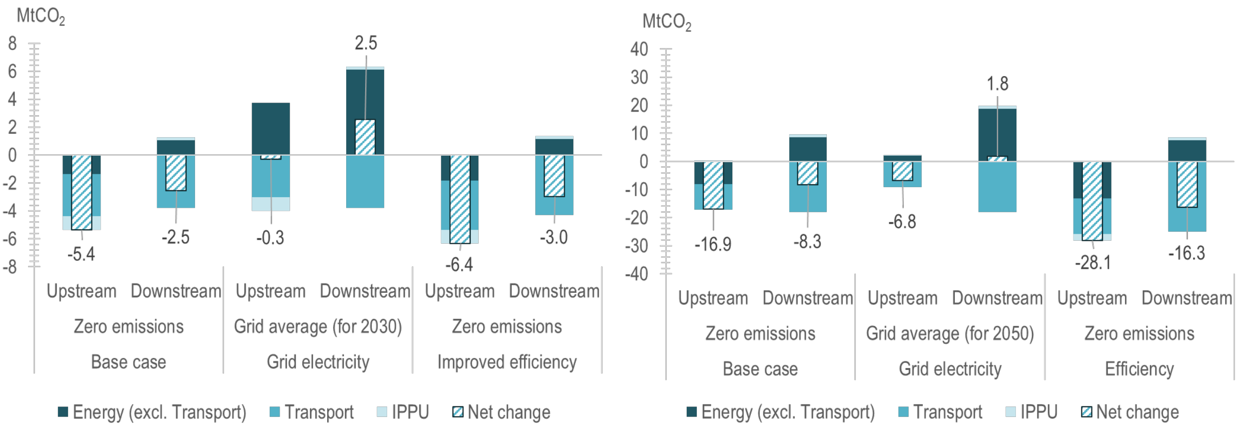
Contributions Towards Japan's Climate Change Mitigation Goals

Using two scenarios – 'scenario 2030' and 'scenario 2050' involving, respectively, 5 and 25 $MtCO_2$ utilised – various combinations of CO_2 sources and end use pathways, and a range of key sensitivities (accounting mode, source of electricity, various process efficiency improvements), an assessment is made of the potential of CCU to contribute towards Japan's climate mitigation goals.

Analysis suggests that using 5 to 25 $MtCO_2$ in CCU applications could potentially drive net CO_2 emissions changes of -5.4 to -17 $MtCO_2$ under base case assumptions. The emissions reduction effect increases to, respectively, -6.4 to -28 $MtCO_2$ with improved efficiency but decreases to -0.3 to -6.8 $MtCO_2$ if grid electricity is assumed as the source of power (rather than 100% zero carbon electricity). Summary results with sectoral impacts are shown below (Figure S.1).

The base case contribution represents between 2 and 6.4% of Japan's estimated mitigation efforts to 2030 and 2050 respectively and could reach over 10% in 2050 if improved efficiency can be achieved.

Figure S.1. CO_2 emissions changes by sector (left, scenario 2030; right, scenario 2050)



Note: 'Upstream' accounting means emissions reductions are counted at the point of CO_2 capture. 'Downstream' accounting instead counts the emissions reduction effect of CCU by zero-rating CO_2-derived product emissions (and therefore does not count emissions reductions when capturing CO_2 at source – see Section 3.3.1). Source: GEMCCU

Achieving best-case results would require, by 2050, the addition of up to 22 GW of new zero carbon electricity generating capacity dedicated to CCU.

Equally, analysis suggests that electricity grid emissions factors lower than 460-500 kgCO_2e/MWh could be sufficient to deliver a net emissions reduction effect in the scenario 2030 base case. This decreases to 175-275 kgCO_2e/MWh in scenario 2050, where higher utilisation rates and a wider portfolio of CCU technologies is employed.

Policy Implications

Analysis using GEMCCU indicates that the most appropriate means to account for the climate mitigation effect of CCU technologies is to count the emissions reduction from capturing CO_2 at source ('upstream' accounting). This requires all downstream emissions of the captured CO_2 to be treated in the same way as fossil CO_2 emissions. Approaches that instead count the climate mitigation 'downstream' miss emissions reduction effects when the CO_2 is integrated into products with long-term storage (e.g. mineralisation technologies).

Zero-rating emissions from algae-derived fuels, assumed on the basis of them being biofuels despite being fed exclusively on fossil CO_2 feedstock, presents a potential emissions accounting "loophole" that could mean the emission reduction effects of CCU are overstated. Further clarification of the measurement and reporting methods for algal fuels is therefore recommended. Under a worst-case scenario (grid electricity supply and accounting of emissions from algal fuel use as fossil CO_2 emissions) the net emissions change from deploying the modelled portfolio of CCU technologies would instead be +2.7 to +3.2 MtCO_2 for scenario 2030 and scenario 2050 respectively.

Technical and market constraints on polycarbonate and mineralisation pathways mean that as little as 300 ktCO_2 utilised would be sufficient to saturate Japan's current markets for these products. Long-term CCU strategies will therefore inevitably involve electro-intensive pathways using hydrogen for electo-fuel production. It is also notable that in scenario 2050 the domestic production of CO_2-derived methanol could “onshore” around 6 $MtCO_2$ onto Japan’s national GHG emissions inventory.

Further modifications to GEMCCU model could help enhance understanding of the climate mitigation potential, and potential constraints, of CCU. Expanding the number of CCU technologies included (currently 4), modifying the scenarios analysed towards different outcomes, building more dynamics into the electricity part of the model, and adding an economic model would all help to improve and expand the results and insights.

1 Introduction

This report provides an assessment of the potential for carbon dioxide capture and utilisation technologies (CCU; sometimes also referred to as “CO2U”) to contribute towards meeting medium- and long-term greenhouse gas (GHG) climate change mitigation goals.

To make this assessment, we use Japan as a national case study, drawing upon the following sources of information:

1. Current and historical emissions (Ministry of Environment 2019).
2. Targets and technologies as set out in Japan’s nationally determined contribution (NDC) and long-term strategy (LTS) under the Paris Agreement (Government of Japan (GOJ) 2015; GOJ 2019).
3. Recently stated ambitions for CCU development as set out in Japan’s CCU Roadmap (Ministry of Economy, Trade and Industry (METI) 2019).

Analysis of the potential climate change mitigation effects of CO_2 utilisation was made using a purpose-built model (the GHG Emissions Model for CCU or “GEMCCU”, IEA GHG 2020). The architecture of GEMCCU is constructed around various CCU technology sub-models drawing from the analytical frameworks previously described in earlier studies in this work programme (IEA GHG 2018c; IEA GHG 2019), and new analysis of CCU technology pathways compiled specifically for this study, as described in the accompanying report (IEA GHG 2020). A key aspect of GEMCCU is the allocation of CCU GHG emissions effects to various reporting categories used for national GHG inventories under Intergovernmental Panel on Climate Change (IPCC) methods (IPCC 2006).

CCU continues to be an emerging topic of interest within climate mitigation policymaking. Previous reports published under this work programme included reviews of recent CCU pollical and regulatory developments around the world alongside, detailed technical evaluations of selected CCU technologies (IEA GHG 2018a, IEA GHG 2018b, IEA GHG 2018c). Over the past year or so, policy developments in these directions have continued apace. Various reports, roadmaps and emerging regulatory developments have been published.

In light of these developments, Section 2 starts with a short review of these recent activities. Section 3 then describes the model and scenarios used for analysis, Section 4 presents the model results, Section 5 sets out some policy considerations based on the results, and Section 6 provides some concluding remarks and areas for further research.

2 Recent Developments

This section sets out a brief update on recent developments for CCUS policy, funding and regulation that have occurred since the review undertaken in 2018 (IEA 2018a). The update is focussed on various international activities as well as more detailed summaries of regional developments in the United States (U.S.) and the European Union.

Developments in Japan are considered in Section 3, where the background to the analysis is described.

2.1 International Activity

Various international reports and initiatives have emerged within the past two years, although some previous activities seem to have declined. These are set out below.

2.1.1 Global CO_2 Initiative

The Global CO_2 Initiative continues to work exclusively on the topic of CCU. Over the past two years it has published various documents including:

1. Techno-Economic Assessment & Life Cycle Assessment (LCA) Guidelines for CO_2 Utilization (V 1.0). Several worked examples of TEAs and LCAs of are also provided, covering:
    a. Oxymethylene ethers
    b. Mineralisation
    c. Methanol
    d. Fertilisers
    e. Domestic heating
2. A CCU Activity Hub. This contains an interactive map highlighting a wide range of activities associated with CCU technologies. The map provides some useful information, but also includes information that can be considered to be somewhat tangential to CCU (for example, presence of a carbon price).

The focus of the Initiative continues to be on engineering-oriented technical analysis of CO_2-derived products on a lifecycle basis.

All information can be accessed at: https://www.globalco2initiative.org/evaluation/

2.1.2 International Energy Agency (IEA)

In September 2019, the IEA published a technical study on CCU (IEA, 2019). In its report, the IEA concluded that the size of future markets for CO_2 are uncertain because of uncertainty over technological maturity, commercial readiness and the role of policy in supporting deployment.

Accounting issues relating to CCU were also assessed, with the conclusion that CO_2 *used* is not the same as CO_2 *avoided*, and that the climate mitigation benefits depend on scalability, use of low-carbon energy, and displacement of products with higher life-cycle emissions.

The authors of the report assert that the application of LCA is needed to help inform decisions about the efficacy of CCU technologies in reducing emissions, and that market dynamics also need to be taken into account. The report also notes that CCU should be considered as a complement to carbon capture and storage (CCS), and not a replacement.

The report's main policy recommendations are:

- Policy and investment decisions for CO_2 utilisation applications should be informed by robust LCA that provides improved understanding and quantification of climate benefits.
- Introduce public procurement guidelines for low-carbon products.
- Establish performance-based standards for products such as building materials, fuels and chemicals to facilitate the uptake of CO_2-derived alternatives.
- Support research, development and demonstration (RD&D) for future applications of CO_2 use that could play a role in a net-zero CO_2 emission economy, including as a carbon source for aviation fuels and chemicals.

2.1.3 Innovation Cool Earth Forum (ICEF)

After sponsoring the CCU Roadmap v1.0 in 2016 and v2.0 in 2017 (Innovation Cool Earth Forum 2017), no subsequent publications have been produced (e.g. a CCU Roadmap version 3.0 is not available). It remains unclear whether work is ongoing in these contexts.

2.1.4 G20 and the Circular Carbon Economy

The 2020 Saudi Arabian G20 Presidency has adopted a "circular carbon economy" (CCE) theme as a main priority of its presidency agenda. The CCE concept is based around 'four Rs' as follows (Williams 2019):

1. Reduce: energy efficiency, non-biomass renewables, and nuclear power.
2. Reuse: carbon capture and utilization.
3. Recycle: natural sinks and bio-energy.
4. Remove: CCS, direct air capture (DAC), and natural sinks.

Thus, CCU, by way of the *reuse* element of CCE, will be on the agenda of the 2020 G20 Summit scheduled for late 2020.

A summary of the CCE concept, and a series of supporting papers and other resources is available at: https://www.cceguide.org/

2.1.5 Voluntary Carbon Markets

The Voluntary Carbon Standard (VCS) is a privately operated, project-based, carbon crediting system. During 2019 the VCS approved one methodology relating to CO_2 utilisation for polymers and is presently considering a second for concrete (Table 2-1).

Table 2-1 Summary information on VCS CCU methodologies

Methodology element	Polymers	Concrete
Title	VM0040 – Methodology for Greenhouse Gas Capture and Utilization in Plastic Materials	Methodology for CO_2 Utilization in Concrete Production
Version/Date	1.0, July 2019	1.0, November 2018
Status	Approved	Under development
Proponent	Newlight Technologies	CarbonCure Technologies
Applicability conditions	Activities that convert CO_2 (and/or CH_4), which would have otherwise been emitted to the atmosphere, into a useful plastic material (long-chain thermopolymer) for sale into the plastics market. Products must: • Be biodegradable. • Retain CO_2 for >100 years, etc. • etc	Activities that convert CO_2, which would have otherwise been emitted into the atmosphere, into concrete products. Products must • Be manufactured using CO_2 as a feedstock in a process that requires lower amounts of cement compared to traditional concrete production processes. • Have the same performance as traditional concrete. • Be used and sold in commercial market etc.
Project boundary	• Facility where plastic materials are produced. • Facilities from which the GHG feedstock is sourced (if not DAC). • Facilities where displaced conventional plastic material is manufactured.	• Facility where concrete materials are produced. • Facilities from which the CO_2 feedstock is sourced (if not DAC). • Facilities where displaced Portland cement is manufactured.
Baseline scenario	Continuation of manufacturing plastic material through traditional processes.	Manufacturing of concrete through traditional processes.
Additionality	Activity Method: regulatory surplus and positive list approach*	Activity Method: regulatory surplus and positive list approach*
Baseline emissions	1. Plastic production (conventional polymer production pathway). 2. GHG feedstock used on the process (avoided emissions i.e. CO_2 not captured in the baseline scenario).	1. Reduced cement usage (due to enhanced cement properties derived from CO_2). 2. Captured CO_2 (avoided emissions i.e. CO_2 not captured in the baseline scenario).
Project emissions	1. Electricity use and fossil fuel combustion at the project production facility. 2. Emissions from the plastic made by the project that is eventually destroyed by incineration.	1. Emissions from the amount of cement used at the project facility 2. Electricity use and fossil fuel combustion at the project facility 3. Emissions associated with the capture, compression and transport of CO_2
Source	https://verra.org/methodology/vm0040-methodology-for-greenhouse-gas-capture-utilization-plastic-materials/	https://verra.org/methodology/methodology-for-co2-utilization-in-concrete-production/

Notes: * As set out in the VCS Methodological Requirements, available at: https://verra.org/project/vcs-program/rules-and-requirements/.

Approved methodologies under the VCS provide the basis for qualifying activities to generate offset credits. The resulting units or credits can be acquired by entities (e.g. companies, organisations, individuals) wishing to make claims regarding their carbon footprint, for example, by counting the credits as offsets against their own emissions.

Methodologies under the VCS consist of components typical of any project-based carbon crediting scheme, such as boundaries, baselines, monitoring and so on. A summary of the two CCU-related methodologies is provided above (Table 2-1).

It is uncertain whether these VCS methodologies would stand up to the scrutiny applied in a regulated carbon market.

2.2 Regional Activity

2.2.1 United States

Policy

The U.S., in accordance with Article 4.19 of the Paris Agreement, has submitted a long-term strategy (LTS) to the United Nations Framework Convention on Climate Change (UNFCCC; U.S. Government 2016). The analyses set out in the LTS foresees CCUS playing an important role within the country's low emissions development. However, unlike the European Union (Section 2.2.2), the analysis does not provide sufficient granularity to determine possible levels of CCU deployment. Presently, no overarching federal policy goals exist that set out the basis for strategic support for CCU.

Incentives

The Inland Revenue Service (IRS) 45Q sequestration tax credit ("45Q") has been supporting CO_2-enhanced oil recovery and geological CO_2 storage activities since 2008. Revisions under The Bipartisan Budget Act of 2018 broadened the scope of 45Q to also cover technologies involving the "beneficial use" of carbon oxides (as reported previously in IEA GHG 2018a; IEA GHG 2018c).[1]

A key aspect constraining full implementation of the 45Q amendments has been the absence of rules regarding the monitoring of beneficial use projects. Under 45Q, taxpayers claiming the benefit must calculate the amount of qualified carbon oxide utilized that, based upon an analysis of lifecycle GHG emissions (LCA), were (i) captured and permanently isolated from the atmosphere, or (ii) displaced from being emitted into the atmosphere.

[1] CCU technologies as covered herein are referred to as "beneficial uses" of carbon oxides under 45Q. The term utilisation is generally reserved for CO_2-EOR activities.

These requirements were clarified by the IRS and Treasury Department in June 2020 as follows:[2]

> ‘ “Lifecycle greenhouse gas emissions” means the aggregate quantity of GHG emissions (including direct emissions and significant indirect emissions such as significant emissions from land use changes), related to the full product lifecycle, including all stages of product and feedstock production and distribution, from feedstock generation or extraction through the distribution and delivery and use of the finished product to the ultimate consumer, where the mass values for all GHGs are adjusted to account for their relative global warming potential.
>
> The taxpayer measures the amount of carbon oxide captured and utilized through a combination of direct measurement and LCA. The measurement and written LCA report must be performed by or verified by an independent third-party. The report must contain documentation consistent with the International Organization for Standardization (ISO) 14044:2006, ‘‘Environmental management—Life cycle assessment—Requirements and Guidelines,’’ as well as a statement documenting the qualifications of the third-party, including proof of appropriate U.S. or foreign professional license, and an affidavit from the third-party stating that it is independent from the taxpayer.
>
> The taxpayer must submit the written LCA report to the IRS and the DOE. The LCA will be subject to a technical review by the DOE, and the IRS, in consultation with the DOE and the EPA, will determine whether to approve the LCA.’

Consequently, the level of 45Q tax credit received will be linked to the amount of carbon oxide utilised (through direct measurement) and the emission savings that arise from the CCU activity as estimated through LCA. The LCA report will therefore require a comparative LCA of the proposed carbon oxidation utilisation activity and the baseline activity that it is assumed to displace.

Funding

In addition to the broadened scope of the 45Q regime, the U.S. Department of Energy, Office of Fossil Energy also provides grant support for CCU related research and development (R&D) activities (as reported previously in IEA GHG 2018a; IEA GHG 2018c).

In June 2020, 11 new CCU projects were selected to receive approximately US$17 million in federal co-funding across four areas of interest for CCU (Table 2-2).[3]

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[2] 26 CFR Part 1, § 1.45Q–4 Utilization of Qualified Carbon Oxide. Published 02/06/2020.

[3] U.S. DOE Press Release: https://www.energy.gov/articles/doe-invests-17-million-advance-carbon-utilization-projects

Table 2-2 Summary of U.S. DOE CCU R&D funding, in 2020

Area of Interest	Number of Projects	Funding	
		Federal	Co-sponsors
Synthesis of Value-Added Organic Products	7	$7 m	$1.7 m
Production of Inorganic Materials: Solid Carbon Products	1	$2 m	$0.5 m
Integrated CO_2 Capture with Algae	2	$6 m	$1.5 m
Production of Inorganic Materials: Maximizing Uptake in Concrete and Cement	1	$2 m	$0.9 m

2.2.2 European Union

Policy

In the European Union (EU) several policy documents have been published over the last two years that chart indicative outlooks for the evolution of CCU technologies within Europe.

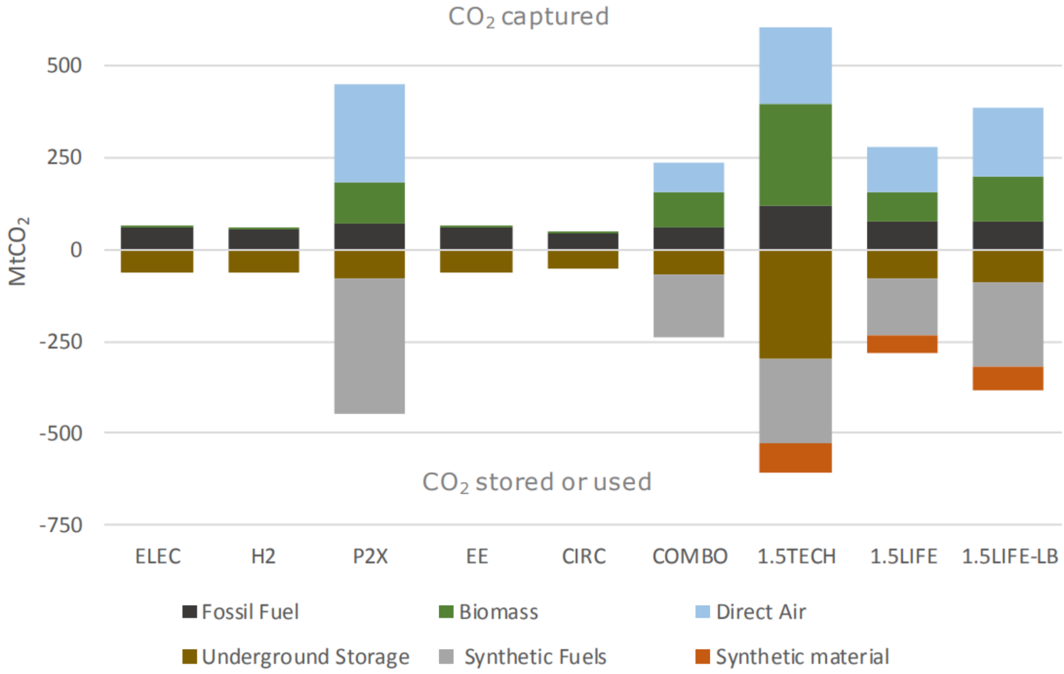
A Clean Planet for All

In November 2018, the European Commission published its long-term strategy for achieving net-zero emissions by 2050, entitled "A Clean Planet for All" (European Commission 2018a). The information therein provides the basis for the EU's LTS under the Paris Agreement.

Europe's political commitment to achieving net-zero emissions, as set out in the LTS, draws from supporting analysis and modelling of potential long-term climate change mitigation pathways for Europe (European Commission 2018b). The modelling used nine different scenarios that included different mixes of mitigation technologies and approaches to achieve net-zero emissions in 2050. More than half of the nine scenarios resulted in a significant role for CCU (Figure 2-1).

Based on the modelling results, levels of CCU technology deployment in 2050 could be in the range of 200-400 million (M) tCO_2 per year, using CO_2 feedstock obtained from a variety of sources including fossil, biomass, and DAC. The main end use of the captured CO_2 is envisaged to be synthetic fuel production (under the Power-to-X scenario and 1.5 TECH), with smaller amounts being used to make synthetic materials. The analysis also suggests that CCU could play a more significant role than CCS in climate change mitigation in Europe in coming years.

Figure 2-1 CO_2 capture, utilisation and storage in the EU, in 2050



Source: European Commission, 2018b

Circular Economy Action Plan

The growing interest in CCU technologies across the EU (as reported previously in IEA GHG 2018a; IEA GHG 2018c), and its envisaged role in meeting Europe's long-term climate mitigation ambitions (as outlined above), has led the EC to commit to exploring possible long-term, systematic, support policies for CCU technologies in coming years. These commitments are being channelled through action on the circular economy.

In the EC's new Circular Economic Action Plan (CEAP; European Commission (EC) 2020), it notes the importance of circularity as a prerequisite for climate neutrality, and the role of carbon removals therein. The CEAP refers to both nature-based removals and technological-based removals including re-use and storage of carbon in products such as mineralisation in building materials. The EC, by way of the CEAP, also made the following commitment:

> 'To incentivise the uptake of carbon removal and increased circularity of carbon, in full respect of the biodiversity objectives, the Commission will explore the **development of a regulatory framework for certification of carbon removals** based on robust and transparent carbon accounting to monitor and verify the authenticity of carbon removals.' (EC, 2020, p. 20)

It will begin preparatory work in these respects in 2021.

Other Activities

Several other influential reports were published in Europe over the period 2018-2020. These include:

- European Commission 2019. "Identification and analysis of promising carbon capture and utilisation technologies, including their regulatory aspects. Final report". by Ramboll, the Institute for Advanced Sustainability Studies, CESR – Center for Environmental Systems Research at the University of Kassel, CE Delft, and IOM Law. January 2019.
- International Association of Oil and Gas Producers (IOGP) 2019. "The potential for CCS and CCU in Europe". Report to the Thirty Second meeting of the European Gas Regulatory forum, 5-6 June 2019. Coordinated by IOGP.
- Zero Emissions Platform (ZEP) 2020. "A method to calculate the positive effects of CCS and CCU on climate change" July 2020.

In addition, a European trade body representing CCU companies was established in late 2017, entitled CO_2 Value Europe. Its stated aim is to make CCU become a key pillar of the transition to a sustainable economy and creating an integrated vision and action plan to develop CCU into a new industrial sector in Europe (CO_2 Value Europe, undated).

The increasing number of studies and industry-led initiatives observed is indicative of a growing interest in the potential of CCU to contribute towards climate mitigation goals in Europe.

Incentives

As reported previously (IEA GHG 2018a; IEA GHG 2018c), the Schaefer Kalk ruling by the European Court of Justice resulted in the EU emissions trading system (ETS) being amended to allow for the deduction of CO_2 used offsite to produce precipitated calcium carbonate (PCC). However, no other uses of CO_2 will be recognised as emission reduction activities within the EU ETS at least until 2030. Rather, CCU demonstration projects will be supported through the Innovation Fund over the next 10 years.

Funding

Two main sources of funding will be available for CCU technologies in the 2020s:

The Innovation Fund

The Innovation Fund will support a range of low carbon technologies through money raised from the auctioning of 450 million EU Allowances in the EU ETS. The EC has estimated that the total fund value could amount to around €10 billion over the period 2020-2030. CCU is included with the range of eligible technologies (as reported previously in IEA GHG 2018a; IEA GHG 2018c). The fund will cover up to 60% of the additional capital and operational costs linked to innovation in the following categories:

- Highly innovative technologies and big flagship projects that can bring on significant emission reductions.

- Cross-cutting projects on innovative low-carbon solutions that lead to emission reductions in multiple sectors, for example through industrial symbiosis (including CCU).
- Small-scale projects with total capital costs under €7.5 million.

Projects will be selected based on the following criteria:

- Effectiveness of greenhouse gas emissions avoidance.
- Degree of innovation.
- Project maturity.
- Scalability.
- Cost efficiency.

The first funding round for large scale innovation projects, with guidelines on calculating relevant costs and GHG emission savings, was launched in September 2020.[4] The guidance and methodology for calculating the GHG emission reductions for projects involving CCU applies the principal reduction at the point of CO_2 capture, and emissions from product use must be counted in the same way as for conventional products (what is referred to herein as "upstream" accounting, as per Section 3.3.1).

Horizon 2020 and Horizon Europe

Horizon 2020 is the EU's research and innovation (R&I) support programme for the period 2014-2020. The EU's Horizon 2020 database system indicates that over €22 million has been committed to CCU related projects to date, covering four projects across various areas (Table 2-3). A further 11 proposals relating to CCU are in the pipeline in the final year of Horizon 2020.[5]

Horizon Europe is the €100 billion successor to Horizon 2020 for the period 2020-2030. Around 35% of the budget of Horizon Europe is dedicated to tackling climate change.

CCU will be covered through Cluster 5: Climate, Energy and Mobility, where similar levels of support for CCU as provided under Horizon 2020 can be expected.

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4 https://ec.europa.eu/info/funding-tenders/opportunities/portal/screen/opportunities/topic-details/innovfund-lsc-2020-two-stage

5 From: https://ec.europa.eu/info/funding-tenders/opportunities/portal/screen/opportunities/horizon-dashboard, H2020 proposals. Accessed, August 2020.

Table 2-3 Summary of EU Horizon 2020 CCU R&D funding to date

Project Title	Topic Code	H2020 EU Contribution
Recycling carbon dioxide in the cement industry to produce added-value additives: a step towards a CO_2 circular economy (RECODE)	SPIRE-08-2017	€ 7.9 m
Turning industrial waste gases (mixed CO/CO_2 streams) into intermediates for polyurethane plastics for rigid foams/building insulation and coatings (Carbon4PUR)	SPIRE-08-2017	€ 7,8 m
From industrial CO_2 streams to added value Fischer-Tropsch chemicals. (ICO2CHEM)	SPIRE-08-2017	€ 5,9 m
The Next Generation of Carbon for the Process Industry (CarbonNext)	SPIRE-05-2016	€ 0.50 m

Source: https://ec.europa.eu/info/funding-tenders/opportunities/portal/screen/opportunities/horizon-dashboard (H2020 Funded Projects)

2.3 Technical Outlooks for CCU

Several recent studies have sought to provide estimates for the deployment potential of CCU technologies over the mid- to long-term (2030 and 2050).

In September 2019, a paper was published in *Nature* that reviewed the technological and economic prospects for CO_2 utilisation and removal (Hepburn et al., 2019). The paper surmises that the capture and use of CO_2 to make products might lower the net costs of reducing emissions or removing CO_2 from the atmosphere. Analysis set out in the paper estimated the utilisation potentials for various CCU product pathways in 2050 (Table 2-4).

Within these different product groups, the authors differentiate between the level of *removal* and the level of *utilisation* achievable, with pathways involving short-term CO_2 retention assumed to offer zero, or limited (e.g. some chemicals), potential for CO_2 removal.

Thus, based on 10 pathways for CCU and removal analysed, they conclude that:

- Some pathways might reduce emissions of CO_2 but have limited potential for its removal (chemicals, fuels and microalgae).
- Other pathways (i.e. construction materials) can both utilize and remove CO_2.

The authors also note that the potential scale of utilization could be considerable and may be economically viable without substantial shifts in prices. A final observation akin to that of most other observers is that that scaling up CCU will not necessarily be beneficial for climate stability; policy should not aim to support utilization *per se*, but should instead seek to incentivize genuine emission reductions and removals on a life-cycle basis, and thus provide incentives for the deployment of CCU that is climate-beneficial.

Table 2-4 CCU technical potential in 2030 and 2050 in recent studies

CCU technology group	$MtCO_2$ utilised	
	2030[a]	2050[b]
Concrete (mineralisation)	150	100 – 1,400
Fuels (methanol, methane, dimethyl ether, and Fischer–Tropsch fuels)		1,000 – 4,200
- Jet fuel production	15	
- Microalgae derived fuel		200 - 900
Chemicals (including methanol)		300 - 600
Polymers/polycarbonate manufacture	10	10 - 50
Carbon fibre	0.1	

Source: [a] Biniek et al., 2020; [b] Hepburn et al., 2019. The authors note that individual totals cannot be arbitrarily summed, since some probably overlap

In June 2020, McKinsey & Company published a Quarterly Article on CCU, building upon previously published articles on a similar theme over recent years (Biniek et al., 2020). According to McKinsey's economic analysis, CCU technologies could form an important part of a portfolio of mitigation options over the medium-term, totalling around 175 $MtCO_2$ use per year (excluding CO_2-enhanced oil recovery) in 2030 (Table 2-4). The authors note that the technical potential is dependent on reducing capture costs, enhancing CO_2 transportation networks, and the emergence of regulatory incentives that support the creation of a market for CO_2.

Other relevant papers may have also been published over this period, but a full review of these is beyond the scope of this report.

3 Modelling GHG Effects

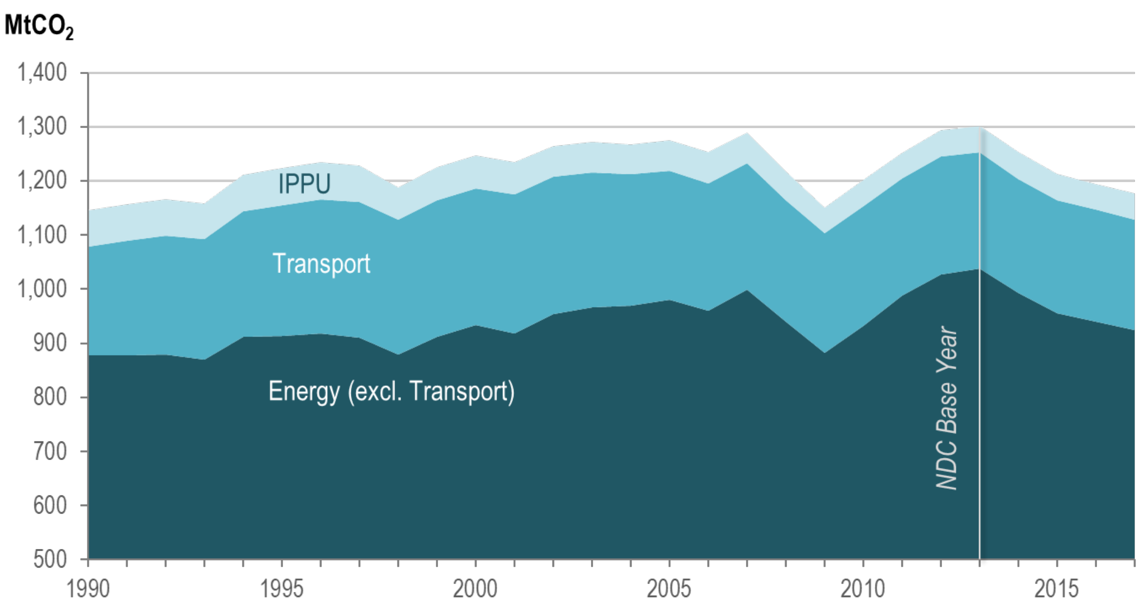
The previous chapter set out a snapshot of international developments for CCU, including specific information on recent activities the U.S. and EU. These activities provide useful framing contexts for assessing the potential role of CCU in meeting Japan's pledged emissions reductions efforts from CCU up to 2050 and beyond.

This section starts by describing the ambitions for climate change mitigation in Japan, and the role of CCU therein. A brief summary of GEMCCU is then provided, along with a description of the scenario's used for analysis, which set the basis for the results of the GHG accounting case study presented in subsequent sections.

3.1 Japan's CO_2 Emissions and Reduction Goals

National CO_2 emissions from power generation and industrial energy use (IPCC category: Energy), transportation (IPCC category: Energy sector) and industrial processes (IPPC category: Industrial Process and Product Use sector; IPPU) totalled 1,176 million tonnes CO_2 ($MtCO_2$) in 2017, representing a 10% reduction since 2013 (Ministry of Environment (MOE), 2019).[6] In 2013, CO_2 emissions from the same activities totalled around 1,300 $MtCO_2$ (Figure 3-1).

Figure 3-1 Japan emissions,CO_2, energy and industrial process, 1990-2017



Source: data from MOE, 2019

[6] Sector emissions described in this report are based the Intergovernmental Panel on Climate Change (IPCC) Common Reporting categories.

Japan has pledged ambitious GHG emission reduction goals in its NDC to 2030 and LTS to 2050 compared to a 2013 baseline. These are summarised by source sector and year below (Table 3-1).

Table 3-1 Japan emissions reduction targets, CO_2 only

Source/sector	NDC reduction target (2030)	LTS reduction target (2050)
Energy-originated CO_2	-25% against 2013 base year	-80% against 2013 base year
Non-energy-originated CO_2	-6.7% against 2013 base year	-80% against 2013 base year

Source: GOJ, 2015; GOJ, 2019

Achieving these goals will require annual CO_2 emissions to be cut by more than 250 $MtCO_2$ by 2030, and a further 550 $MtCO_2$ between 2030 and 2050. Meeting these ambitious targets will require deep transformations in the way energy is used in all sectors of Japan's economy.

In addition, Prime Minister Yoshihide Suga, in a recent address to Parliament, said that the country will become carbon neutral by 2050, using a range of technologies including carbon recycling (Guardian, 2020). A ratcheting of climate ambition can therefore be expected in coming years.

3.2 The Role of CCU in Meeting Japan's Emissions Reduction Goals

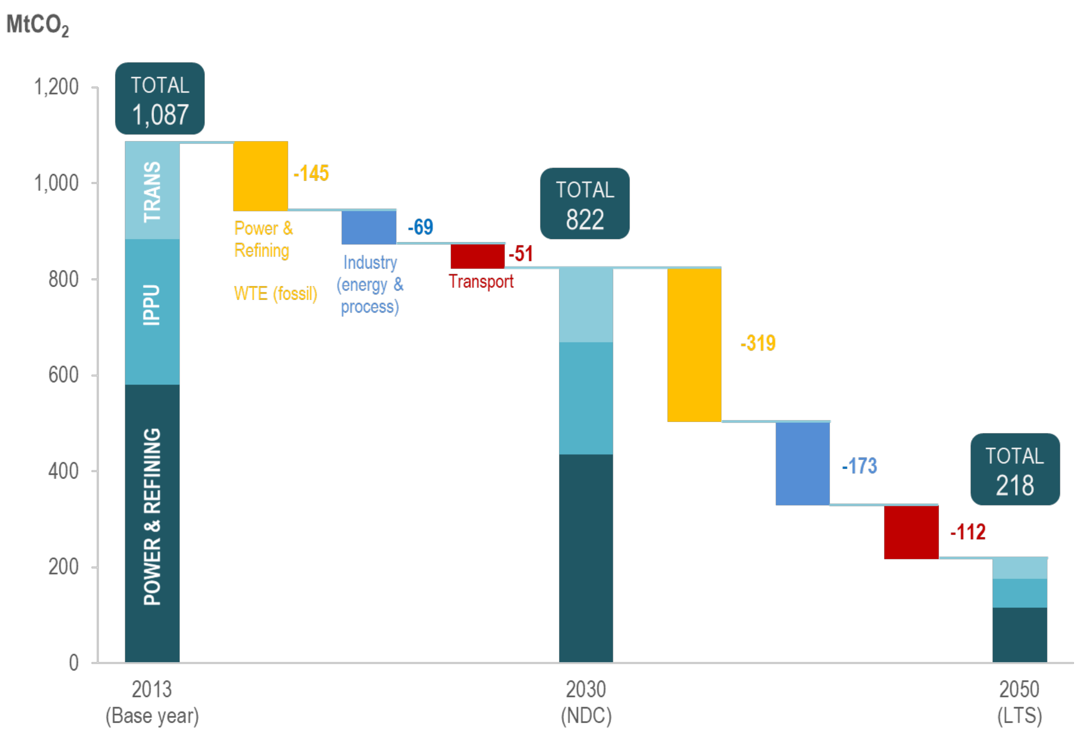
Various CCU technologies can contribute towards meeting Japan's emissions reduction goals. The capture of CO_2 from large point sources can reduce energy and industrial emissions, and its utilisation in products can substitute and displace various chemicals, fuels and mineral materials that are presently made using fossil carbon (e.g. crude oil). Utilisation of CO_2 can also store CO_2 in products over the long-term, reduce dependence on imports of primary fossil carbon, and – where short-term product storage is coupled with DAC – support the closing of the carbon loop between technosphere and atmosphere.

The connections between potential CCU emissions reduction effects and specific IPCC GHG reporting categories for Japan are summarised below (Table 3-2; Figure 3-2). The data shown is a sub-set of all of national CO_2 emissions shown in Figure 3-1, based on the selection of candidate point sources suitable for capture and product and process emissions that could be impacted. Three types of CCU emissions effects can be noted:

1. Emission reduction through capture of CO_2 from a point source.
2. Emission changes that could occur through product substitution, depending on how GHG emissions accounting is applied (e.g. emissions from transport fuel use; emission from CO_2-derived plastic incineration at end-of-life).
3. Secondary emissions reductions resulting from a decrease in activity (e.g. reduced requirement for petroleum refining as a consequence of novel CCU fuel production).

The typology of emissions changes described is a fundamental consideration for the design of the CCU model as summarised further below.

Figure 3-2 Emissions reduction targets by sector, CO_2, 2013-2050



Source: Authors, derived from: MOE 2019; GOJ, 2015; GOJ, 2019. Note: Industry includes energy and process emissions, which is different to the IPPU reporting category (which includes only process emissions).

The data show that a significant burden for emissions cuts will fall on the electricity supply and the iron & steel industries, alongside the need for significant efforts to decarbonize the road transport sector. Collectively, these three sectors alone will need to reduce emissions by 218 $MtCO_2$ by 2030—around 85% of the emission reduction effort set out in Japan's NDC—and a further 484 $MtCO_2$ over the period 2030-2050.

Japan has identified several CCU technologies that it considers relevant to supporting national emission reduction goals. The NDC, for example, refers to the use of technologies which uses CO_2 as feedstock as a mitigation technology for the chemicals sector. The LTS widely refers to using CCU including establishing the first commercial scale CCU technology by 2023 and more widespread adoption of CCU technologies from 2030. The METI has also published a *Roadmap for Carbon Recycling Technologies* ("CCU Roadmap"; METI 2019), which provides more detailed ambitions in respect of CCU RD&D and deployment over the next 30 years or so.

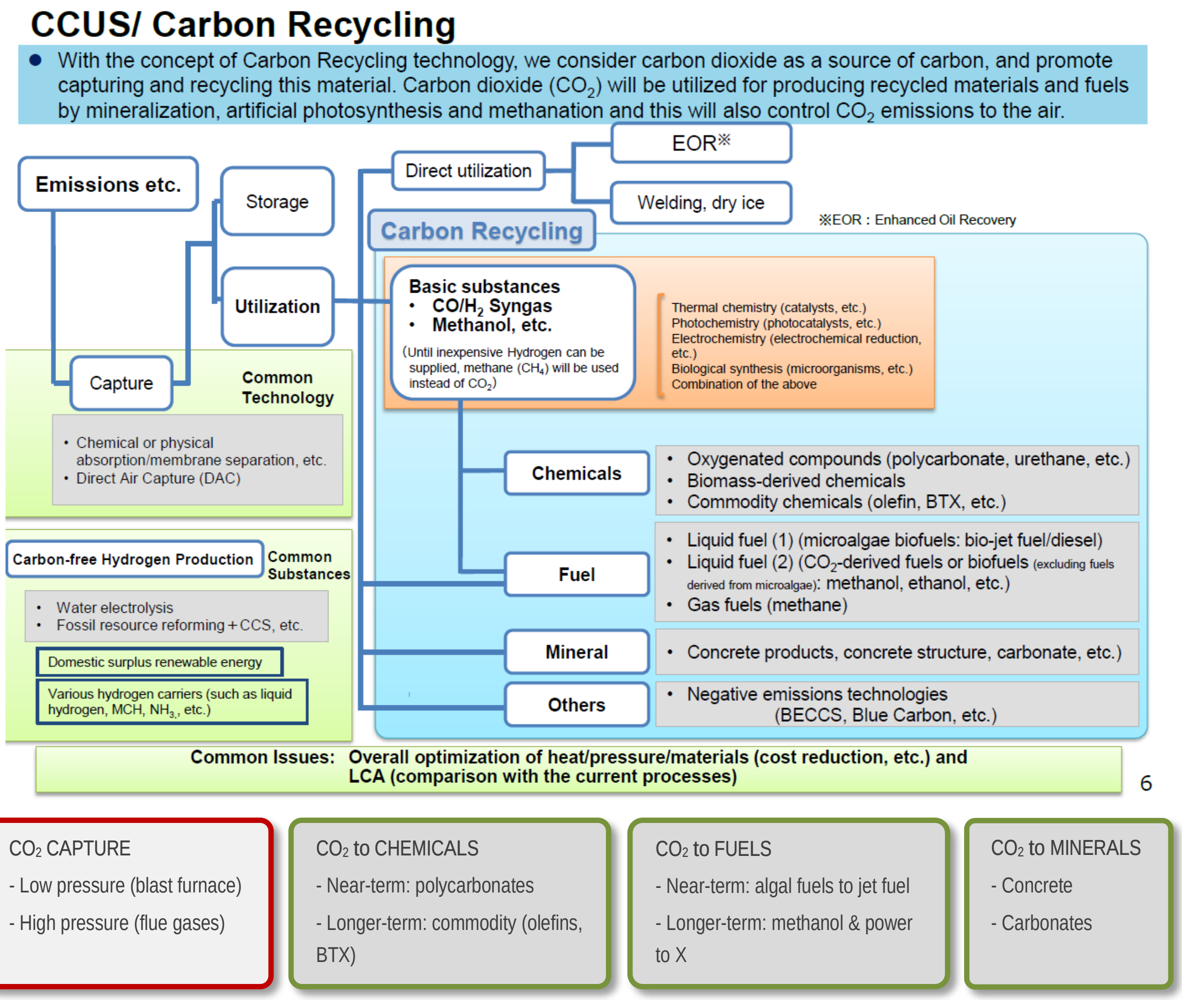
Table 3-2 CO_2 emissions by sector, reduction targets and potential impacts of CCU activities

	IPCC Source/Sector	IPCC Category	Activity	Million tonnes CO_2 Base Year 2013	Latest 2017	NDC Target 2030	NDC Target (Reduction to 2030)	LTS Target 2050	LTS Target (Reduction 2030-2050)	CCU effect[1]
ENERGY (excl. Transport)	Fuel Combustion	1.AA				-25%		-80%		
	Public Electricity and Heat Production	1.A.1.a	Coal & natural gas power	521.5	454.5	391.1	-130.4	104.3	-286.8	1
	Petroleum Refining	1.A.1.b	Refining	41.8	35.8	31.3	-10.4	8.4	-23.0	1, 2
	Venting	1.B.2.c.i.2	Venting from natural gas	0.20	0.25	0.15	-0.05	0.04	-0.11	1
	Iron and Steel	1.A.2.a	Iron & Steel	157.6	139.8	118.2	-39.4	31.5	-86.7	1
	Chemicals	1.A.2.c	Chemicals	48.6	43.7	36.5	-12.2	9.7	-26.7	1, 2
	Non-metallic Minerals	1.A.2.f	Incl. cement	29.9	27.1	22.5	-7.5	6.0	-16.5	1
	Other	1.A.2.g	Quarrying (gravel & stone) etc	32.4	29.6	24.3	-8.1	6.5	-17.8	2
	Waste Incineration with Energy Recovery included as Biomass**			23.0	25.4	25.4	-	25.4	-	1
	Waste Incineration with Energy Recovery included as Fossil Fuels			16.7	17.4	12.5	-4.2	3.3	-9.2	1
	Sub-total			*849*	*748*	*637*	*-212*	*170*	*-467*	
TRANS	Domestic Aviation	1.A.3.a	Fuel	10.1	10.4	7.6	-2.5	2.0	-5.6	3
	Road Transportation	1.A.3.b	Fuel	193.4	183.9	145.1	-48.4	38.7	-106.4	3
	Sub-total			*204*	*194*	*153*	*-51*	*41*	*-112*	
IPPU	Process Emissions	2.				-6.7%		-80%		
	Cement Production	2.A.1	Limestone calcination	26.8	26.4	25.0	-1.8	5.4	-19.6	1
	Ammonia Production	2.B.1	Reformer offgas	1.93	1.73	1.80	-0.13	0.39	-1.42	1
	Ethylene Oxide	2.B.8.d	Offgas	0.22	0.23	0.20	-0.01	0.04	-0.16	1, 2
	Iron & Steel	2.C.1.b	Pig iron blast furnace	6.04	5.55	5.63	-0.40	1.21	-4.42	1
	Sub-total			*35.0*	*33.9*	*32.7*	*-2.3*	*7.0*	*-25.7*	
Total				1,087	976	822	-265	217	-604	

Source: Authors, derived from: MOE 2019; GOJ, 2015; GOJ, 2019. [1]See text above for description of emissions effects.

The CCU Roadmap envisages a broad suite of activities over the near- and longer-term, which are summarised graphically below (Figure 3-1).

Figure 3-3 Summary of Japan's CCU Roadmap objectives



Source: METI, 2019, with text box annotations by authors

The combination of emissions by sector, emission reduction targets, and the goals of the CCU Roadmap described above provide the strategic context for development of the modelling and analysis presented in the remainder of this report.

3.3 Overview of the CCU Energy and Emissions Model (GEMCCU)

The analysis undertaken in this study uses the bespoke GHG energy and emissions model for CCU ("GEMCCU") developed in this study. As described in IEA GHG 2020, GEMCCU provides quantified estimates on the levels of emission reductions achievable through capturing CO_2 at point sources and the implications for energy and CO_2 emissions of converting this CO_2 to useable products that can substitute fossil-derived incumbents in sectors such as transport and chemicals.

GEMCCU allows the trade-offs involved with utilising CO_2 to be quantified. The activation energy required to reuse CO_2 molecules poses a significant burden on energy supply, indicating a need for new sources of carbon-free electrical energy – such as renewables and nuclear energy – if emission reductions are to be achieved. The model provides insights on the levels of energy input required, the amount of hydrogen (H_2) production that will be needed, and the resultant energy content of produced fossil substitutes.

GEMCCU also allows for sensitivities to be assessed for a range of model inputs. Changing CO_2 utilisation efficiency, or energy efficiency and H_2 (electrolysis) production efficiency can be used to guide R&D priorities.

The GEMCCU model architecture and calculations draw heavily on previous studies completed in earlier phases of the IEA GHG work programme (as partly summarised in IEAGHG, 2018), and thus, the inputs are largely empirical rather than hypothetical.[7] However, some CCU process models – primarily ethanol (EtOH) upgrading – were built from a theoretical base. Updates to the information gathered in 2017, plus the inclusion of additional pathways, were needed to align GEMCCU with the technology choices Japan has highlighted in its CCU Roadmap (Figure 3-3).

The primary input variable controlling all GEMCCU is *tCO_2 captured for utilisation.* All sub-model rates and functions within the sub-models are normalised to tCO_2 utilised. The input mass of CO_2 is then partitioned within the model between sources and end uses, which are selected by the user. Sub-models within GEMCCU cover:

1. **CO_2 capture**. Calculates the mass of CO_2 generated, the energy penalty and the process (fugitive) emissions associated with capturing the input mass of CO_2 from the selected source category.
2. **CCU process**. Calculates the CO_2-derived product output, energy demand and combustion and process emissions associated with the mass of CO_2 input to the CCU activity. Presently GEMCCU contains sub-models for:
    a. CO_2 methanol (MeOH) production.
    b. CO_2 polyols and polymers.
    c. Closed reactor algae cultivation with EtOH to jet (EtJ) upgrading.
    d. CO_2 mineralisation to make recycled aggregates.
3. **Electricity emission factor**. Calculates an emission factor for electricity used across different processes. Various choices are built into GEMCCU, ranging from zero emissions (i.e., renewables or nuclear) to grid emission factors for selected years.[8]
4. **CCU product market**. Determines market conditions for CO_2-derived products. Key factors included are product demand, current levels of domestic production versus product imports, product usage, CO_2 retention in CO_2-derived products, end-of-life

[7] Based on data collected from primarily investigations undertaken in 2017, where CCU plant operators were visited and data on site performance collected to assess mitigation effects from different CCU pathways.
[8] For the Japan model, this includes the calculation of grid emission factors aligned to NDC and LTS mitigation pathways for 2030 and 2050 respectively

pathways, and market dynamics arising from the introduction domestically produced CO_2-derived alternatives.

5. **Allocation of outputs**. The calculated emissions and emissions reductions within each process sub-model are allocated to appropriate IPCC GHG inventory reporting categories, taking into account product market characteristics in respect of current domestic production, imports and end-use categories assumed for Japan.

GEMCCU outputs are calculated as relative net changes in sector emissions. A more detailed model specification is set out in IEAGHG (2020). A schematic of the GEMCCU architecture is presented below (Figure 3-4).

3.3.1 Key features and assumptions

Operating mode

GEMCCU operates on a steady state basis and does not take account of any dynamic changes in exogenous factors such as electricity demand, materials inputs and product demand over time. The grid electricity GHG sub-model does include a dynamic element insomuch as the additional electricity required to power CCU processes is taken into account and fed into calculating the target grid emissions factor for the relevant period.

Accounting mode

GEMCCU incorporates two GHG accounting modes, termed “upstream” and “downstream”. This allows the effects of two alternative means of allocating GHG emissions reduction to be assessed (see also IEA GHG 2018b; IEA GHG 2019).

Upstream

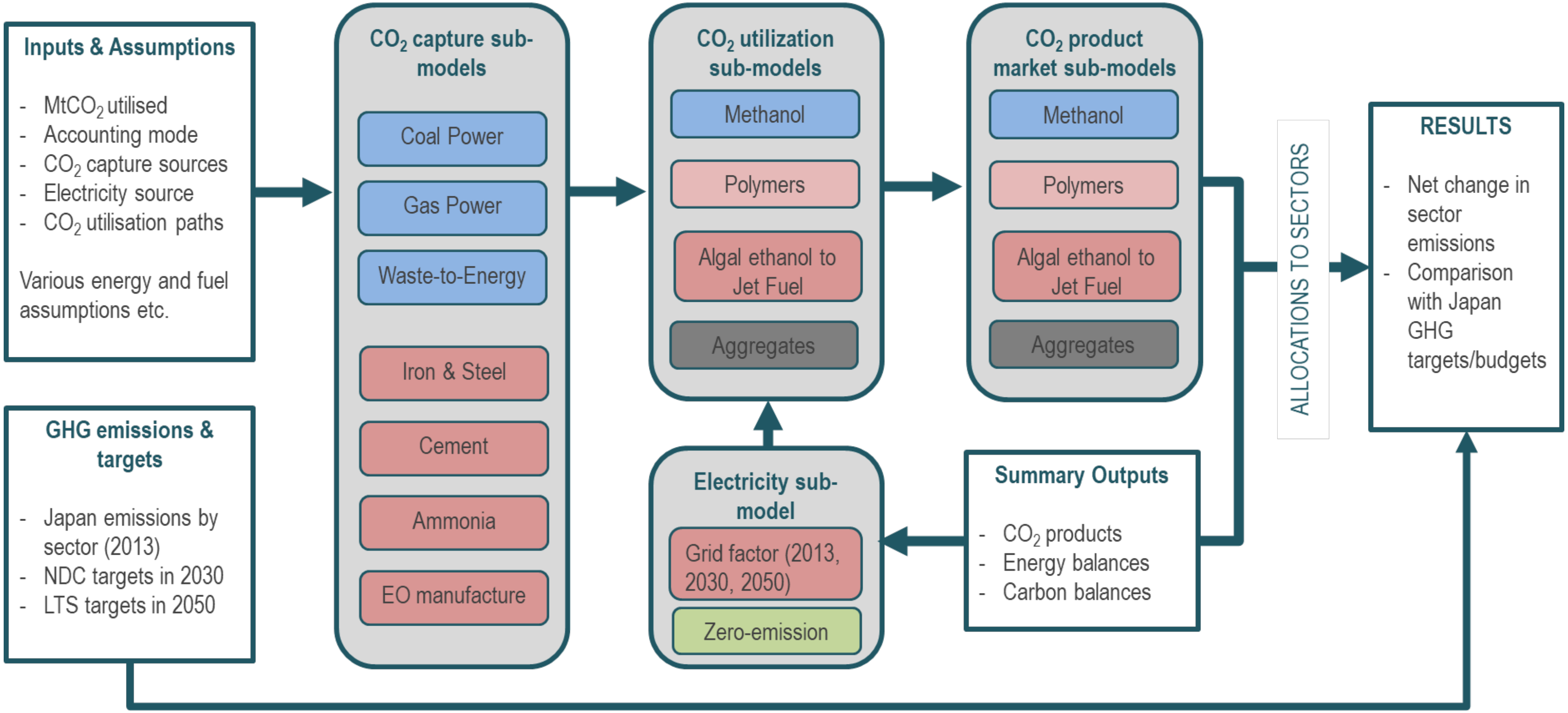
In upstream mode, captured CO_2 is counted as an emissions reduction at source. This means the emission reduction effect of capturing CO_2 is allocated to the source sectors where capture occurs. Consequently, any emissions of the captured CO_2 occurring downstream of the point of capture—such as fugitive emissions, process emissions and product emissions—are counted as a positive emission, so as to avoid double counting of the emission reduction effect.

Downstream

In downstream mode, captured CO_2 is not counted as an emissions reduction at source, and not deducted from the sector emissions total where capture takes place. Rather, all CO_2 generated from the capturing sector continues to be counted as emitted from the sector. This mode allows any emissions of the captured CO_2 occurring downstream of the point of capture—such as fugitive emissions, process emissions and product emissions—to be zero-rated (i.e., not counted as a positive emission).

In either accounting mode, other GHG effects arising from various substitution and displacement effects are counted in addition to the effects of capturing and utilising CO_2.

Figure 3-4 Architecture of GEMCCU



Source: Carbon Counts

Grid Electricity

The estimated electricity required to power CCU processes is fed into the Electricity GHG sub-model, where the required emissions factor for the entire electricity supply system in 2030 and 2050 is calculated to align with Japan's NDC and LTS emissions targets.[9]

Availability of CO_2 for Capture

The availability of CO_2 for capture is not adjusted by any displacement effects arising from CCU deployment. Where changes in sector outputs due to product substitution lead to changes in emissions in a given sector—for example, reduced chemicals demand due to substitution by CO_2-derived alternatives—these feedbacks are not currently incorporated into GEMCCU. Assuming a moderate scale of CCU deployment is modelled, these effects will not have material impacts on the availability of CO_2 for capture.

The net GHG changes are, however, included in the GEMCCU outputs.

Process Performance

GEMCCU allows assumed CCU process efficiencies to be easily modified. Changes to efficiency can be applied as sensitivities to assess the effects of potential CCU technology improvements that could result from R&D and experience with demonstration projects. Options and sensitivity values included are:

- **CO_2 utilisation efficiency**: Baseline (see IEA GHG 2020); 50% improvement; 100% improvement.[10]
- **Process energy efficiency**: Baseline (see IEA GHG 2020); 50% improvement; 100% improvement.
- **Electrolyser efficiency**: Baseline (see IEA GHG 2020); 10% improvement; 20% improvement.

A 100% improvement in CO_2 utilisation efficiency means that all input CO_2 is utilised in product manufacture, leading to increased product yields. Improvement in CO_2 utilisation may be possible through better recycling of input CO_2, and improved processing to enhance CO_2 contact with catalysts etc.

Most of the fuel consumed in CCU process is for process heating. The model assumes that all of this is provided through dedicated steam generation. Process integration within chemical complexes could allow for greater use of heat recovery, leading to improvements in fuel consumption per unit process.

The scope for electrolyser performance improvement is uncertain, but this option is included should the user wish to include this variable as a sensitivity.

[9] The electricity demand in GEMCCU is assumed to remain stable in 2030 and 2050 and equal to the average demand for the period 2013-2017.
[10] CO_2 capture efficiency is excluded.

3.4 Scenarios for CCU Deployment in Japan

Using Japan's CCU ambitions described above, and the architecture of GEMCCU, two scenarios have been taken forward for modelling in this study.

3.4.1 Base Scenarios

Scenario 2030

This scenario sees fairly ambitious albeit limited levels of CCU deployment that are broadly aligned to Japan's ambitions for the technology in 2030. It is assumed that 5 $MtCO_2$ will be captured for utilisation in 2030, with sources limited to one or two large coal-fired power plants, one waste-to-energy facility,[11] one or two large blast furnaces, and high purity CO_2 sources. Utilisation technologies are focussed on non-H_2 based applications in accordance with proposals in the CCU Roadmap[12]

Scenario 2050

This scenario sees a five-fold increase in CCU deployment after 2030, with 25 $MtCO_2$ being utilised in 2050. The range of CO_2 source sectors also increases compared to Scenario 1 to include greater contributions from natural gas fired power plants, cement plants, and more blast furnaces. Utilization sees a significant increase in the areas of algal EtOH to EtJ (albeit with gasoline and diesel as by-products) and new methanol production uses (which now has the potential to fulfil a number of roles in chemicals or fuels production).

The base scenarios described are limited by the technical potential of the various CO_2 sources and CCU pathways. For example, all high purity CO_2 sources are rapidly utilised by 2030, and thus any further deployment in these sectors is constrained beyond 2030. Similarly, the markets for certain CO_2 products such as polymers become rapidly saturated (assuming these products aren't suitable for export in significant volumes) and, thus, CO_2 is pushed into other utilisation pathways where demand for the resulting products is more elastic.

3.4.2 Sensitivities

Two sensitivities are applied to each base scenario.

Electricity Source

This switches the source of electricity assumed in the base scenarios from 100% carbon-free electricity to the grid emissions factors aligned with the NDC and LTS decarbonisation targets.

[11] Waste-to-energy includes negative emissions through the capture of a portion of biogenic CO_2 originating from organic waste combustion (see IEA GHG, 2020).
[12] As indicated in the CCU Roadmap, although upgrading of algal EtOH to jet fuel will require significant amounts of H_2 for hydrogenation.

Process Efficiency

The second variation of the base scenarios is centred on efficiency improvements in CO_2 utilisation, process energy use and H_2 production.

The scenarios and sensitivities are summarised below (Table 3-3).

Table 3-3 Summary of CCU deployment scenarios and sensitivities

BASE scenario		2030	2050
$MtCO_2$ utilised		5	25
Capture sources	Coal power	2.0 $MtCO_2$	2.0 $MtCO_2$
	Gas power	-	6.0 $MtCO_2$
	Waste to energy	0.5 $MtCO_2$	2.0 $MtCO_2$
	Iron & steel	1.3 $MtCO_2$	10 $MtCO_2$
	Cement	-	3.8 $MtCO_2$
	Ammonia*	1.0 $MtCO_2$	1.0 $MtCO_2$
	Ethylene Oxide*	0.2 $MtCO_2$	0.2 $MtCO_2$
Utilisation pathways	Polymers	0.12 $MtCO_2$	0.12 $MtCO_2$
	Algal jet fuel	4.72 $MtCO_2$	14.0 $MtCO_2$
	Methanol	-	10.7 $MtCO_2$
	Aggregates	0.16 $MtCO_2$	0.16 $MtCO_2$
Electricity source		Zero-emission	Zero-emission
SENSITIVITY, electricity			
Electricity source		2030 Grid	2050 Grid
SENSITIVITY, efficiency			
CO_2 utilization efficiency		50% improvement vs base	100% improvement vs base
Process energy efficiency		25% improvement vs base	50% improvement vs base
H_2 production (electrolyser) efficiency		10% improvement vs base	20% improvement vs base

Notes: *high purity CO_2 sources.

3.4.3 Accounting Mode

In addition to the scenarios and sensitivities described, each base scenario is run in upstream and downstream accounting mode to gain insights into how different GHG accounting approaches might influence the outcomes.

To reduce the number of results and complexity of analysis, only the upstream accounting mode is used for the sensitivities (for reasons explained further below).

4 Results

The results from GEMCCU under the two scenarios, the two accounting modes and the various sensitivities described in Section 3.4 are presented below. The results start with scenario 2030, where detailed analysis of the CO_2 emissions effects, CO_2-derived product output and the associated energy balances are summarised. Detailed sector-by-sector analysis is also included. Results for scenario 2050 are then presented following the same approach. An in-depth analysis of electricity supply effects is also included.

4.1 Scenario 2030

4.1.1 Summary

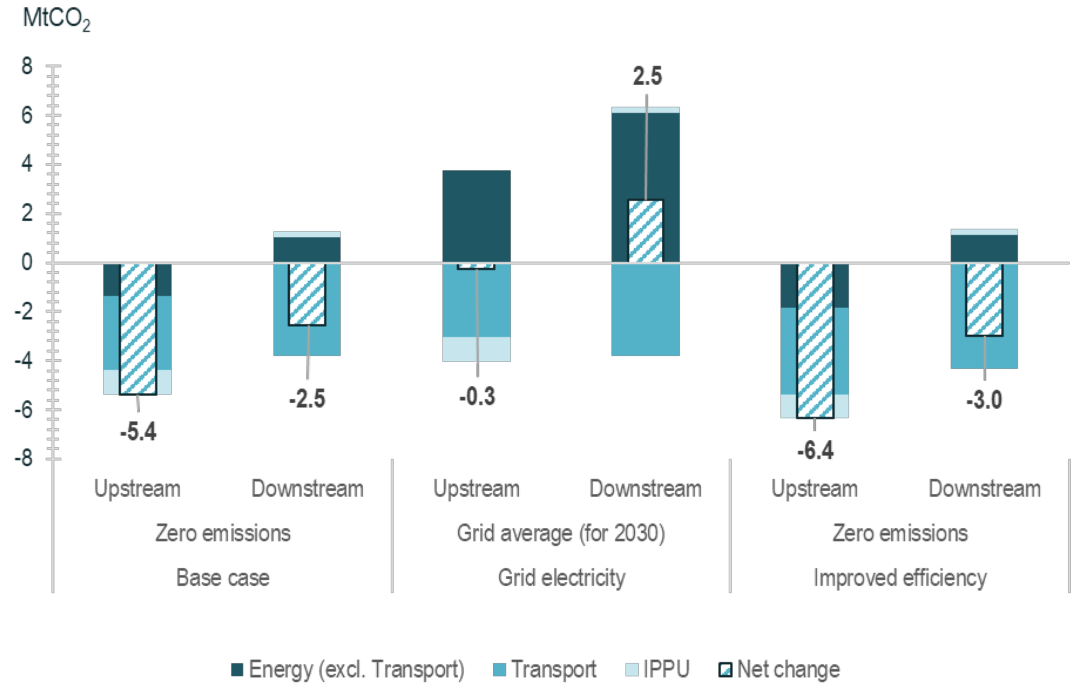
In scenario 2030, 5 $MtCO_2$ is captured for utilisation across the whole of Japan, derived from coal power plants, waste-to-energy (WtE) plants, iron and steel blast furnaces and high purity sources in the chemicals sector. The captured CO_2 is used to manufacture PPs, recycled aggregates and as feedstock for the cultivation of algae in closed bioreactors (for EtJ production pathways; Table 3-3).

Outputs from GEMCCU using upstream accounting indicate that, under a best-case scenario, capturing and utilising 5 $MtCO_2$ in 2030 could reduce Japan's GHG emissions by up to 6.4 $MtCO_2$ (improved efficiency, 100% zero emissions electricity supply). Under a less optimistic scenario (base efficiency, grid electricity) the emissions reduction effect of CCU deployment could be negligible at around -300 $ktCO_2$ in 2030 (Figure 4-1). This equates to around a 2 to 2.5% contribution towards Japan's emissions reduction ambitions to 2030 in the relevant sectors (see Figure 3-2).

The results also show that the sectoral distribution of GHG effects from CCU is variable. Substitution of fossil derived fuels with algal derived EtJ and associated by-products (gasoline and diesel) drives significant emissions reductions in the Transport sector in all cases (-3 $MtCO_2$, albeit subject to accounting issues discussed below). Emissions reductions at point sources in Energy and IPPU categories are smaller, particularly when the electricity source is modified to include fossil (grid connected) plants in the supply mix (from -2.8 to +2.8 $MtCO_2$).

If CCU processes are not powered exclusively by zero carbon electricity sources, emissions reduction gains in the Transport sector are essentially offset by increases in the electricity supply sector. In other words, CCU has the potential to simply shift emissions from one reporting category to another.

Figure 4-1 CO_2 emissions changes, scenario 2030



Note: grid emission factor = 0.390 $kgCO_2/MWh$

Where improved efficiency across CCU processes is assumed, there are obvious positive gains in emissions reductions, totalling around 18% compared to the base case. The overwhelming majority of these gains (around 97%) arise from increasing CO_2 utilisation rates by 50% compared to the base case (i.e. by reducing CO_2 fugitive emissions by 50%). This improves performance in several ways:

1. By avoiding the wastage of energy in capturing CO_2 that ends up vented to the atmosphere without any productive purpose.
2. By reducing fugitive CO_2 emissions during processing.
3. By increasing CO_2-derived product yields per unit of CO_2 input.[13]

Switching from upstream to downstream accounting mode results in significantly lower calculated emission reductions from CCU. In the base case, for example, there is a 2.9 $MtCO_2$ emissions increase in downstream mode compared to upstream, a pattern that repeats across all sensitivities. In the case of improved efficiency, this ‘gap’ between the two accounting modes increases further to 3.4 $MtCO_2$. This discrepancy indicates that the zero-rating of CO_2 emissions from product use do not fully allocate GHG effects downstream relative to upstream. Two principal reasons drive this discrepancy:

1. Emissions from algal-derived fuels, which are considered by GEMCCU to be biogenic CO_2, are zero-rated in both up- and downstream accounting modes. As a result, the GHG effect is amplified in the upstream mode because the emission reductions effect

[13] GEMCCU increases output to account for these changes, rather than reducing CO_2 supply.

of capturing CO_2 for use in algal bioreactors is attributed and counted, whereas it is not in downstream mode.[14]

2. Some of captured CO_2 ends up locked into CO_2-derived products over the long-term (aggregates, long-life plastics (from polymers) and algal biomass during EtOH production). This CO_2 is not counted as an emission in either up- or downstream accounting mode. However, the captured CO_2 that ends up stored in these products is only allocated as an emission reduction effect in upstream mode, but not in downstream mode. Consequently, stored CO_2 is essentially 'lost' in the emissions accounts in downstream mode because no reduction is attributed for capture, but also no downstream benefits accrue from zero-rating emissions from these products compared to emissions from incumbents.

These differences result in upstream and downstream accounts being unable to balance unless such effects are taken into account. This offers some useful policy insights as discussed further below (Section 5.2). Given the issues described, the remainder of the analysis presented largely *exclude* the GEMCCU results for the downstream accounting mode.

The overall CO_2-derived product and energy balances for scenario 2030 are shown below (Table 4-1). The results from GEMCCU suggest that capturing and utilising 5 $MtCO_2$ for product manufacture will require around 78 to 82 PJ of primary energy (coal, gas, zero carbon electricity, municipal solid waste), a significant part of which is used to produce around 200-230,000 tonnes H_2 via electrolysis. The total energy content of the resulting fuel products is around 42 PJ, indicating an energy conversion efficiency of 54%.[15] In terms of electricity, the demand for utilising 5 $MtCO_2$ could require an additional 2 to 3 GW of new generating capacity,[16] which would need to be deployed in parallel with other efforts aimed at decarbonizing Japan's power sector.

Capturing and utilising 5 $MtCO_2$ (less than 1% of Japan's total CO_2 emissions in 2030 if the NDC target is met), can meet around a quarter of domestic jet fuel demand and virtually all of Japan's current PP output. Production of almost 5 Mt recycled aggregates from air pollution control residues (APCr) would utilise around 80% of the APCr estimated to be available for utilisation. As such, even at this moderate level of CCU deployment, the technical potential for further CO_2 utilisation in low energy carbonation reactions (i.e. PP and recycled aggregate making) seem limited. Therefore, efforts to go beyond 5 $MtCO_2$ utilisation will need to focus on substitute fuel products, as shown in scenario 2050.[17]

[14] It is debatable whether this approach is correct.
[15] Although a portion of captured CO_2 is used to make non-energetic products, the amount of energy involved in their production is relatively small.
[16] Assuming a 60-85% load factor.
[17] Or other chemicals not yet included in GEMCCU.

Table 4-1 CO_2-derived product and energy balances, scenario 2030

Sensitivity	Base case / Grid electricity			Improved efficiency		
	Units	TJ	% of current demand	Units	TJ	% of current demand
CO_2-derived product output						
Methanol (t)	-	-	-	-	-	-
Jet fuel (t)	746,033	31,930	22%*	870,561	37,260	26%*
Gasoline (t)	150,427	6,769	0.40%	175,536	7,899	26%
Diesel (t)	80,703	3,672	0.24%	94,174	4,285	0.47%
Polyols (t)	545,455	-	97%	571,429	-	101%
Aggregates (t)	4,923,077	-	2.6%	4,923,077	-	2.6%
Energy demand						
Primary						
Coal (Mt)	230	6,473		230	6,473	
Natural gas (bcm)	0.404	19,180		0.455	21,155	
Secondary						
Electricity (GWh)	13,949	50,216		14,647	52,727	
Electricity (GW)	1.9-2.4			2.0-2.6		
Other						
Hydrogen (kt)	202	28,597		235	33,347	
MSW (Mt)	159	1,618		159	1,618	

Notes: * domestic aviation only. Electricity can be considered as primary energy where not derived from fossil sources. The Grid electricity scenario does not account for additional coal and natural gas required to meet the electricity demand shown. MSW = municipal solid waste.

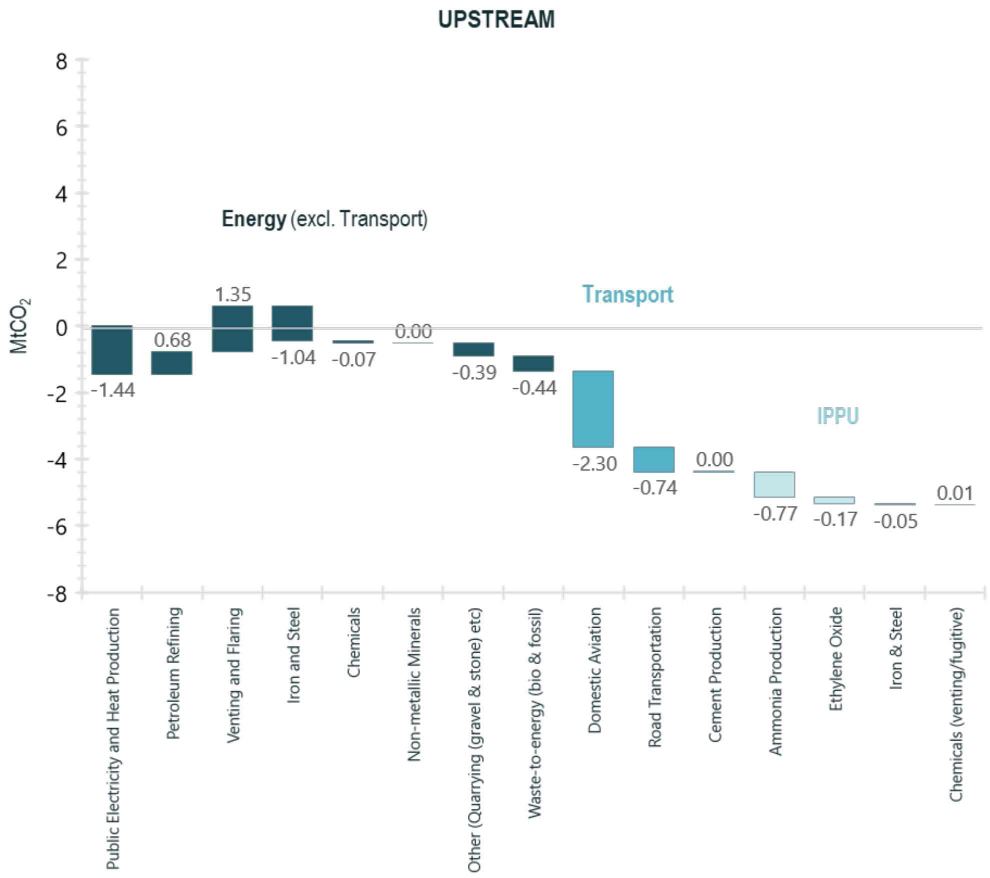
4.1.2 Sector-by-Sector

Energy (excluding Transport)

Analysis presented covers IPCC reporting categories 1.A.1 and 1.A.2, which are collectively referred to as Energy (excluding category 1.A.3 – Transport; see Table 3-2).

Net emission reductions within Energy of 1.3 to 1.8 $MtCO_2$ are achieved in scenarios where all CO_2 utilisation processes, including H_2 production, use zero carbon electricity sources. In these cases, 3 $MtCO_2$ emissions are avoided by capturing 5 $MtCO_2$ from point sources (power plants including WtE; iron & steel; chemicals). These reductions are partly offset by 2.2 $MtCO_2$ of new emissions in the refinery sector attributable to algal jet fuel production (of which 856 $ktCO_2$ is from energy use and 1.35 $MtCO_2$ from venting and fugitive emissions of captured CO_2). A further 178 $ktCO_2$ reduction is achieved through the displacement of petroleum refinery capacity by alternative fuel production and 389 $ktCO_2$ emissions are reduced through the displacement of general aggregate extraction by recycled aggregates (Figure 4-2).

Figure 4-2 CO_2 emissions changes by sector, base case, scenario 2030



Note: Chemicals (fugitive) is added as a new IPPU reporting category

In the Chemicals sector, the capture of 47 ktCO_2 of Energy emissions from ammonia and ethylene oxide (EO) production facilities, and the 148 ktCO_2 emissions reduction resulting from the substitution of epoxides by CO_2-derived PP, leads to emissions reductions of 195 ktCO_2. However, these gains are largely offset by the emissions of 127 ktCO_2 attributable to the heat load for CO_2-derived PP production (net reductions of 68 ktCO_2; Figure 4-2).

Improving efficiency across CCU processes has the effect of reducing direct emissions from algal jet fuel production to 1.8 MtCO_2 and increasing refinery displacement effects to -210 ktCO_2 because of the higher yields of alternative fuels (Figure 4-3). The collective result is a reduction of around 450 ktCO_2 in refining emissions compared to the base case.

If grid electricity with an emissions factor consistent with Japan's 2030 NDC ambitions is instead assumed,[18] a 3.7 MtCO_2 emissions increase occurs in the energy sector. In this scenario, the emissions gains described above are offset by a 5.1 MtCO_2 increase in emissions from electric power generation needed to meet the demand presented by CCU processes (Figure 4-4).

[18] 0.390 kgCO_2/MWh

Figure 4-3 CO_2 emissions changes by sector, imp. efficiency, scenario 2030

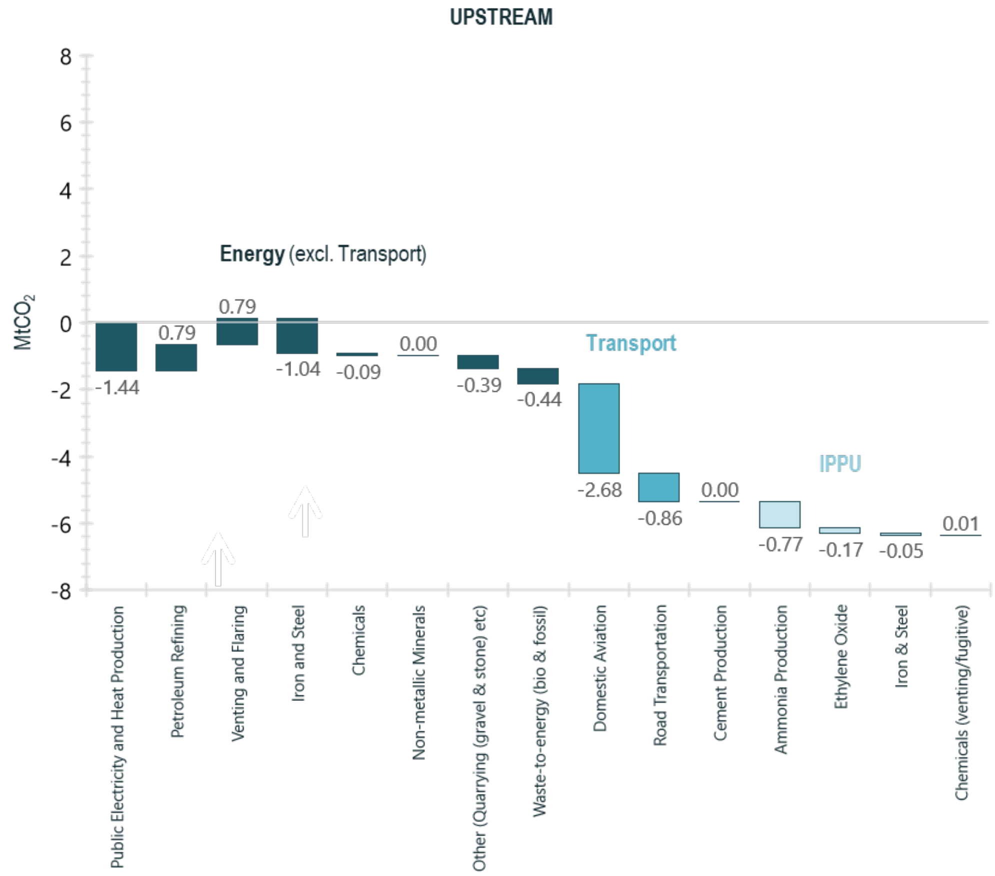
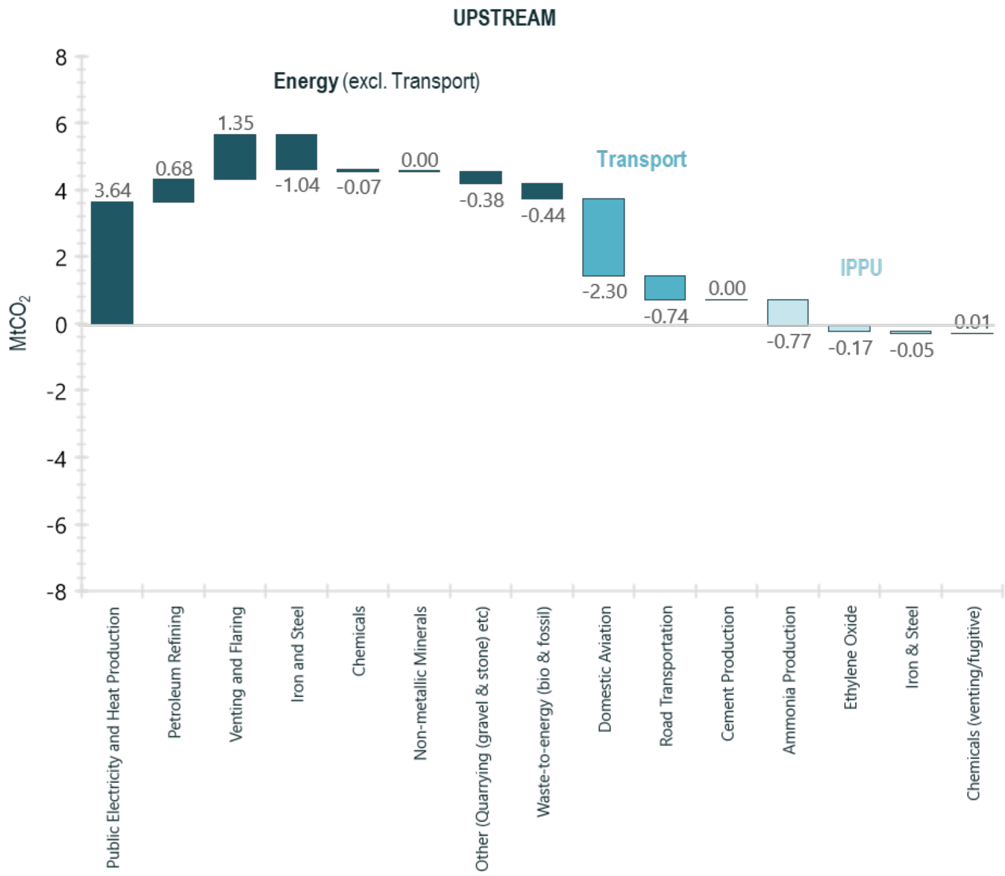


Figure 4-4 CO_2 emissions changes by sector, grid electricity, scenario 2030



Transport

Analysis presented here covers IPCC reporting categories 1.A.3.a and 1.A.3.b (Table 3-2).

Emission reductions of 3 to 3.8 $MtCO_2$ are achieved across all scenarios, the higher number reflecting the improved efficiency scenario. Of this, 2.3 to 2.7 $MtCO_2$ reduction occurs in Domestic Aviation (assuming all produced fuels are used domestically) and 740 to 865 $ktCO_2$ reduction in the Road Transportation sector.

GEMCCU assumes that emissions from alternative fuels derived from algal EtOH can be treated in the same way as biofuels and therefore the end-use emissions are zero. However, because the algae are exclusively fed CO_2 from fossil sources, there is some doubt over whether this is a credible accounting method (as discussed further below; Section 5.2).

IPPU

Analysis presented here covers IPCC reporting category 2.A.1, 2.B.1, 2.B.8.d, 2.C.1.b (see Table 3-2) and a new category "Chemicals (fugitive)" presently not included in IPCC 2006.

Emission reductions of almost 1 $MtCO_2$ are achieved across all sensitivities, primarily through the capture of process CO_2 emissions from iron and steel and chemical production facilities. Only slight variations occur when improving efficiency above the base case, which creates marginal improvements in the PP making process through higher product yields.

Full cross chain GHG effects for all scenarios and sensitivities generated in GEMCCU are presented in Annex A.

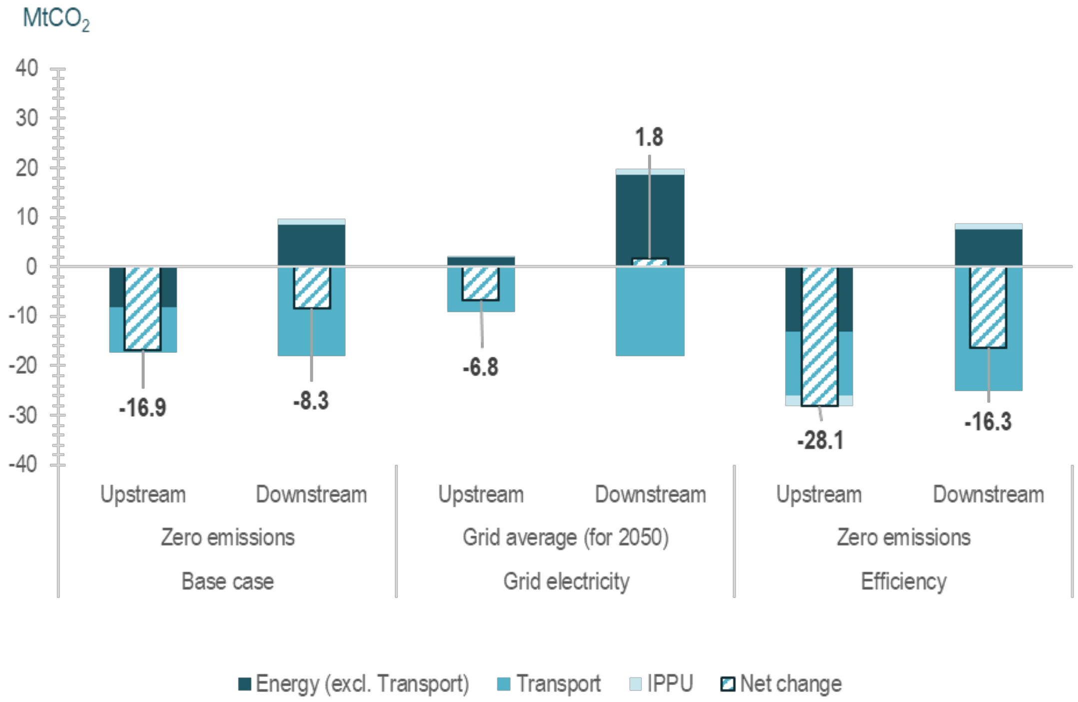
4.2 Scenario 2050

4.2.1 Summary

In scenario 2050, 25 $MtCO_2$ is captured for utilisation across the whole of Japan, derived from the same sources as in scenario 2030 with the addition of capture from gas fired power plants and cement kilns. The captured CO_2 is used to manufacture the same range of CO_2-derived products as in scenario 2030 with the addition of MeOH (Table 3-3).

Outputs from GEMCCU indicate that, under the best-case scenario (improved efficiency, zero emissions electricity supply), capturing and utilising 25 $MtCO_2$ in 2050 could reduce Japan's GHG emissions by up to 28 $MtCO_2$. Under the less optimistic scenario (base efficiency, grid electricity), emissions reductions from CCU deployment would still occur, albeit at a lower level of around 6.8 $MtCO_2$ (Figure 4-5; excluding the results from downstream accounting mode). These estimated reductions equate to between 1 to 4.6% contribution towards Japan's emissions reduction ambitions for the period 2030 to 2050 within the relevant sectors (see Figure 3-2).

Figure 4-5 CO_2 emissions changes, scenario 2050



Note: grid emission factor = 0.104 $kgCO_2/MWh$

The results also show that, in the same way as for scenario 2030, the sectoral distribution of GHG effects of CCU is variable. Substitution of fossil derived transport fuels by both CO_2-derived MeOH (for petroleum blending) and algal derived EtJ and associated by-products (gasoline and diesel) drives significant emissions reductions in the Transport sector in all cases (9 to 13 $MtCO_2$, excluding downstream accounting, and subject to clarifying accounting issues for algal fuels). Emissions reductions at point sources in Energy and IPPU categories are smaller and more variable, particularly when the electricity source is modified to include fossil (grid connected) plants in the supply mix.

Where improved efficiency across CCU processes is assumed, there is a 66% gain in emissions reductions compared to the base case. As in scenario 2030, the majority of this gain, albeit a smaller amount of around 75%, is attributable to increasing CO_2 utilisation rates comparted to the base case (i.e. by reducing CO_2 fugitive emissions by 100%).

The overall CO_2-derived product and energy balances for scenario 2050 are shown below (Table 4-2). The results from GEMCCU suggest that capturing and utilising 25 $MtCO_2$ for product manufacture will require around 580 to 600 PJ of primary energy (coal, gas, zero carbon electricity, municipal solid waste), a significant part of which is used to produce around 1.8 to 2.4 million tonnes H_2 via electrolysis. The total energy content of resulting fuel products is around 260 to 350 PJ, indicating an energy conversion efficiency of 45-58%.[19] In terms of

[19] Although a portion of captured CO_2 is used in non-energetic products, the amount of energy involved in their production is relatively small.

electricity, the amount needed to utilise 25 Mt CO_2 could require the addition of around 14 to 22 GW of new generating capacity that would need to be deployed alongside parallel efforts to decarbonize Japan's power sector.[20]

Table 4-2 CO_2-derived product and energy balances, scenario 2050

Sensitivity	Base case / Grid electricity			Improved efficiency		
	Units	TJ	% of current demand	Units	TJ	% of current demand
CO_2-derived product output						
Methanol (t)	5,936,178	134,751	330%	7,780,050	176,607	432%
Jet fuel (t)	2,212,810	94,708	65%*	3,099,548	132,661	92%
Gasoline (t)	446,181	20,078	1.2%	624,979	28,124	1.7%
Diesel (t)	239,373	10,891	0.70%	335,296	15,256	0.98%
Polyols (t)	568,182	-	101%	625,000	-	111%
Aggregates (t)	5,384,615	-	2.9%	5,384,615	-	2.9%
Energy demand						
Primary						
Coal (Mt)	1,042	29,388		1,042	29,388	
Natural gas (bcm)	3.3	167,590		2.9	158,059	
Secondary						
Electricity (GWh)	105,190	378,684		113,165	407,394	
Electricity (GW)	14-20			15-22		
Other						
Hydrogen (kt)	1,785	253,243		2,392	339,382	
MSW (Mt)	635	6,473		635	6,473	

Notes: * domestic aviation only. Electricity can be considered as primary energy where not derived from fossil sources. The Grid electricity scenario does not account for additional coal and natural gas required to meet the electricity demand shown. MSW = municipal solid waste.

Capturing and utilising 25 $MtCO_2$, which would be around 12% of Japan's total CO_2 emissions in 2050 if the LTS target is met, can potentially meet a large portion of domestic jet fuel demand, all of Japan's current PP output and also create a large MeOH industry.

Presently, Japan uses around 1,800 ktMeOH per year, all of which is imported. Building a domestic CO_2-derived MeOH industry at the scale outlined (5,900 ktMeOH per year) would result in production emissions that presently occur in third countries being "onshored" to Japan. There would also be a need to find other uses that can drive new demand aligned to the extra production. In GEMCCU, all MeOH production exceeding current demand is pushed into fuel blending with gasoline.

[20] Assuming a 60-85% load factor.

Production of over 5 Mt recycled aggregates from air pollution control residues (APCr) would utilise more than 85% of the APCr estimated to be available for utilisation.[21] As noted above in scenario 2030, levels of PP demand and availability of APCr significantly constrain the potential to increase the use of CO_2 in carbonation reactions without finding new pathways (e.g. large scale concrete curing and production of other CO_2-derived chemicals).[22]

4.2.2 Sector-by-Sector

Energy (excluding Transport)

Net emission reductions within Energy of 8.2 to 13.2 $MtCO_2$ are achieved in scenarios where all CO_2 utilisation processes, including H_2 production, use zero carbon electricity sources. In these cases, 17.2 $MtCO_2$ of energy emissions are avoided by capturing 25 $MtCO_2$ from point sources (power plants including WtE; iron & steel blast furnaces; chemicals; cement kilns). These effects are partly offset by 6.5 $MtCO_2$ of new emissions in the refinery sector attributable to algal jet fuel production (of which 2.5 $MtCO_2$ is from energy use and 4 $MtCO_2$ from venting and fugitive emissions of captured CO_2).

A further reduction of 1.3 $MtCO_2$ is achieved through the displacement of petroleum refinery capacity by alternative fuel production and 425 $ktCO_2$ emissions are reduced through the displacement of general aggregate extraction by recycled aggregates (Figure 4-6). In the Chemicals sector, the net emission reduction effects are similar to scenario 2030 (a 70 $ktCO_2$ reduction), although in scenario 2050, these gains are offset by 4.3 $MtCO_2$ of new emissions generated for raising heat during the production of MeOH. This results in a net increase of 4.23 $MtCO_2$ from energy emissions in the Chemicals sector (Figure 4-6).

Improved efficiency across CCU processes reduces emissions by 2.9 $MtCO_2$ from algal jet fuel production and 1.5 $MtCO_2$ from MeOH production, with minor gains in other pathways. The most significant effects are the elimination of venting and fugitive emissions, increased yields due to greater productive use of CO_2, and, to a lesser extent, improvements in energy efficiency. Petroleum refinery displacement effects increase to 1.9 $MtCO_2$ (570 $ktCO_2$ higher than the base case) because of the higher yields of CO_2-derived fuels, however, this also drives a 1 $MtCO_2$ increase in the sector's fuel use emissions due to higher throughput. Collectively, improved efficiency leads to net reductions in the Energy sector by 5 $MtCO_2$ relative to the base case (Figure 4-7).

[21] It is uncertain whether current levels of APCr would be available in 2050, given the significant reductions in fossil fuel power plants envisaged in the LTS.
[22] These pathways are not yet included in GEMCCU.

Figure 4-6 CO_2 emissions changes by sector, base case, scenario 2050

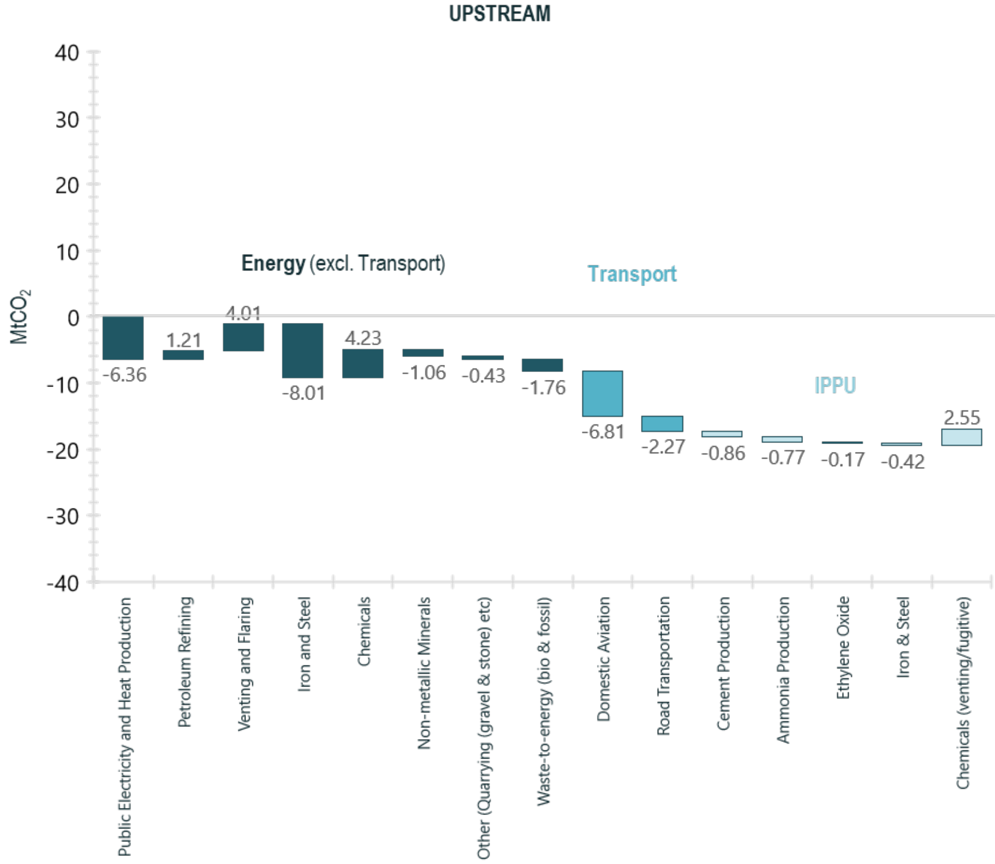


Figure 4-7 CO_2 emissions changes by sector, imp. efficiency, scenario 2050

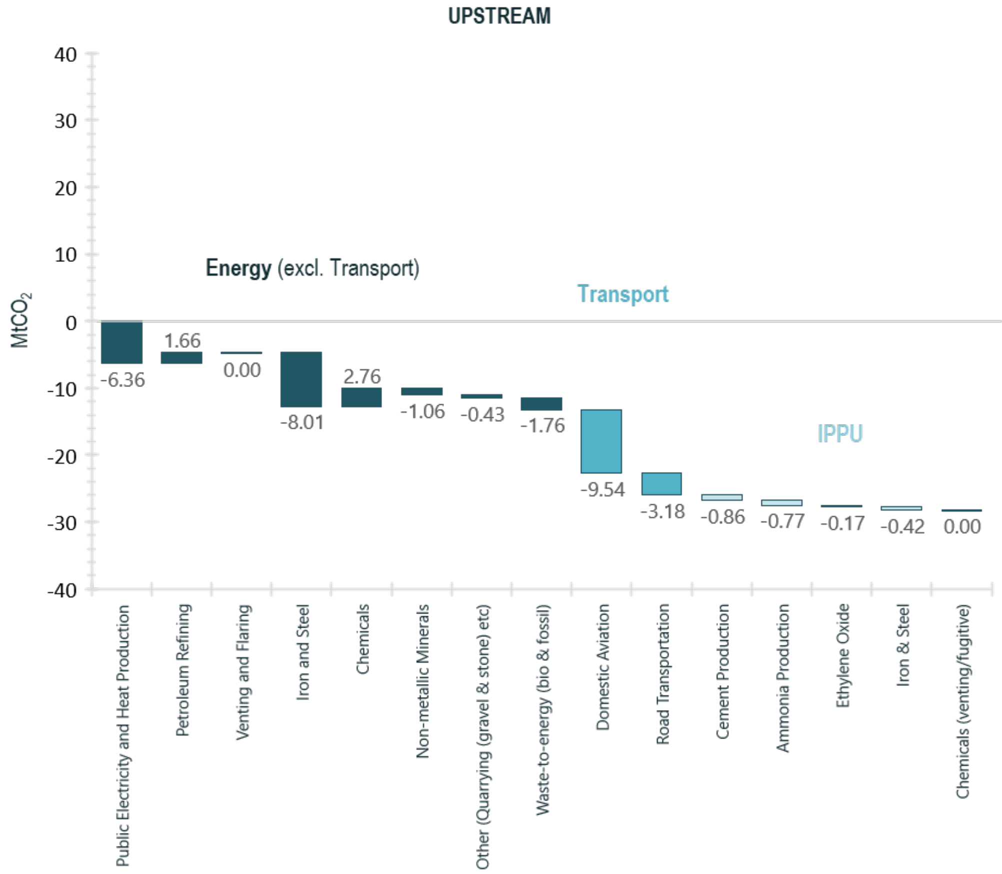
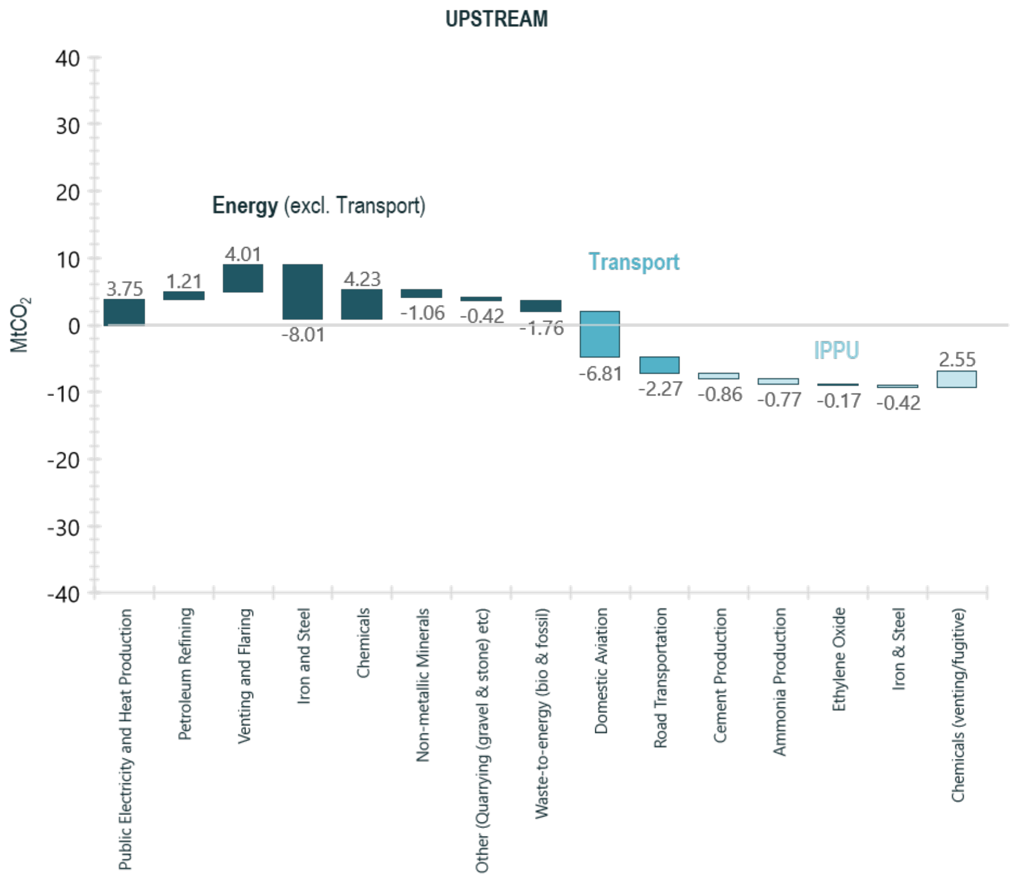


Figure 4-8 CO_2 emissions changes by sector, grid electricity, scenario 2050



Source: GEMCCU, authors. Note: Chemicals (fugitive) is added as a new IPPU reporting category

If grid electricity with an emissions factor consistent with Japan's 2050 LTS ambition is instead assumed,[23] Energy emissions switch from a net reduction of -8.3 $MtCO_2$ to a net increase in emissions of 2 $MtCO_2$ in the base case. This 10 $MtCO_2$ emissions swing offsets the gains described above, the electricity generation sector that is needed to meet the demand for CCU processes (Figure 4-8).

Transport

Emission reductions of 9 to 22 $MtCO_2$ are achieved across all scenarios, the higher number reflecting the improved efficiency scenario. Of this, a 2.3 to 9.5 $MtCO_2$ reduction occurs in Domestic Aviation (assuming all produced jet fuel is used domestically). Road transportation emissions decrease by 2.3 to 3.2 $MtCO_2$ through substitution of fossil derived fuels. The highest reductions reflect the significant gains in algal EtJ production from improving efficiency, where under the improved efficiency scenario venting and fugitive losses are entirely eliminated and all input CO_2 is used to make product. This is probably an unrealistic assumption but is nonetheless helpful for illustrative purposes.

[23] 0.104 $kgCO_2/MWh$

Even though scenario 2050 includes significant amounts of MeOH blending with gasoline, the emissions reduction gains in the Transport sector are marginal. In the upstream accounting mode, MeOH combustion emissions must be counted meaning that the blending simply leads to gasoline emissions being replaced by MeOH emissions. When switching to downstream accounting mode, road transport emissions reduce significantly at the cost of significant increases in other parts of the Energy sector (Figure 4-5).

As noted under scenario 2030 results, because GEMCCU assumes that emissions from algal derived fuels are biogenic and can therefore be zero-rated, some emission reductions still occur in the Road Transportation sector through substitution of petroleum products by fuels derived from algal pathways (-2.3 $MtCO_2$).

IPPU

Unlike in scenario 2030, IPPU emissions vary significantly across different sensitivities in scenario 2050, ranging from +325 $ktCO_2$ to -2.2 $MtCO_2$. The positive emissions arise because of the significant amount of venting and fugitive CO_2 emissions occurring during MeOH production in the Chemicals sector (2.6 $MtCO_2$), that offsets the 2.2 $MtCO_2$ of industrial process emissions captured from iron and steel furnaces, chemicals facilities and cement kilns. Under the improved efficiency sensitivity, fugitive CO_2 losses are eliminated, hence the swing in reductions seen for IPPU sector within this scenario.

More detailed data on cross chain GHG effects for all scenarios and sensitivities applied in GEMCCU are set out in Annex A.

5 Policy Implications

5.1 Contexts

Various studies continue to highlight the significant climate change mitigation potential from utilising CO_2 to make products, with recent estimates of theoretical CO_2 demand in 2050 in the order of 100-1,000 $MtCO_2$ (Table 2-4). In parallel, many OECD country governments are continuing to demonstrate strong interest in CCU as part of long-term emissions reduction goals (Section 2 and Section 3.2). Ambitious pledges towards circular economy and climate change mitigation in the U.S., Europe and Japan all involve significant use of CCU technologies. To accompany these pledges, various funding and incentives programmes are being introduced for the coming decade (see Section 2.2).

In Japan, R&D funding for CCU is primarily channelled through the New Energy and Industrial Technology Development Organization (NEDO). The NEDO has provided around US$35 million per year for CCU over the period 2015-2020,[24] and its budget for 2020-2024 includes an allocation of US$5.7 million to support to a demonstration site for three CCU projects covering concrete, chemicals and gas-to-lipids bioprocessing (Japan Electric Power Information Center-USA 2020). Drawing upon these figures and the data presented in Section 2.2, committed funding for CCU RD&D in the U.S., Europe and Japan to 2030 could exceed US$700 million.[25] Such a sum appears quite modest given the apparent expectations of the technology. Significantly greater efforts will likely be needed to scale-up from the presently small amount of CO_2 that is being utilised in industrial processes.

Future R&D efforts clearly need a sound analytical base that can help discern priorities aligned to credible deployment pathways. The GEMCCU can provide insights in these respects. Although the scenarios used for this study can be considered somewhat arbitrary,[26] the tying together of national emissions data, emission reduction ambitions, CO_2 utilisation processes and national product markets has allowed an integrated, aggregate view of the GHG effects arising from a portfolio of CCU technology choices. This has allowed various insights to be drawn as summarised below.

The chemicals industry is often seen as a strong candidate for CCU deployment. Results from GEMCCU suggest that pathways such as polycarbonate production from CO_2-derived PPs might offer only limited emissions gains due to technical and market constraints. The

[24] US$23 million per year for bio jet fuel and US$13 million for advanced H_2 production using electrolysis.
[25] Assumes U.S. DOE continues R&D funding at around $17 million per year, and 1 $MtCO_2$ for CCU could supported through 45Q. Plus 1% of the climate funding earmarked in Horizon Europe is channelled to CCU (€35m over 10 years to 2030) plus 1 $MtCO_2$ for CCU could be channelled through the EU Innovation Fund at €50/tCO_2.
[26] For example, the amount of CO_2 utilisation modelled, the partitioning of sources, and, to an extent, the end use pathways, in each scenario can be viewed as largely speculative. On the other hand, the end use pathways were aligned to the technology plan in the CCU Roadmap and constrained by apparent technical and market factors identified for some CO_2 derived products.

Japanese market for PPs becomes saturated at around 120 ktCO_2 utilisation, which delivers net emissions reductions of around 60 ktCO_2 (see Section 4.1.2). Most other chemicals production pathways involving C1 building blocks, such as methanation (to CH_4), MeOH and EtOH pathways, all depend on significant supply of low carbon electricity, which is a structural constraint for widespread CCU deployment (see Section 5.4).

Similarly, CCU pathways involving mineralisation reactions, while posing low energy demands, also tend to be constrained by other factors such the rate of CO_2 utilisation per unit final production (often less than 20%), constraints on the availability of other feedstocks, and the low value, high bulk, resultant product.

The potential of algal fuels also faces uncertainty. Although several trials and demonstrations have been undertaken around the world (see, for example, analysis in IEA GHG 2018c for indicative start-up and shutdown rates), few, if any, commercial scale algal fuel production facilities exist today.[27] The CO_2 uptake rates of algae in closed bioreactor systems is also uncertain. The data used in GEMCCU suggest that significant amounts of feedstock CO_2 may be lost as fugitive emissions during production, indicating a potential source of wastage (see also Section 5.4 below). Other factors, such as EtOH production rates and the energy penalty of fractional distillation of low concentrations of EtOH in seawater medium, also presents barriers.

Finally, although they are arbitrary, the amounts of CO_2 modelled in each scenario are somewhat trivial when set against Japan's projected emissions under its NDC and LTS, accounting for only 1 to 12% of total CO_2 emissions in 2030 and 2050 respectively. However, when placed in context with current global CO_2 capture rates – presently around 40MtCO_2 (Global CCS Institute 2020) excluding the 200 MtCO_2 or so used for urea production and merchant CO_2 markets – the scenarios still require Japan to deploy over the next 10 years CO_2 capture at rates equivalent to 10% of today's total global deployment. That is not an insignificant undertaking. The energy requirements involved are also significant, with scenarios from GEMCCU indicating that over the next 30 years Japan might need to develop more than 20 GW of new zero-emissions power capacity dedicated solely to CCU applications.

5.2 Accounting

Emissions accounting frameworks for CCU continue to be a topic of uncertainty. There is a common misconception regarding CO_2 derived products that because they incorporate CO_2 that would otherwise be emitted to atmosphere, then, at least for short-term retention applications, the emissions from the use of such products may be counted as zero emissions (i.e. zero rated). This assumption is incorrect as it is entirely dependent on how the emissions reductions are calculated and allocated (see also Accounting mode in Section 3.3.1):

[27] For example, Algenol, Sapphire Energy and Solazyme have all seemingly to have transitioned away from algal fuel production and towards manufacturing food additives and nutraceuticals.

1. If the capture of CO_2 at point sources is counted as an emission reduction at source, then any subsequent re-emission from product use must be counted as an emission (i.e. positively rated). This is correct, as ultimately the CO_2 is emitted to and accumulates in the atmosphere. GEMCCU refers to this method as "upstream" accounting.
2. Conversely, if the product use emissions are zero rated, then the capture of CO_2 cannot be counted as emissions reduction at source, and therefore all captured CO_2 must be added onto the emissions inventory of the facility where the source is captured. GEMCCU resolves this through the "downstream" accounting mode.

GEMCCU has shown, however, that problems can arise in balancing the CO_2 accounts when operating in downstream mode. This is because, at a portfolio level, some of the captured CO_2 is locked up in products (e.g. in mineralisation applications or in algal biomass) and therefore the emissions reduction benefits of employing CCU are essentially 'lost' in the emissions accounts. In other words, where a CO_2-derived product does not emit CO_2 upon its use, there is no emission reduction gain arising from zero-rating its emissions.

To balance the accounts while zero-rating emissions from CO_2-derived products with short-term retention, a mixed accounting system is needed. Such as system would apply upstream accounting to CO_2-derived products involving long-term storage, and downstream accounting to products with only short-term CO_2 retention. Such accounting architecture will be extremely difficult to implement in practice, however, as it would involve careful tracing of CO_2 molecules from different capture sources to different end uses. Complexity would be further exacerbated in situations where a single CO_2 source is being used for multiple end-uses. A further corollary to the problem is that if there is no emission reduction is counted when capturing CO_2 at point sources (as would be the case in downstream accounting) the incentives to the operator for capturing the CO_2 in the first place is eliminated.

For the reasons described, it is strongly recommended that emissions accounting frameworks for CCU apply an upstream accounting methodology that allocates the CO_2 emission reduction at source. Other forms of incentive may therefore be needed to support product markets for CO_2-derived products with only short-term retention.

A further finding of GEMCCU is that CCU deployment, in some circumstances, will lead to the "onshoring" of CO_2 emissions. In the case of Japan, domestic production of 6 million tonnes CO_2-derived MeOH production in scenario 2050 could lead to the onshoring of 2.8 to 6.8 $MtCO_2$ direct emissions (depending on assumed efficiency) to meet the required manufacturing heat load.[28] A further 62,000 GWh of electricity is also required. Presently, the same level of MeOH supply would result in emissions of around 3 $MtCO_2$ that occurs offshore in MeOH production plants largely located in the Middle East.

[28] If all derived from natural gas.

5.3 Measurement, Reporting and Verification

Building GEMCCU has identified several issues relating to the measurement, reporting and verification (MRV) frameworks and the guidance for compiling national GHG inventories.

The first of these relates to the treatment of fuels derived from algae cultivated in closed bioreactors using CO_2 as feedstock. The general accounting principle applied to the emissions of any biogenically-derived product is that the emissions are zero-rated to avoid double counting. This is how GEMCCU calculates emissions from algal-derived fuels, and hence 25 $MtCO_2$ captured in 2050 leads to 28 $MtCO_2$ emissions reduction (i.e. the calculated reduction exceeds the amount of CO_2 captured, improved efficiency scenario, which seems unfathomable). In this situation, around 10 $MtCO_2$ emissions from algae-derived fuels are not counted as an emission, and hence the significant level of reductions achieved.

The approach to biogenic CO_2 emissions accounting is based on current IPCC GHG inventory guidelines (e.g. IPCC 2006), where the method assumes that plant growth absorbs CO_2 from the atmosphere and emits CO_2 to the atmosphere upon harvesting. Both these changes are recorded and accounted in national GHG inventory accounts as relative carbon stock changes in the Forestry and Other Land Use ("FOLU") reporting category. Subsequent combustion of bioenergy does therefore not need to be recorded as an emission in the Energy sector account as this would lead to double counting in both AFOLU and Energy accounts (see IEA GHG 2014).

However, in situations where the algae exclusively consume fossil CO_2 in their growth cycle, it is a matter of debate whether emissions from these products should be zero-rated since they are not absorbing atmospheric CO_2. In zero-rating these emissions, something of a paradox is created: electro-conversion of fossil CO_2 to fuel (e.g. MeOH) does require the CO_2 product emissions to be counted, whereas biological conversion by algae does not. It is beyond the scope of this report to propose appropriate accounting methods for fuels derived from algae fed on fossil CO_2, although it is essential to note a need for the topic to be considered in future discussions on national GHG inventory compilation.

A further minor matter for national GHG inventory compilation is the treatment of venting and fugitive losses of captured CO_2 in the chemicals sector. Presently there is no suitable reporting category within which to include these emissions, and hence a new category in IPPU of "Venting and fugitive emissions from CO_2-derived chemicals production" seems warranted.

5.4 Decarbonizing Electricity

A well-known facet of CCU is the importance of the electricity source. Results from GEMCCU have reaffirmed this topic, where the source of process electricity is critical in determining whether CCU delivers economy-wide net emissions reductions or not in both scenario 2030 and scenario 2050 (Figure 4-1 and Figure 4-5).

In scenario 2030, for example, where electricity is assumed to be supplied from a grid including fossil power plants (i.e. at a grid emissions rate consistent with Japan's NDC target in 2030) emissions and reductions are more or less equal, leading to marginal gains (-300 ktCO_2 for 5 MtCO_2 captured for utilisation). In scenario 2050, the switch to grid electricity has less pronounced effects as a lower grid emission factor is assumed (consistent with Japan's LTS target). This results in economy-wide net emissions reductions changing from -17 MtCO_2 to around -7 MtCO_2.

In both cases, the results are also highly contingent on significant decarbonization of the power sector, either through dedicated zero-emissions power capacity for CCU, or through wider measures to decarbonize grid electricity supplies. Using the sensitivities in GEMCCU, the "break-even" grid emissions intensity for both scenarios has been calculated (i.e. the point where emissions equal reductions for the scenarios employed, and thus, net-zero is achieved). The results for scenario 2030 and scenario 2050 differ significantly, reflecting the differences in end use technologies between the two.

For scenario 2030, where a higher proportion of CO_2 is utilised for algal fuel production and, to a lesser extent, low energy applications like mineralisation and PP production, the break-even grid emissions intensity levels are much higher than in Scenario 2050. The results indicate a grid emissions intensity of between 460 to >500 kgCO_2e/MWh is sufficient (Figure 5-1). This suggests the near-term prospects for effective CCU deployment tied to grid electricity supply in Japan seem good. However, it is important to remain mindful that in scenario 2030, emissions of around 3.5 MtCO_2 are essentially "lost" in the accounts by the zero rating of emissions from combusting algal fuels. If these were to be added back on, the break-even point would be much lower.

In scenario 2050, the introduction of MeOH and the constraints on low energy CO_2 utilisation pathways results in a more electro-intensive CCU production portfolio. In this case, the break-even grid emissions intensity is much lower than in scenario 2030, ranging 175 to 275 kgCO_2e/MWh (Figure 5-2). This highlights the longer-term linkage between the deployment of CCU and the decarbonization of electricity supply. In the same way as in scenario 2030, around 10 to 11 MtCO_2 is "lost" through the algal fuel pathway in scenario 2050. Adding these emissions would mean much lower grid emissions intensity would be needed to break-even.

A further notable finding from the charts below (Figure 5-1, Figure 5-2) is the slope of the lines. Both charts suggest that measures to improve the efficiency by which CO_2 is utilised will have the most significant effect on overall CCU process performance. This is a topic that has hitherto received little attention, since most desk-based theoretical assessments assume 100% efficient conversion and have rather concentrated on other performance measures such as reducing energy consumption. The clear environmental gains available from increasing CO_2 utilisation efficiency (Section 4.1.1), suggest that the topic should feature more prominently in future RD&D efforts.

Figure 5-1 CO_2 emissions change against grid emissions intensity, scenario 2030

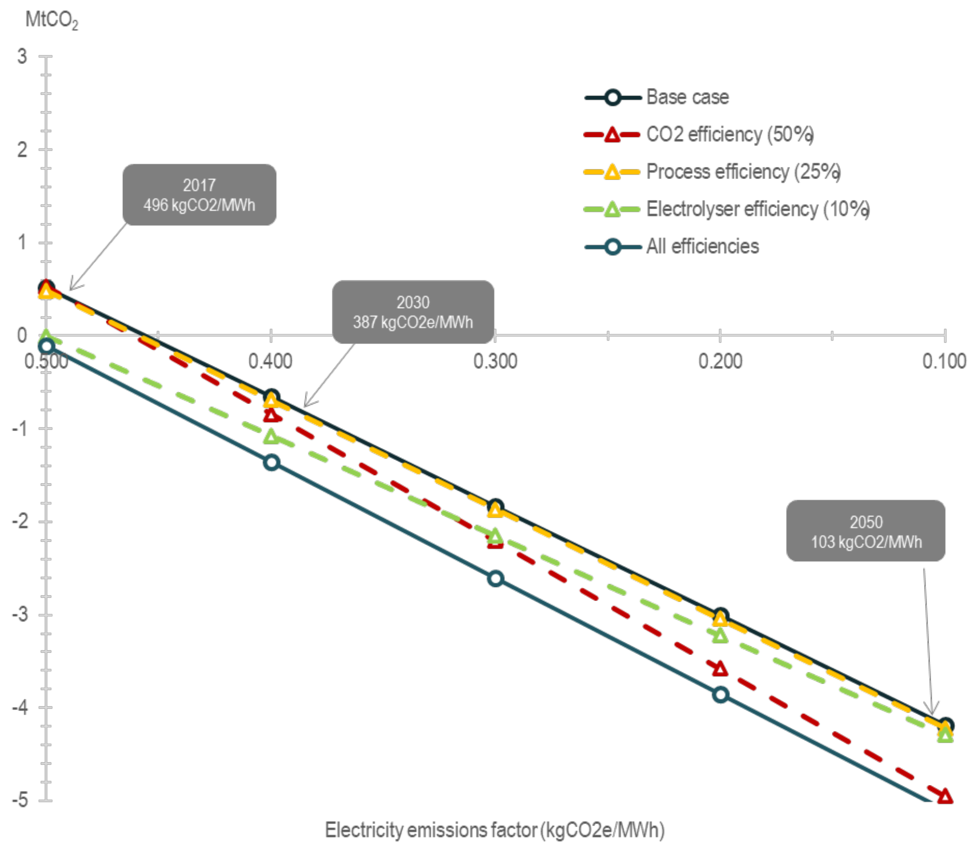
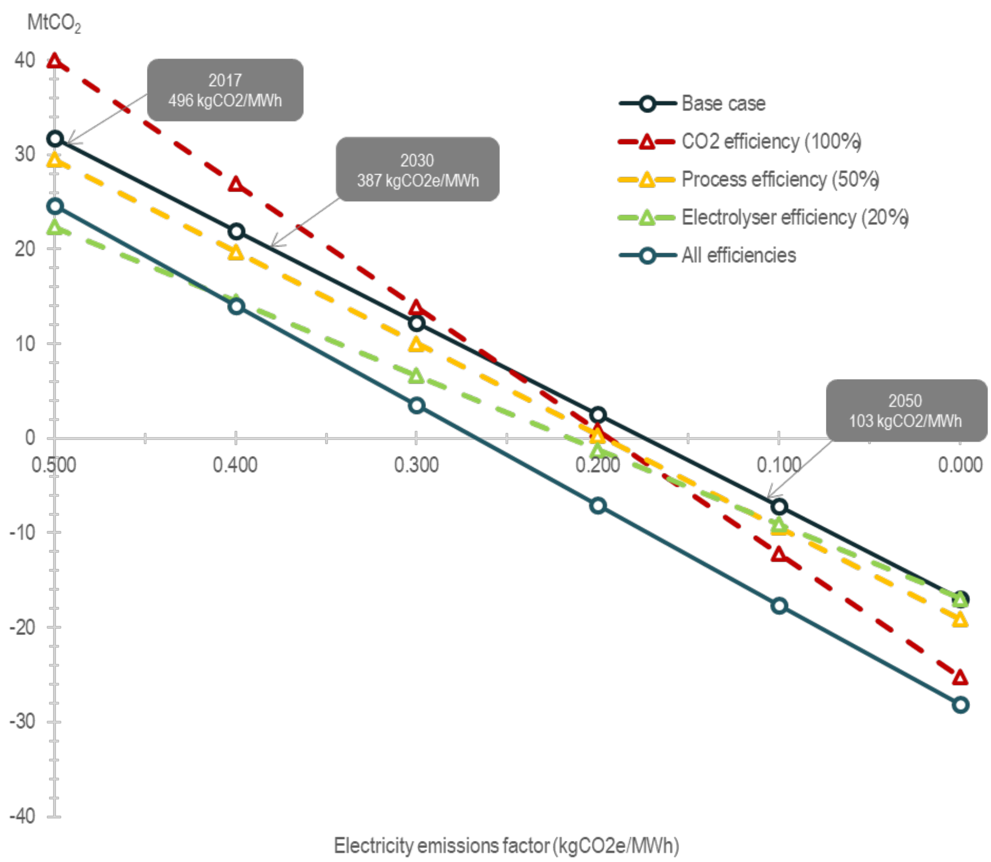


Figure 5-2 CO_2 emissions change against grid emissions intensity, scenario 2050



6 Conclusions

Many OECD countries continue to highlight the important role that carbon capture and utilisation (CCU) technologies could play within their national decarbonisation strategies. Desk-based evaluations of CCU mitigation potential are also raising expectations, suggesting that CO_2 utilisation rates in the order of 100 $MtCO_2$ to 1.1 $GtCO_2$ could be reached by 2050 under scenarios of comprehensive and sustained climate action. In pursuit of these goals, RD&D funding for CCU technologies in the U.S., European Union and Japan could exceed US$700 million over the next 10 years.

The bespoke model developed for this study – the Greenhouse Gas Emissions Model for Carbon Capture and Utilisation (GEMCCU) – has allowed an integrated, aggregate, assessment of the potential of a portfolio of CCU technologies to contribute towards Japan's national climate change mitigation goals. Such an integrated assessment of CCU at a national level has so far been missing from the scientific and policy literature. Sensitivity analysis has provided insights that can guide RD&D priorities over coming years, while emissions accounting and attendant policy implications for various CCU are also revealed.

The GEMCCU results indicate that deploying 5 to 25 $MtCO_2$ utilisation (referred to respectively as 'scenario 2030' and 'scenario 2050'), could lead to -5.4 to -16.9 $MtCO_2$ net CO_2 emissions changes in Japan of under base case assumptions. The contribution increases to -6.4 to -28.1 $MtCO_2$ under improved efficiency scenarios and decreases to -0.3 to -6.8 $MtCO_2$ if grid electricity is assumed as the source of power (rather than 100% zero carbon electricity). The base case emissions reduction represents between 2 and 6.4% of Japan's estimated mitigation effort to 2030 and 2050 respectively. Improving CCU performance increases this to over 10% by 2050.

The best-case results from GEMCCU rely on significant amounts of zero carbon electricity (up to 22 GW of new capacity by 2050) and the possible overstatement of emissions reductions due to a potential loophole in GHG accounting rules for algal-derived biofuels. In respect of the latter, the use of a zero emissions factor for fuels derived from the biological conversion of fossil CO_2 by algae (like other biofuels) may be incorrect since the algae are exclusively fed on fossil CO_2 during cultivation. The assumed approach to measurement, reporting and verification of CO_2-derived fuels presents something of a paradox: for fuels derived from biological conversions, emissions are not counted, whereas emissions from e-fuels produced through electro conversion (e.g. methanol) are. If the zero emissions assumption for algal fuels is modified, results from GEMCCU are significantly altered, resulting in the addition of between 3 to 10 $MtCO_2$ emissions to the net emissions changes outlined above. Thus, under a worst-case scenario (grid electricity supply with algal fuels counted as fossil CO_2 emissions) net emissions change would be in the range +2.7 to +3.2 $MtCO_2$ for scenario 2030 and scenario

2050 respectively. Further clarification of the greenhouse gas measurement, reporting and verification rules applicable to algal biofuels therefore seems essential

GEMCCU has also reaffirmed the importance of electricity source to the climate efficacy of CCU, although perhaps not to the levels previously considered. Analysis suggests that electricity grid emissions factors lower than 460-500 $kgCO_2e$/MWH could be sufficient to deliver a net emissions reduction effect (scenario 2030). This decreases to 175-275 $kgCO_2e$/MWh where a broader portfolio of CCU technologies is employed (scenario 2050). Both outcomes are, however, entirely contingent on the zero-rating of algal fuel emissions as described previously and would need to be significantly lower if emissions from algal derived fuels were instead counted like fossil CO_2.

GEMCCU has also proved useful in identifying the technical and market constraints on some CCU technologies, primarily polycarbonate and mineralisation pathways. Although these routes require only limited amounts of energy, CO_2 utilisation rates are low and market and technical issues constrain deployment. Analysis suggests that as little as 300 $ktCO_2$ utilised would be sufficient to saturate the Japanese market for the resulting products. Indications are that long-term CCU strategies will therefore inevitably involve electro-intensive pathways using hydrogen to produce electro-fuels. GEMCCU also reveals that creating a domestic CO_2-derived methanol industry could “onshore” up to 6 $MtCO_2$ emissions to Japan’s national GHG emissions inventory.

Future modifications and the use of new scenarios and analysis in GEMCCU could provide further policy insights. Options include:

- Adding more CCU sub-models to expand the portfolio of options available for assessment; for example, adding CO_2 concrete curing and other novel chemical production pathways. Availability of data on these processes could, however, limit possibilities.
- Applying a bigger range of scenarios; for example, attempting to resolve the model for a target level of contribution towards Japan’s greenhouse gas emission reduction goals,
- Applying the model to different jurisdictions.
- Building more dynamic functions into the model; for example, in order to account for changes in the electricity supply over time, and asses how that affects the availability of CO_2, the grid emissions factor etc.
- Including an economic model that could provide critical information on, for example, potential capital and operating costs and costs savings associated with different scenarios for technology deployment.

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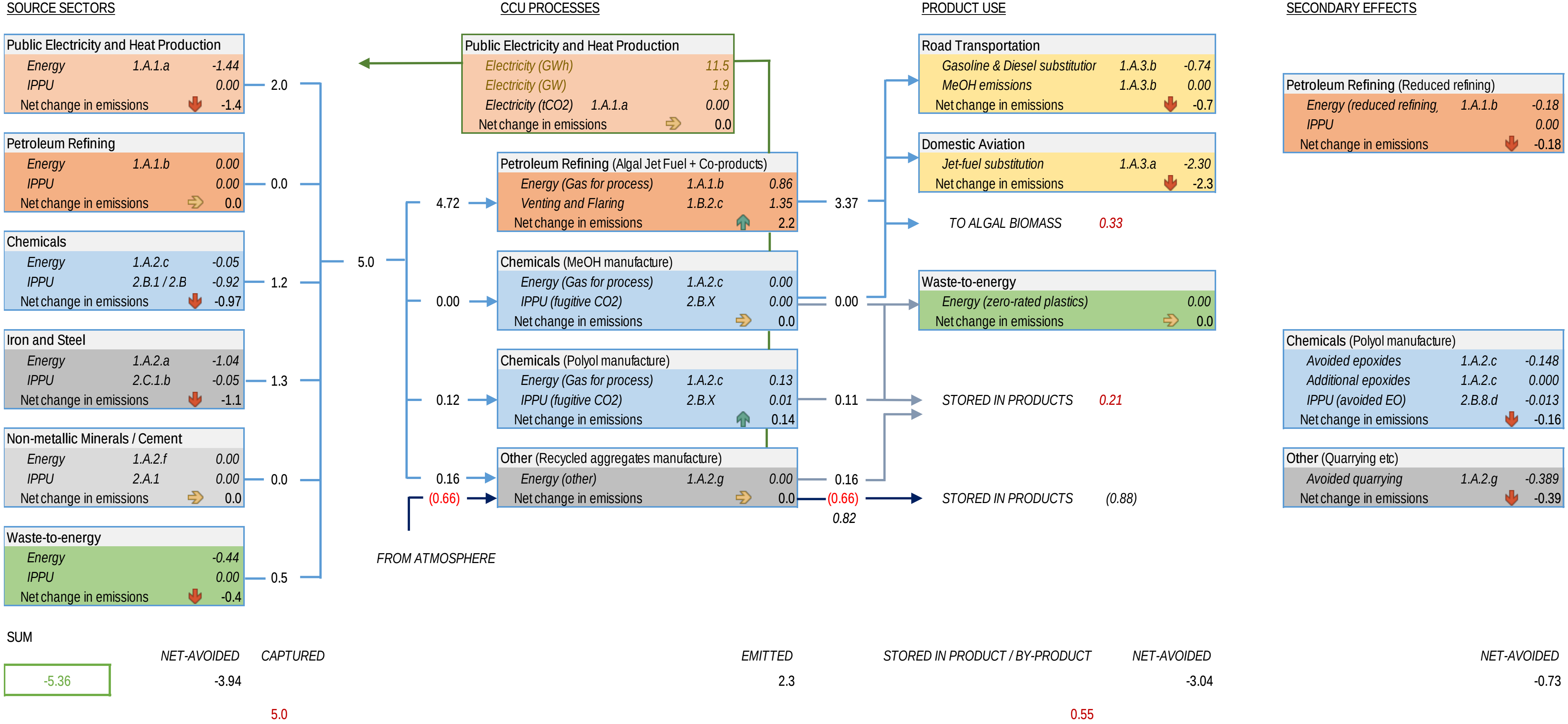
Annex A – CO_2 Flows for Modelled Scenarios

Accounting mode	Upstream
Electricity source	Zero emissions
Capture sources	Scenario 2030 (5 Mt)
Utilisation pathways	Scenario 2030 (5 Mt)
Modelled CO2 utilisation rate (Mt)	5
CO2 use efficiency (vs. BL)	Baseline
Process energy efficiency (vs. BL)	Baseline
H2 electrolyser efficiency (vs. BL)	Baseline

CCU product output	*tonnes/yr*	*% of current annual domestic demand*
Methanol	0	0%
Polyols	545,455	97%
Jet fuel (domestic)	746,033	22%
Gasoline	150,427	0.40%
Diesel	80,703	0.24%
Aggregates	4,923,077	2.65%

Hydrogen demand
202 kt/yr



Accounting mode	Downstream
Electricity source	Zero emissions
Capture sources	Scenario 2030 (5 Mt)
Utilisation pathways	Scenario 2030 (5 Mt)
Modelled CO2 utilisation rate (Mt)	5
CO2 use efficiency (vs. BL)	Baseline
Process energy efficiency (vs. BL)	Baseline
H2 electrolyser efficiency (vs. BL)	Baseline

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Gasoline	150,427	0.40%
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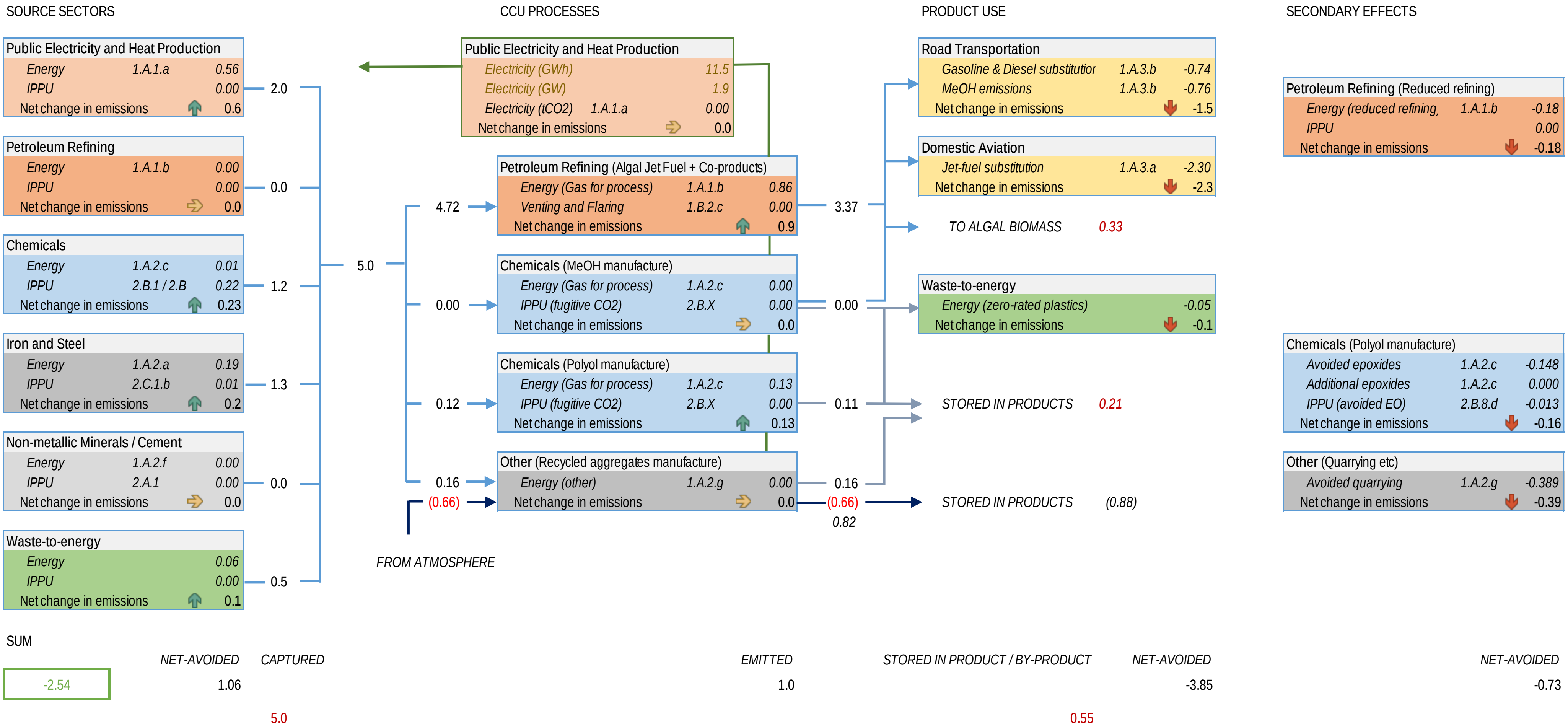
Aggregates	4,923,077	2.65%

Hydrogen demand
202 kt/yr



Accounting mode	Upstream
Electricity source	2030 grid factor (NDC compliant)
Capture sources	Scenario 2030 (5 Mt)
Utilisation pathways	Scenario 2030 (5 Mt)
Modelled CO2 utilisation rate (Mt)	5
CO2 use efficiency (vs. BL)	Baseline
Process energy efficiency (vs. BL)	Baseline
H2 electrolyser efficiency (vs. BL)	Baseline

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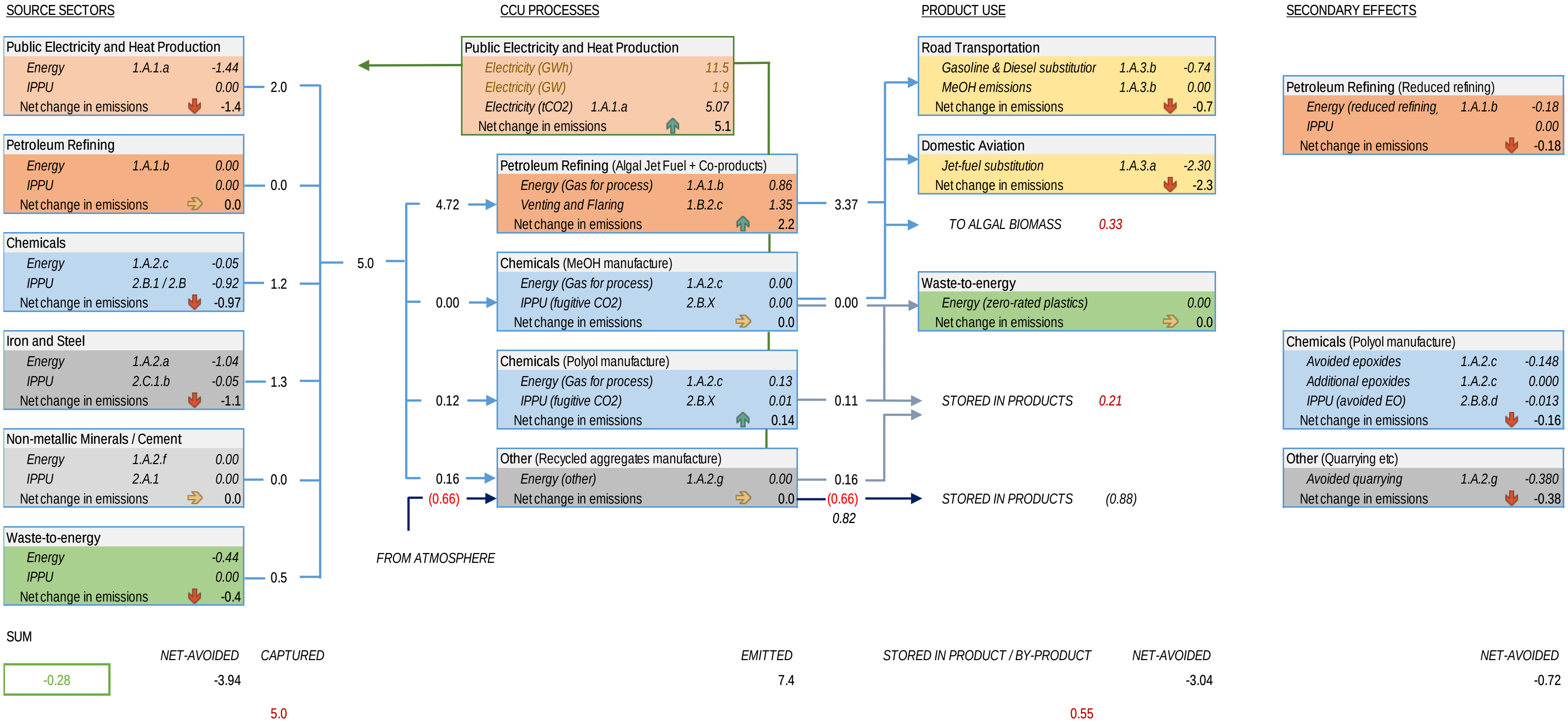
Hydrogen demand
202 kt/yr



Accounting mode	Downstream
Electricity source	2030 grid factor (NDC compliant)
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Utilisation pathways	Scenario 2030 (5 Mt)
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Process energy efficiency (vs. BL)	Baseline
H2 electrolyser efficiency (vs. BL)	Baseline

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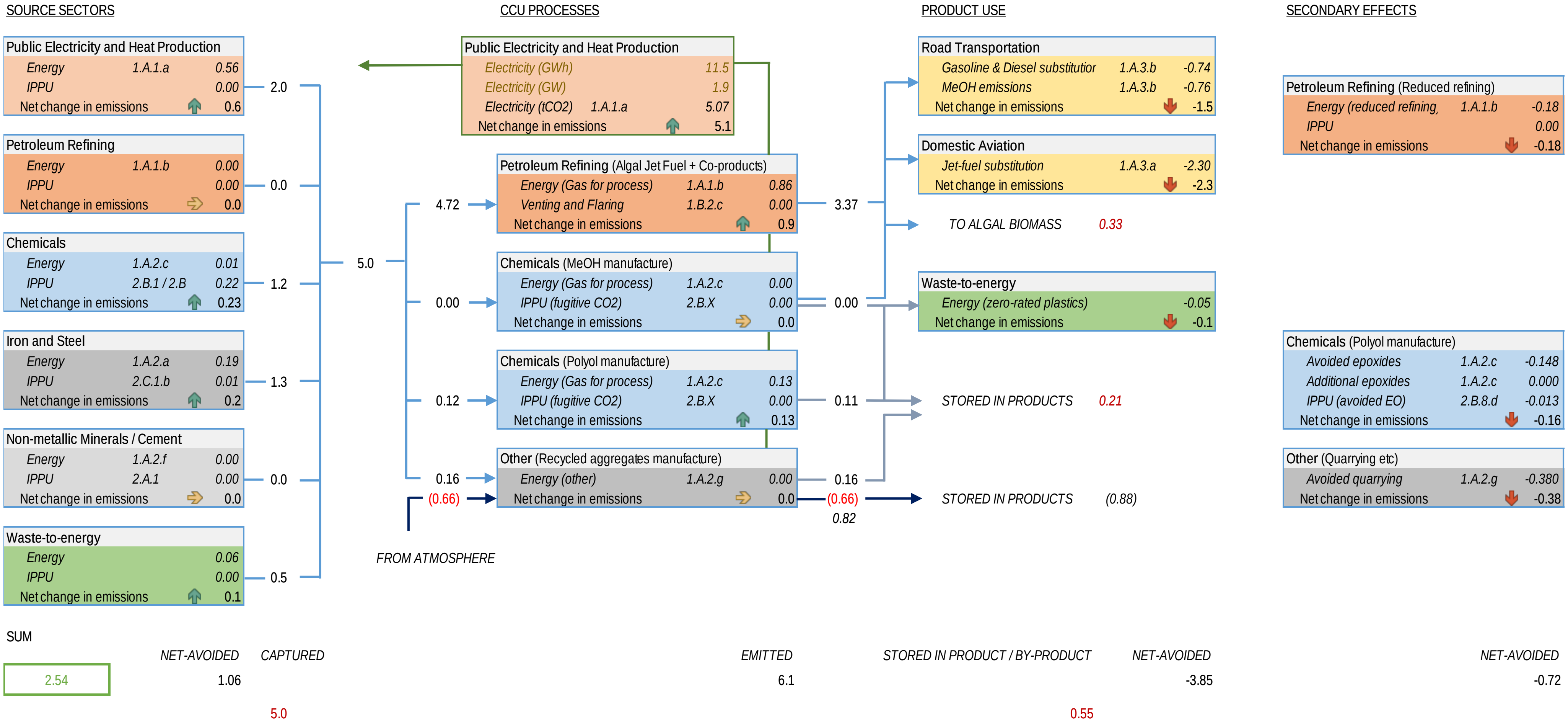
Gasoline	150,427	0.40%
Diesel	80,703	0.24%
Aggregates	4,923,077	2.65%

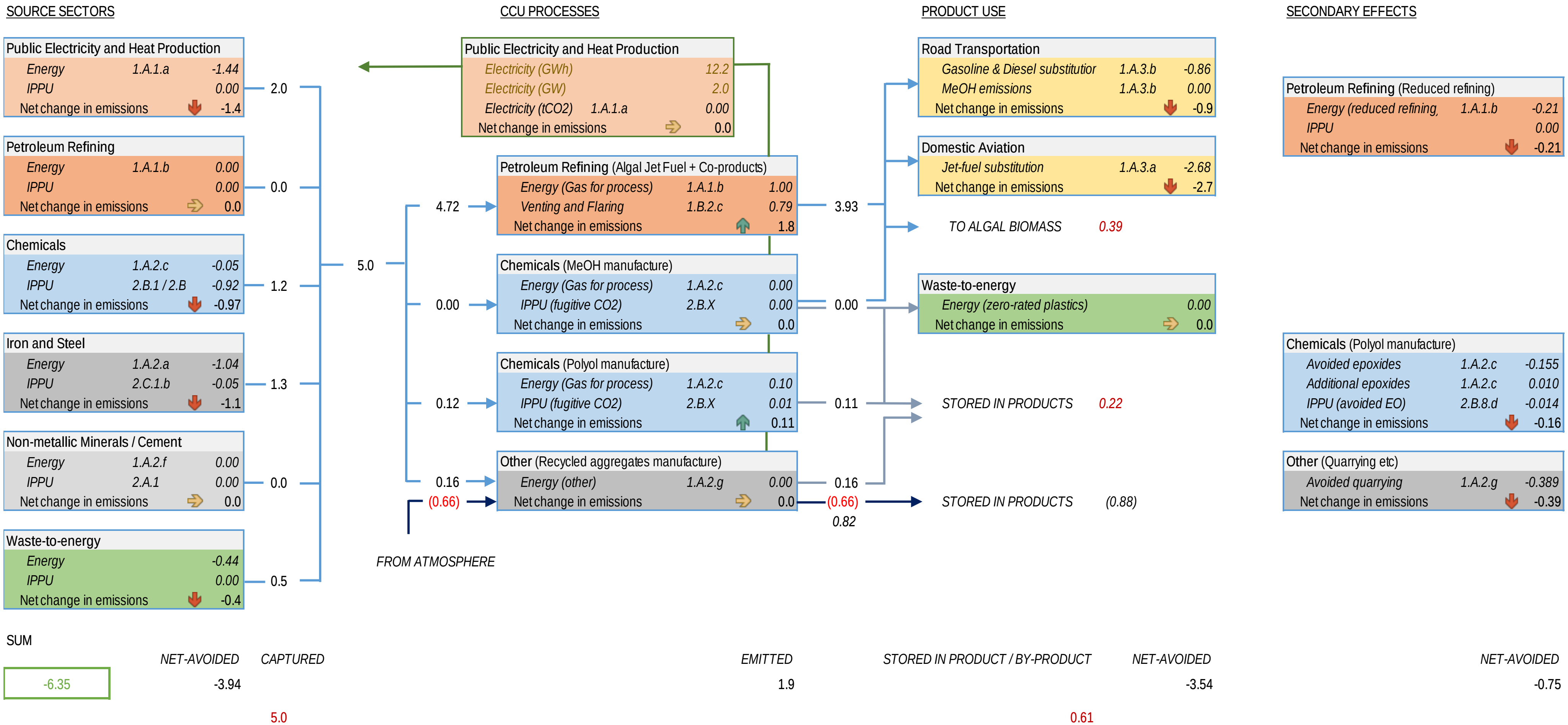
Hydrogen demand
202 kt/yr



Accounting mode	Upstream
Electricity source	Zero emissions
Capture sources	Scenario 2030 (5 Mt)
Utilisation pathways	Scenario 2030 (5 Mt)
Modelled CO2 utilisation rate (Mt)	5
CO2 use efficiency (vs. BL)	50%
Process energy efficiency (vs. BL)	25%
H2 electrolyser efficiency (vs. BL)	10%

CCU product output	*tonnes/yr*	*% of current annual domestic demand*
Methanol	0	0%
Polyols	571,429	101%
Jet fuel (domestic)	870,561	26%
Gasoline	175,536	0.47%
Diesel	94,174	0.28%
Aggregates	4,923,077	2.65%

Hydrogen demand
235 kt/yr



Accounting mode	Downstream
Electricity source	Zero emissions
Capture sources	Scenario 2030 (5 Mt)
Utilisation pathways	Scenario 2030 (5 Mt)
Modelled CO2 utilisation rate (Mt)	5
CO2 use efficiency (vs. BL)	50%
Process energy efficiency (vs. BL)	25%
H2 electrolyser efficiency (vs. BL)	10%

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Gasoline	175,536	0.47%
Diesel	94,174	0.28%
Aggregates	4,923,077	2.65%

Hydrogen demand
235 kt/yr

SOURCE SECTORS

Public Electricity and Heat Production		
Energy	*1.A.1.a*	*0.56*
IPPU		*0.00*
Net change in emissions		0.6

2.0

Petroleum Refining		
Energy	*1.A.1.b*	*0.00*
IPPU		*0.00*
Net change in emissions		0.0

0.0

Chemicals		
Energy	*1.A.2.c*	*0.01*
IPPU	*2.B.1 / 2.B*	*0.22*
Net change in emissions		0.23

1.2

Iron and Steel		
Energy	*1.A.2.a*	*0.19*
IPPU	*2.C.1.b*	*0.01*
Net change in emissions		0.2

1.3

Non-metallic Minerals / Cement		
Energy	*1.A.2.f*	*0.00*
IPPU	*2.A.1*	*0.00*
Net change in emissions		0.0

0.0

Waste-to-energy		
Energy		*0.06*
IPPU		*0.00*
Net change in emissions		0.1

0.5

5.0

CCU PROCESSES

Public Electricity and Heat Production		
Electricity (GWh)		*12.2*
Electricity (GW)		*2.0*
Electricity (tCO2)	*1.A.1.a*	*0.00*
Net change in emissions		0.0

4.72

Petroleum Refining (Algal Jet Fuel + Co-products)		
Energy (Gas for process)	*1.A.1.b*	*1.00*
Venting and Flaring	*1.B.2.c*	*0.00*
Net change in emissions		1.0

3.93

0.00

Chemicals (MeOH manufacture)		
Energy (Gas for process)	*1.A.2.c*	*0.00*
IPPU (fugitive CO2)	*2.B.X*	*0.00*
Net change in emissions		0.0

0.00

0.12

Chemicals (Polyol manufacture)		
Energy (Gas for process)	*1.A.2.c*	*0.10*
IPPU (fugitive CO2)	*2.B.X*	*0.00*
Net change in emissions		0.10

0.11

0.16

(0.66)

Other (Recycled aggregates manufacture)		
Energy (other)	*1.A.2.g*	*0.00*
Net change in emissions		0.0

0.16

(0.66)

0.82

FROM ATMOSPHERE

PRODUCT USE

Road Transportation		
Gasoline & Diesel substitution	*1.A.3.b*	*-0.86*
MeOH emissions	*1.A.3.b*	*-0.76*
Net change in emissions		-1.6

Domestic Aviation		
Jet-fuel substitution	*1.A.3.a*	*-2.68*
Net change in emissions		-2.7

TO ALGAL BIOMASS *0.39*

Waste-to-energy	
Energy (zero-rated plastics)	*-0.06*
Net change in emissions	-0.1

STORED IN PRODUCTS *0.22*

STORED IN PRODUCTS *(0.88)*

SECONDARY EFFECTS

Petroleum Refining (Reduced refining)		
Energy (reduced refining	*1.A.1.b*	*-0.21*
IPPU		*0.00*
Net change in emissions		-0.21

Chemicals (Polyol manufacture)		
Avoided epoxides	*1.A.2.c*	*-0.155*
Additional epoxides	*1.A.2.c*	*0.010*
IPPU (avoided EO)	*2.B.8.d*	*-0.014*
Net change in emissions		-0.16

Other (Quarrying etc)		
Avoided quarrying	*1.A.2.g*	*-0.389*
Net change in emissions		-0.39

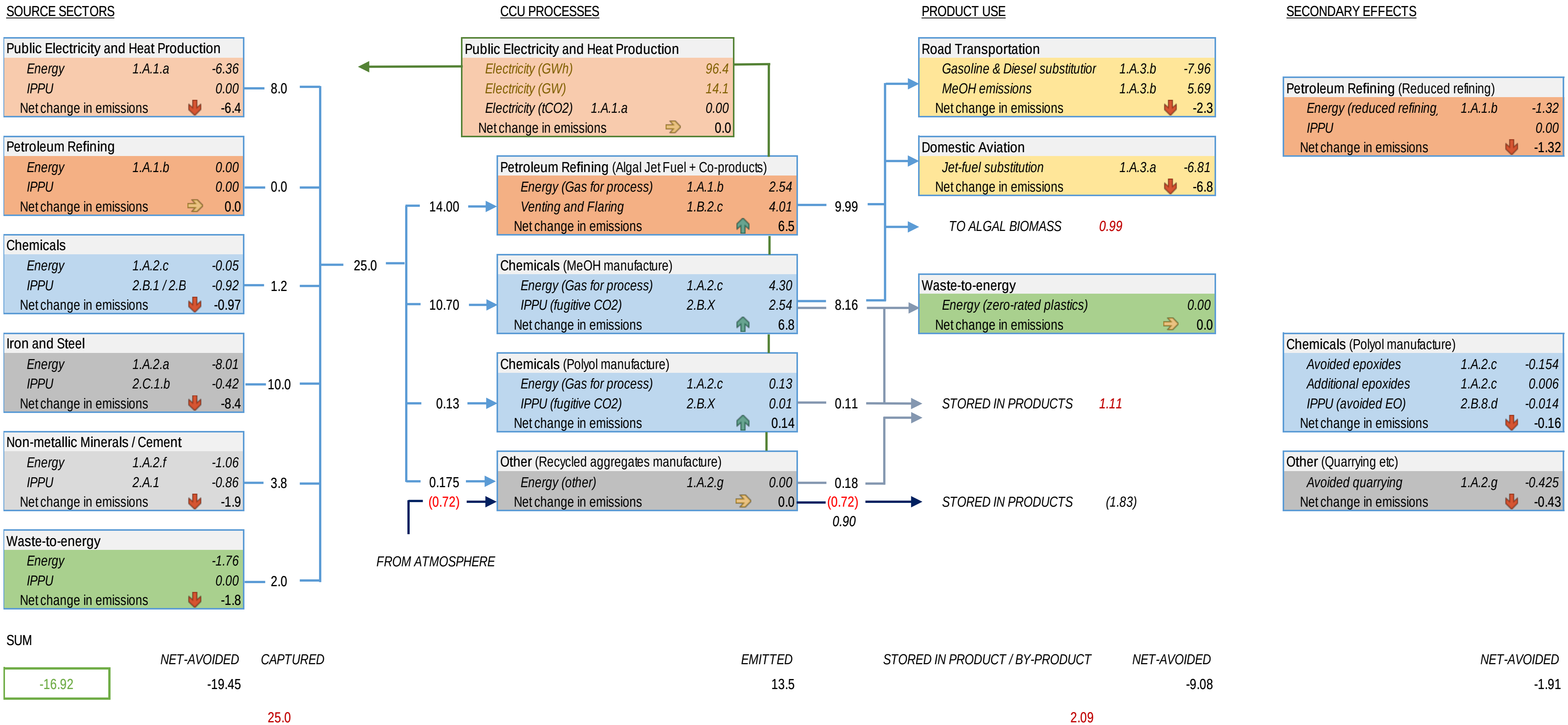
SUM

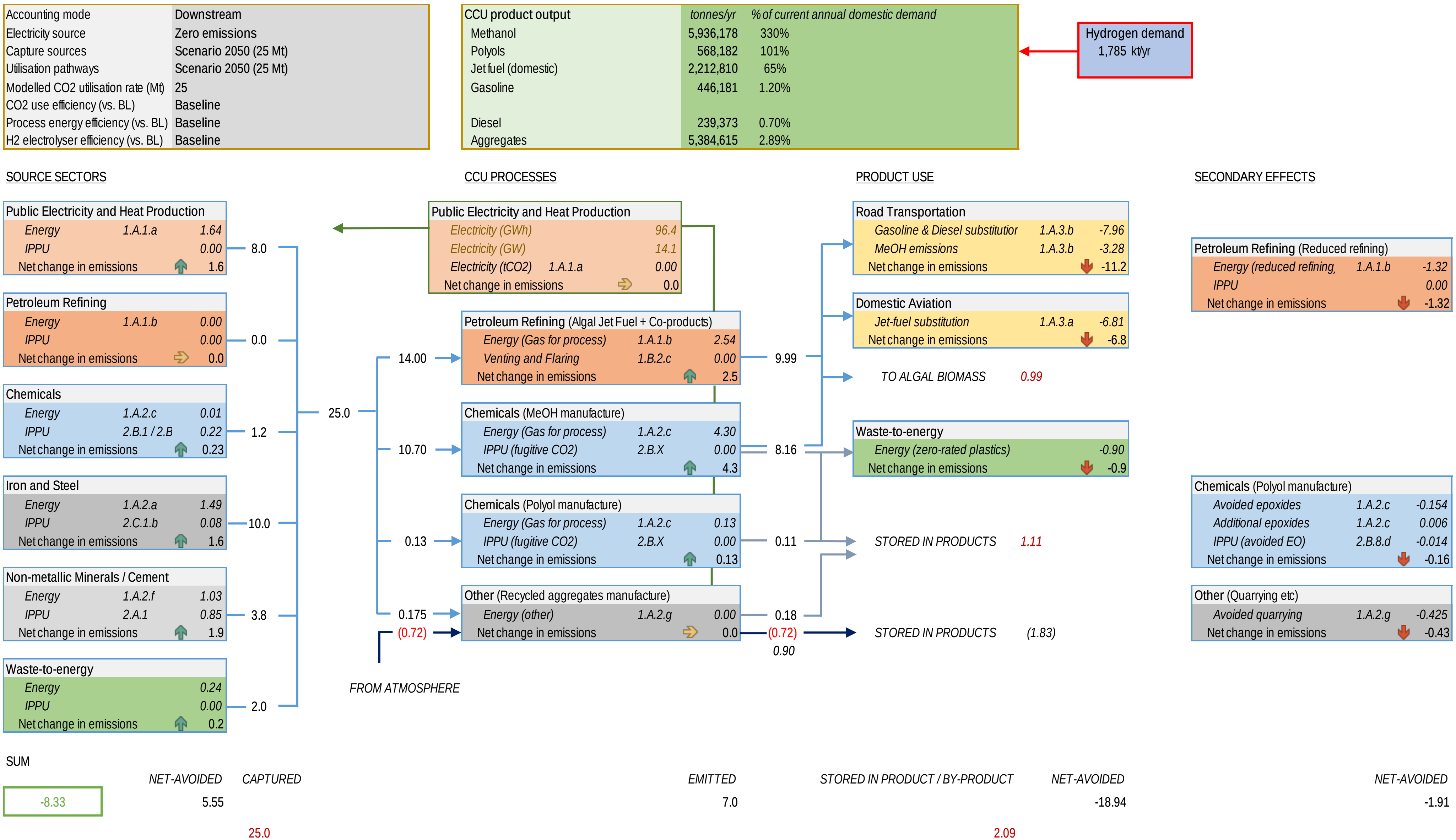
SUM	*NET-AVOIDED*	*CAPTURED*	*EMITTED*	*STORED IN PRODUCT / BY-PRODUCT*	*NET-AVOIDED*	*NET-AVOIDED*
-2.96	1.06	5.0	1.1	0.61	-4.36	-0.75

Accounting mode	Upstream
Electricity source	Zero emissions
Capture sources	Scenario 2050 (25 Mt)
Utilisation pathways	Scenario 2050 (25 Mt)
Modelled CO2 utilisation rate (Mt)	25
CO2 use efficiency (vs. BL)	Baseline
Process energy efficiency (vs. BL)	Baseline
H2 electrolyser efficiency (vs. BL)	Baseline

CCU product output	*tonnes/yr*	*% of current annual domestic demand*
Methanol	5,936,178	330%
Polyols	568,182	101%
Jet fuel (domestic)	2,212,810	65%
Gasoline	446,181	1.20%
Diesel	239,373	0.70%
Aggregates	5,384,615	2.89%

Hydrogen demand
1,785 kt/yr



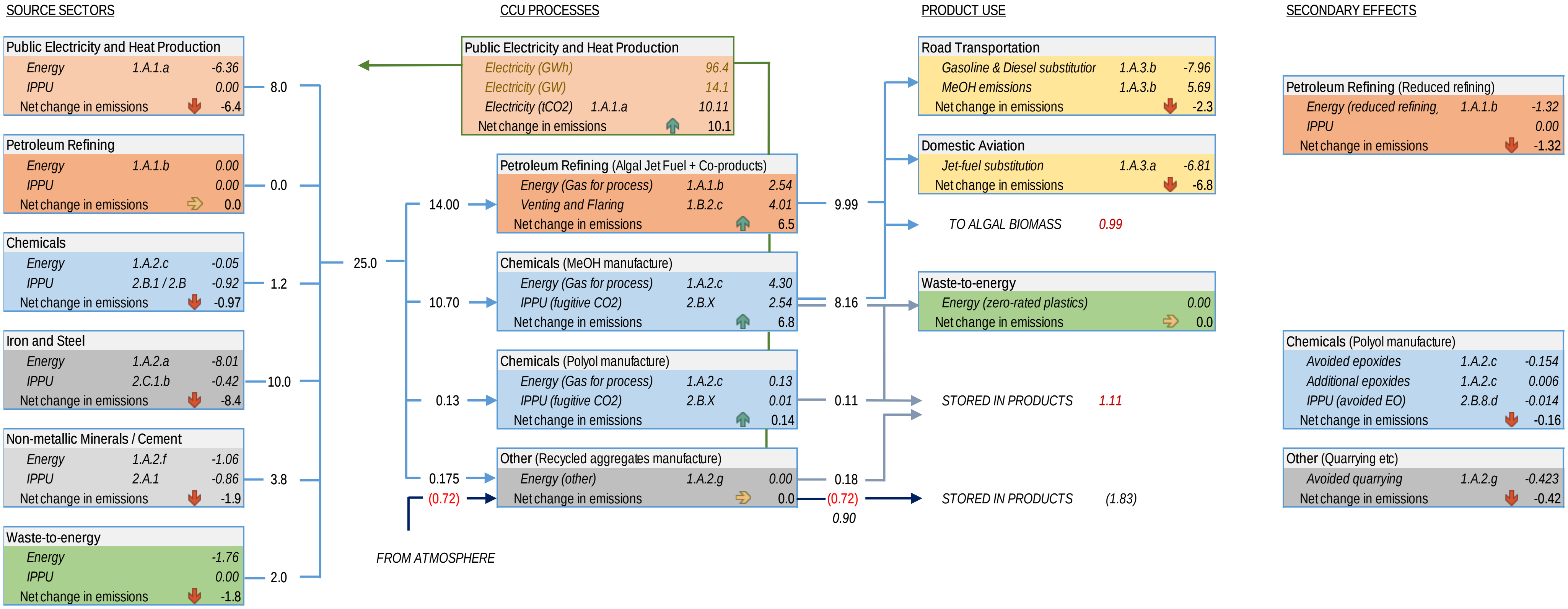


Accounting mode | Downstream
Electricity source | Zero emissions
Capture sources | Scenario 2050 (25 Mt)
Utilisation pathways | Scenario 2050 (25 Mt)
Modelled CO2 utilisation rate (Mt) | 25
CO2 use efficiency (vs. BL) | Baseline
Process energy efficiency (vs. BL) | Baseline
H2 electrolyser efficiency (vs. BL) | Baseline
CCU product output | tonnes/yr | % of current annual domestic demand
Methanol | 5,936,178 | 330%
Polyols | 568,182 | 101%
Jet fuel (domestic) | 2,212,810 | 65%
Gasoline | 446,181 | 1.20%
Diesel | 239,373 | 0.70%
Aggregates | 5,384,615 | 2.89%
Hydrogen demand
1,785 kt/yr
SOURCE SECTORS
CCU PROCESSES
PRODUCT USE
SECONDARY EFFECTS
Public Electricity and Heat Production
Energy 1.A.1.a 1.64
IPPU 0.00
Net change in emissions 1.6
8.0
Petroleum Refining
Energy 1.A.1.b 0.00
IPPU 0.00
Net change in emissions 0.0
0.0
Chemicals
Energy 1.A.2.c 0.01
IPPU 2.B.1 / 2.B 0.22
Net change in emissions 0.23
1.2
Iron and Steel
Energy 1.A.2.a 1.49
IPPU 2.C.1.b 0.08
Net change in emissions 1.6
10.0
Non-metallic Minerals / Cement
Energy 1.A.2.f 1.03
IPPU 2.A.1 0.85
Net change in emissions 1.9
3.8
Waste-to-energy
Energy 0.24
IPPU 0.00
Net change in emissions 0.2
2.0
25.0
Public Electricity and Heat Production
Electricity (GWh) 96.4
Electricity (GW) 14.1
Electricity (tCO2) 1.A.1.a 0.00
Net change in emissions 0.0
14.00
Petroleum Refining (Algal Jet Fuel + Co-products)
Energy (Gas for process) 1.A.1.b 2.54
Venting and Flaring 1.B.2.c 0.00
Net change in emissions 2.5
9.99
10.70
Chemicals (MeOH manufacture)
Energy (Gas for process) 1.A.2.c 4.30
IPPU (fugitive CO2) 2.B.X 0.00
Net change in emissions 4.3
8.16
0.13
Chemicals (Polyol manufacture)
Energy (Gas for process) 1.A.2.c 0.13
IPPU (fugitive CO2) 2.B.X 0.00
Net change in emissions 0.13
0.11
0.175
(0.72)
Other (Recycled aggregates manufacture)
Energy (other) 1.A.2.g 0.00
Net change in emissions 0.0
0.18
(0.72)
0.90
FROM ATMOSPHERE
Road Transportation
Gasoline & Diesel substitution 1.A.3.b -7.96
MeOH emissions 1.A.3.b -3.28
Net change in emissions -11.2
Domestic Aviation
Jet-fuel substitution 1.A.3.a -6.81
Net change in emissions -6.8
TO ALGAL BIOMASS 0.99
Waste-to-energy
Energy (zero-rated plastics) -0.90
Net change in emissions -0.9
STORED IN PRODUCTS 1.11
STORED IN PRODUCTS (1.83)
Petroleum Refining (Reduced refining)
Energy (reduced refining 1.A.1.b -1.32
IPPU 0.00
Net change in emissions -1.32
Chemicals (Polyol manufacture)
Avoided epoxides 1.A.2.c -0.154
Additional epoxides 1.A.2.c 0.006
IPPU (avoided EO) 2.B.8.d -0.014
Net change in emissions -0.16
Other (Quarrying etc)
Avoided quarrying 1.A.2.g -0.425
Net change in emissions -0.43
SUM
-8.33
NET-AVOIDED 5.55
CAPTURED 25.0
EMITTED 7.0
STORED IN PRODUCT / BY-PRODUCT 2.09
NET-AVOIDED -18.94
NET-AVOIDED -1.91

Accounting mode	Upstream
Electricity source	2050 grid factor (LTS compliant)
Capture sources	Scenario 2050 (25 Mt)
Utilisation pathways	Scenario 2050 (25 Mt)
Modelled CO2 utilisation rate (Mt)	25
CO2 use efficiency (vs. BL)	Baseline
Process energy efficiency (vs. BL)	Baseline
H2 electrolyser efficiency (vs. BL)	Baseline

CCU product output	*tonnes/yr*	*% of current annual domestic demand*
Methanol	5,936,178	330%
Polyols	568,182	101%
Jet fuel (domestic)	2,212,810	65%
Gasoline	446,181	1.20%
Diesel	239,373	0.70%
Aggregates	5,384,615	2.89%

Hydrogen demand
1,785 kt/yr



SUM	NET-AVOIDED	CAPTURED	EMITTED	STORED IN PRODUCT / BY-PRODUCT	NET-AVOIDED	NET-AVOIDED
-6.81	-19.45		23.6		-9.08	-1.91
		25.0		2.09		

Accounting mode	Downstream
Electricity source	2050 grid factor (LTS compliant)
Capture sources	Scenario 2050 (25 Mt)
Utilisation pathways	Scenario 2050 (25 Mt)
Modelled CO2 utilisation rate (Mt)	25
CO2 use efficiency (vs. BL)	Baseline
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Hydrogen demand
1,785 kt/yr

SOURCE SECTORS

Public Electricity and Heat Production			
Energy	*1.A.1.a*	*1.64*	
IPPU		*0.00*	8.0
Net change in emissions		1.6	

Petroleum Refining			
Energy	*1.A.1.b*	*0.00*	
IPPU		*0.00*	0.0
Net change in emissions		0.0	

Chemicals			
Energy	*1.A.2.c*	*0.01*	
IPPU	*2.B.1 / 2.B*	*0.22*	1.2
Net change in emissions		0.23	

Iron and Steel			
Energy	*1.A.2.a*	*1.49*	
IPPU	*2.C.1.b*	*0.08*	10.0
Net change in emissions		1.6	

Non-metallic Minerals / Cement			
Energy	*1.A.2.f*	*1.03*	
IPPU	*2.A.1*	*0.85*	3.8
Net change in emissions		1.9	

Waste-to-energy			
Energy		*0.24*	
IPPU		*0.00*	2.0
Net change in emissions		0.2	

25.0

CCU PROCESSES

Public Electricity and Heat Production		
Electricity (GWh)		*96.4*
Electricity (GW)		*14.1*
Electricity (tCO2)	*1.A.1.a*	*10.11*
Net change in emissions		10.1

Input	Petroleum Refining (Algal Jet Fuel + Co-products)			Output
	Energy (Gas for process)	*1.A.1.b*	*2.54*	
14.00	*Venting and Flaring*	*1.B.2.c*	*0.00*	9.99
	Net change in emissions		2.5	

Input	Chemicals (MeOH manufacture)			Output
	Energy (Gas for process)	*1.A.2.c*	*4.30*	
10.70	*IPPU (fugitive CO2)*	*2.B.X*	*0.00*	8.16
	Net change in emissions		4.3	

Input	Chemicals (Polyol manufacture)			Output
	Energy (Gas for process)	*1.A.2.c*	*0.13*	
0.13	*IPPU (fugitive CO2)*	*2.B.X*	*0.00*	0.11
	Net change in emissions		0.13	

Input	Other (Recycled aggregates manufacture)			Output
0.175	*Energy (other)*	*1.A.2.g*	*0.00*	0.18
(0.72)	Net change in emissions		0.0	(0.72)
				0.90

FROM ATMOSPHERE

PRODUCT USE

Road Transportation		
Gasoline & Diesel substitutior	*1.A.3.b*	*-7.96*
MeOH emissions	*1.A.3.b*	*-3.28*
Net change in emissions		-11.2

Domestic Aviation		
Jet-fuel substitution	*1.A.3.a*	*-6.81*
Net change in emissions		-6.8

TO ALGAL BIOMASS *0.99*

Waste-to-energy	
Energy (zero-rated plastics)	*-0.90*
Net change in emissions	-0.9

STORED IN PRODUCTS *1.11*

STORED IN PRODUCTS *(1.83)*

SECONDARY EFFECTS

Petroleum Refining (Reduced refining)		
Energy (reduced refining	*1.A.1.b*	*-1.32*
IPPU		*0.00*
Net change in emissions		-1.32

Chemicals (Polyol manufacture)		
Avoided epoxides	*1.A.2.c*	*-0.154*
Additional epoxides	*1.A.2.c*	*0.006*
IPPU (avoided EO)	*2.B.8.d*	*-0.014*
Net change in emissions		-0.16

Other (Quarrying etc)		
Avoided quarrying	*1.A.2.g*	*-0.423*
Net change in emissions		-0.42

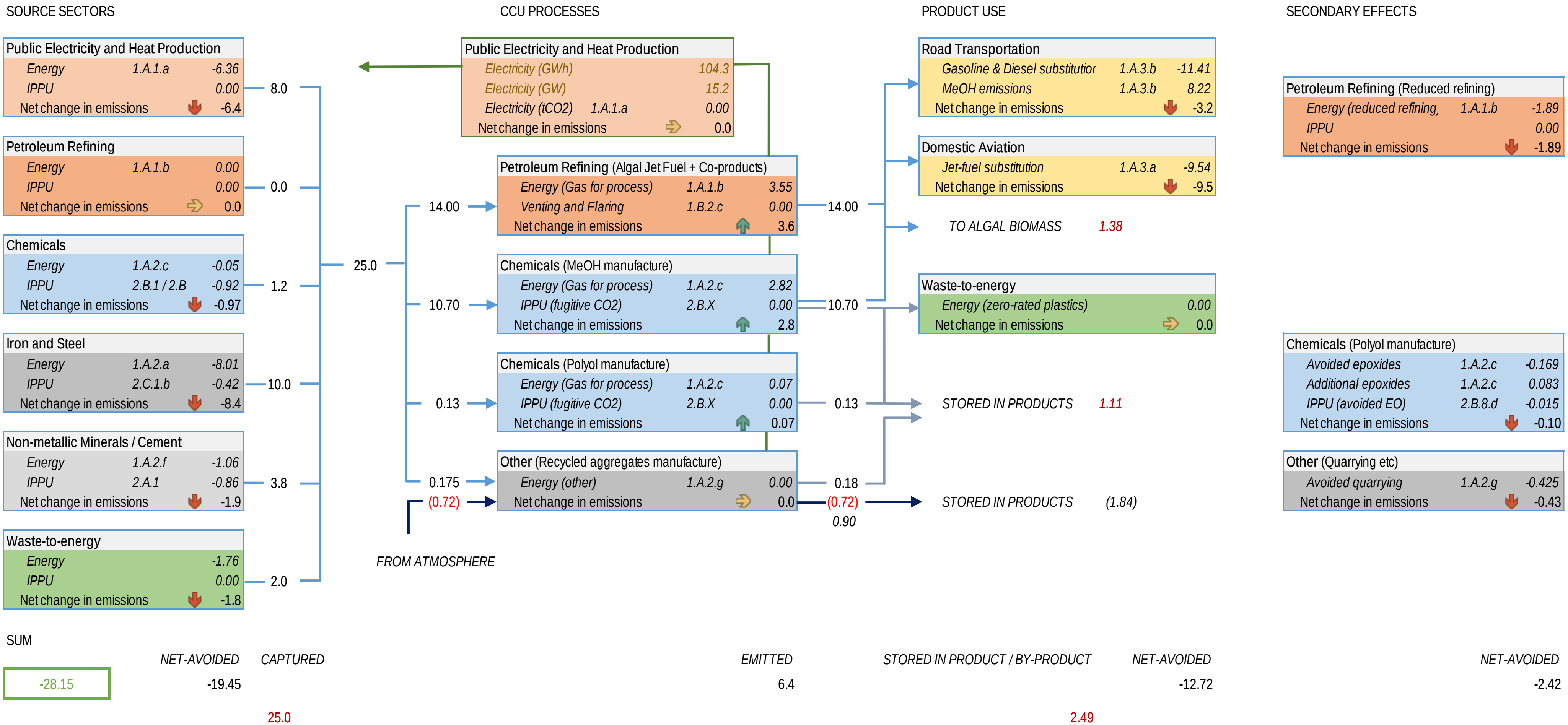
SUM

SUM	*NET-AVOIDED*	*CAPTURED*	*EMITTED*	*STORED IN PRODUCT / BY-PRODUCT*	*NET-AVOIDED*	*NET-AVOIDED*
1.78	5.55	25.0	17.1	2.09	-18.94	-1.91

Accounting mode	Upstream
Electricity source	Zero emissions
Capture sources	Scenario 2050 (25 Mt)
Utilisation pathways	Scenario 2050 (25 Mt)
Modelled CO2 utilisation rate (Mt)	25
CO2 use efficiency (vs. BL)	100%
Process energy efficiency (vs. BL)	50%
H2 electrolyser efficiency (vs. BL)	20%

CCU product output	*tonnes/yr*	*% of current annual domestic demand*
Methanol	7,780,050	432%
Polyols	625,000	111%
Jet fuel (domestic)	3,099,548	92%
Gasoline	624,979	1.68%
Diesel	335,296	0.98%
Aggregates	5,384,615	2.89%

Hydrogen demand
2,392 kt/yr



Accounting mode	Downstream
Electricity source	Zero emissions
Capture sources	Scenario 2050 (25 Mt)
Utilisation pathways	Scenario 2050 (25 Mt)
Modelled CO2 utilisation rate (Mt)	25
CO2 use efficiency (vs. BL)	100%
Process energy efficiency (vs. BL)	50%
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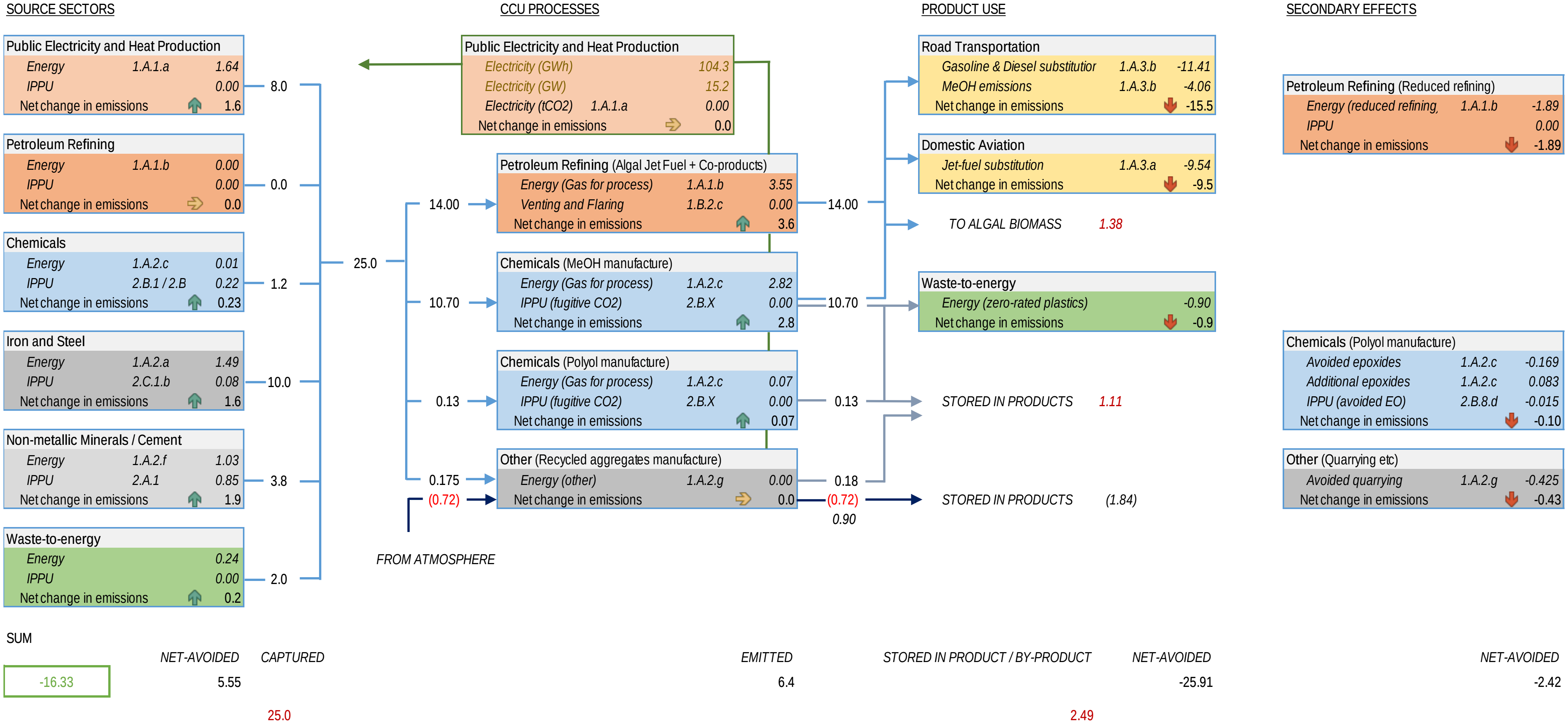

Evaluating technology options to mitigate greenhouse gas emissions

IEA Greenhouse Gas R&D Programme

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