Annexures

Annexure 1. Changes to stock GCAM 6.0 in this study

GCAM 6.0 is the newest version of the open-source model GCAM released on 7 June 2022 and includes several improvements compared to previous versions, particularly a disaggregated industry sector and updated assumptions on the production, transportation and end-use of hydrogen (GCAM 2023b). For a succinct explanation of the general modelling capabilities and features of GCAM, see (GCAM 2023a).

Several changes to model parameters and assumptions have been performed on the stock, i.e., a fresh downloadable version of GCAM 6. These changes are mentioned in Table A1. Most of these changes are similar or in line with the model GCAM-CEEW, an updated and modified in-house model for India based on GCAM 5.2. The latter has been used in numerous published reports (Chaturvedi and Malyan 2022; Chaturvedi, Nagarkoti, and Ramakrishnan 2018; Chaturvedi, Koti, and Chordia 2021), including exploring India's net-zero pathways (Chaturvedi and Malyan 2022). Note that the model used in the current study does not include a detailed (India-specific) disaggregation of the buildings and transport sectors, as done in GCAM-CEEW, as these changes are still in progress. The main assumptions of GCAM-CEEW include - the complete phasing out of refined liquids in agricultural energy use by 2050, the complete phase of traditional biomass in cooking by 2030, and non-economic barriers to EV penetration, like charging infrastructure, in passenger transport, which are completely overcome by 2050. For a detailed rationale of the model assumptions and parameters of GCAM-CEEW, see the supplementary information (Chaturvedi and Malyan, 2022).

Table A1. Overview of changes made in the current model compared to a stock GCAM v6.0.

	Sector	Change: Parameters/Assumptions	Rationale
1.	Socioeconomics	• Population • Labour force, Labour productivity	Same as GCAM-CEEW
2.	Electricity	• Capital costs • OM fixed & variable costs • Shareweight assumptions • Others (e.g. backup costs, wind subResource, Low hydrogen capital costs)	Same as GCAM-CEEW
3.	Industry	• Fuel costs to Industry • Shareweight assumptions	Same as GCAM-CEEW

		• Income elasticities for the different industrial sectors.	Same as GCAM-CEEW
4.	Building	• Floor space assumptions • Shareweight assumptions	Same as GCAM-CEEW
		• Degree days	Incorporated population-weighted degree days using population dataset from Wang, Meng, and Ying Long 2022
5.	Transport	• Shareweight assumptions	Same as GCAM-CEEW

Source: Authors' compilation

GDP growth rate assumption

Table A2. Growth rate assumptions were used in the study.

	2020-2025	2025-2030	2030-2035	2035-2040	2040-2045	2045-2050	2050-2070
Nominal GDP growth rate (%)	7.5%	6.8%	6.1%	5.5%	5.0%	4.5%	3.5%

Source: Authors' compilation

A1.1. Energy efficiency improvements

The following are the energy efficiency improvements assumed for the various industrial sectors in the current study.

Table A2. Table showing the exogenous energy efficiency improvements in various industry sectors in GCAM

Sector	Improvement
Iron and Steel	Average CAGR of **0.58%** from 2010 to 2050
Cement	Average CAGR of **0.5%** from 2010 to 2050
Aluminium	Average CAGR of **0.5%** from 2010 to 2050

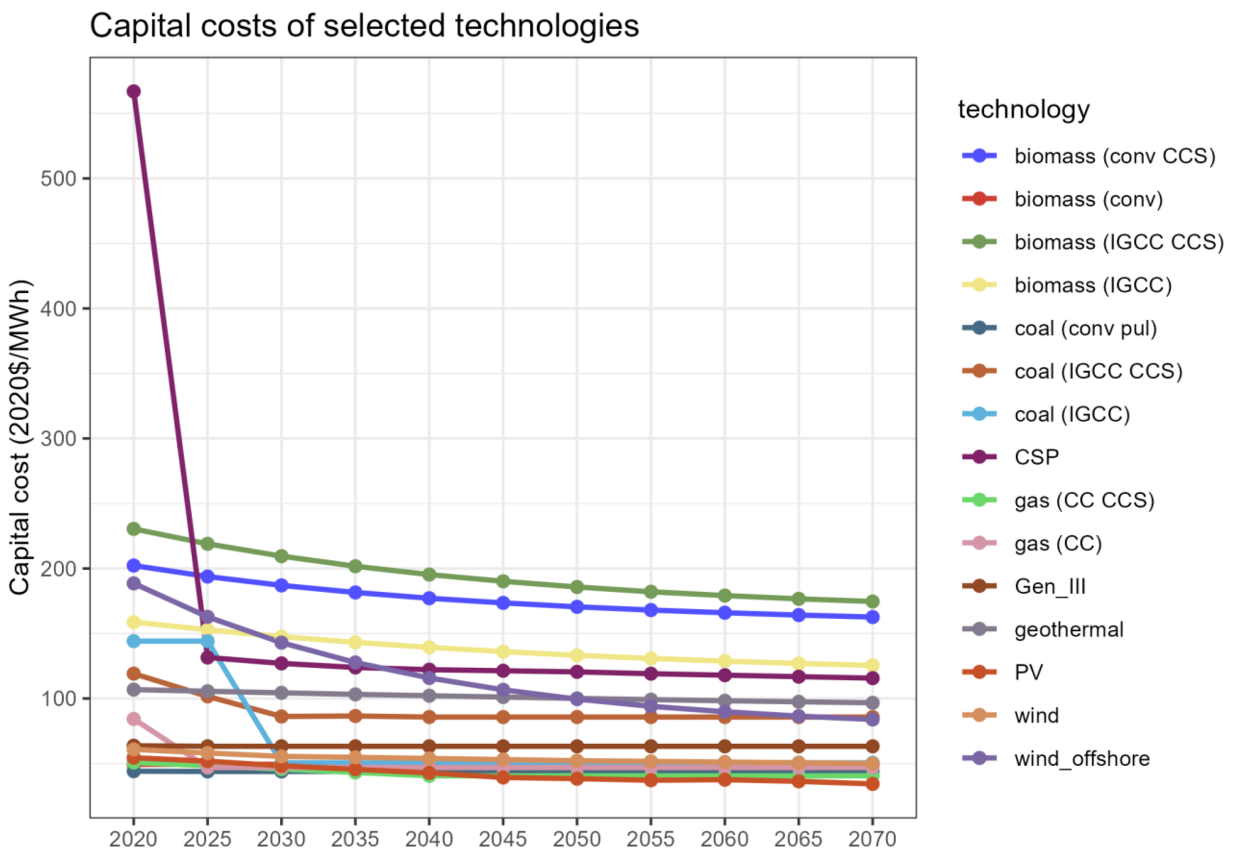
Fertiliser	Average CAGR of **0.5%** from 2010 to 2050
Others (agriculture energy use, mining energy use, construction energy use)	Average **0.09%** CAGR from 2020 to 2050

Source: Authors' compilation

A1.2 Techno-economic assumptions

Electricity System

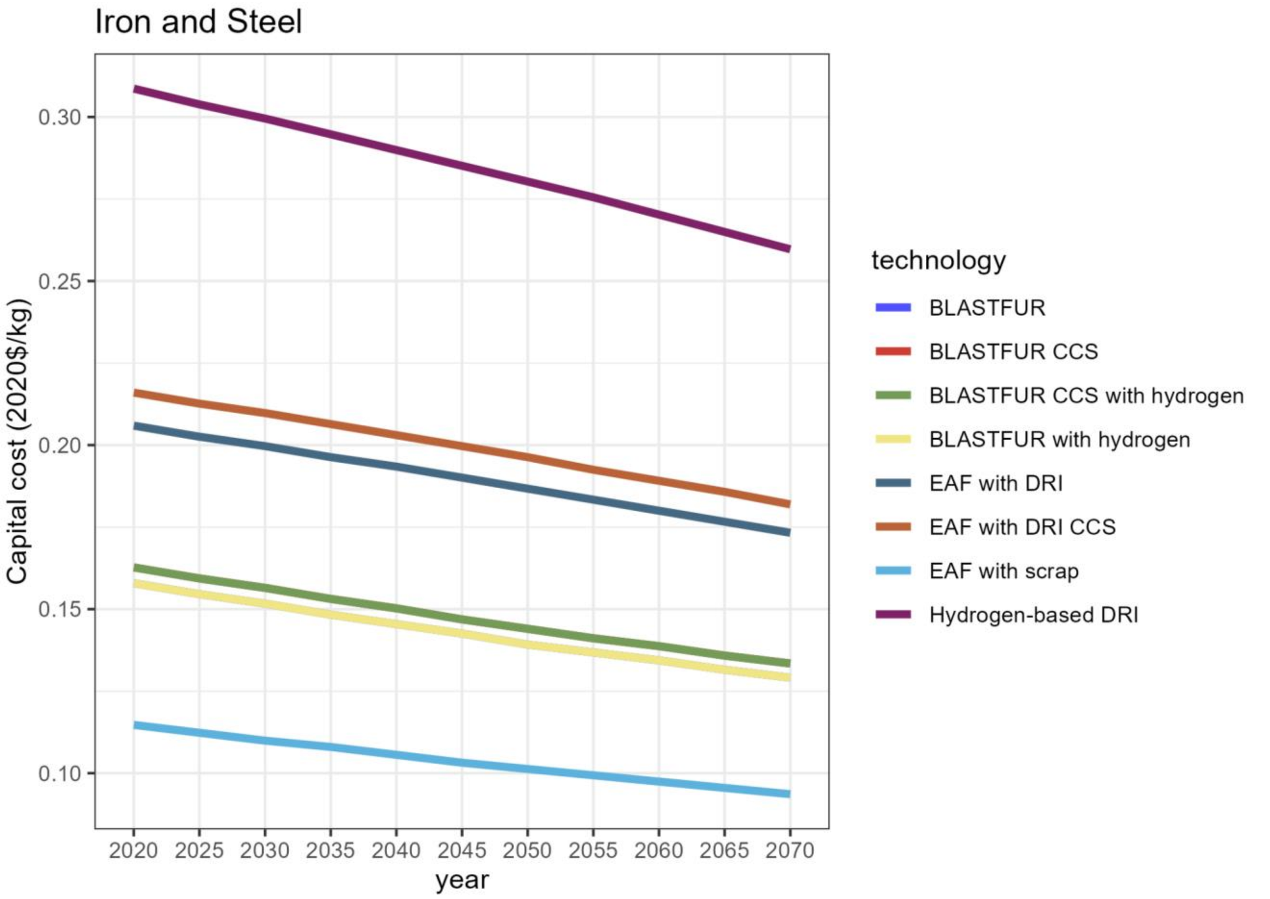
Figure A1: Capital cost (overnight capital cost) assumptions for different technologies in the electricity system used in this study.



Source: Authors' analysis

Iron and Steel sector

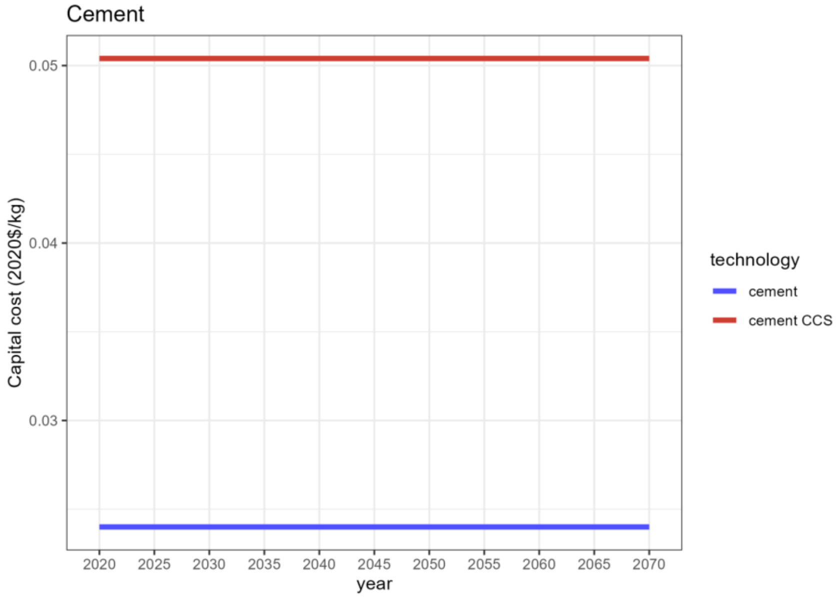
Figure A2: Capital cost (overnight capital cost) assumptions for different technologies in the iron and steel sector used in this study.



Source: Authors' analysis

Cement sector

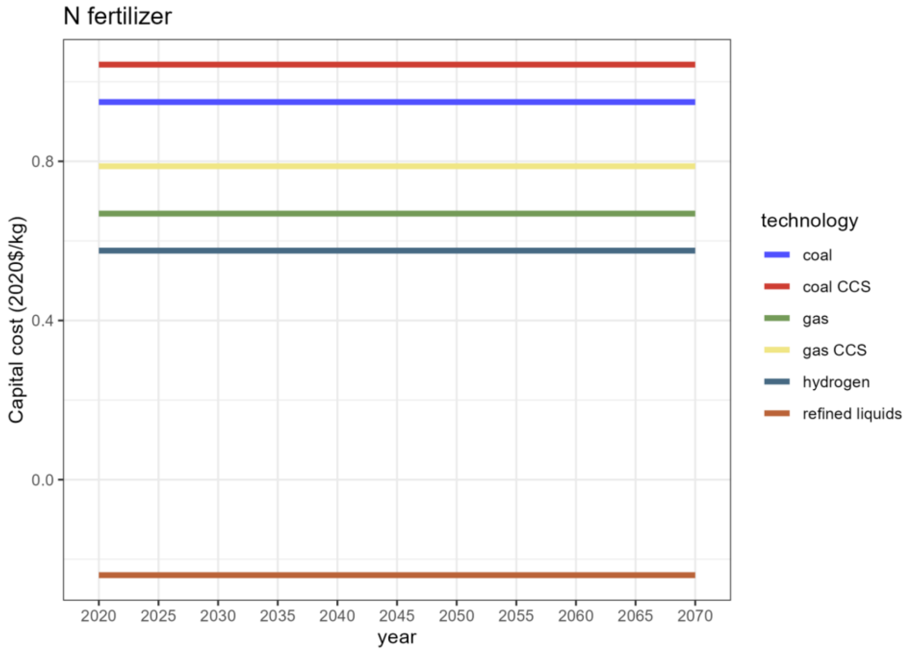
Figure A3: Capital cost (overnight capital cost) assumptions for the cement sector used in this study.



Source: Authors' compilation

Fertilizer sector

Figure A4: Capital cost (overnight capital cost) assumptions for different technologies in the fertilizer sector used in this study.



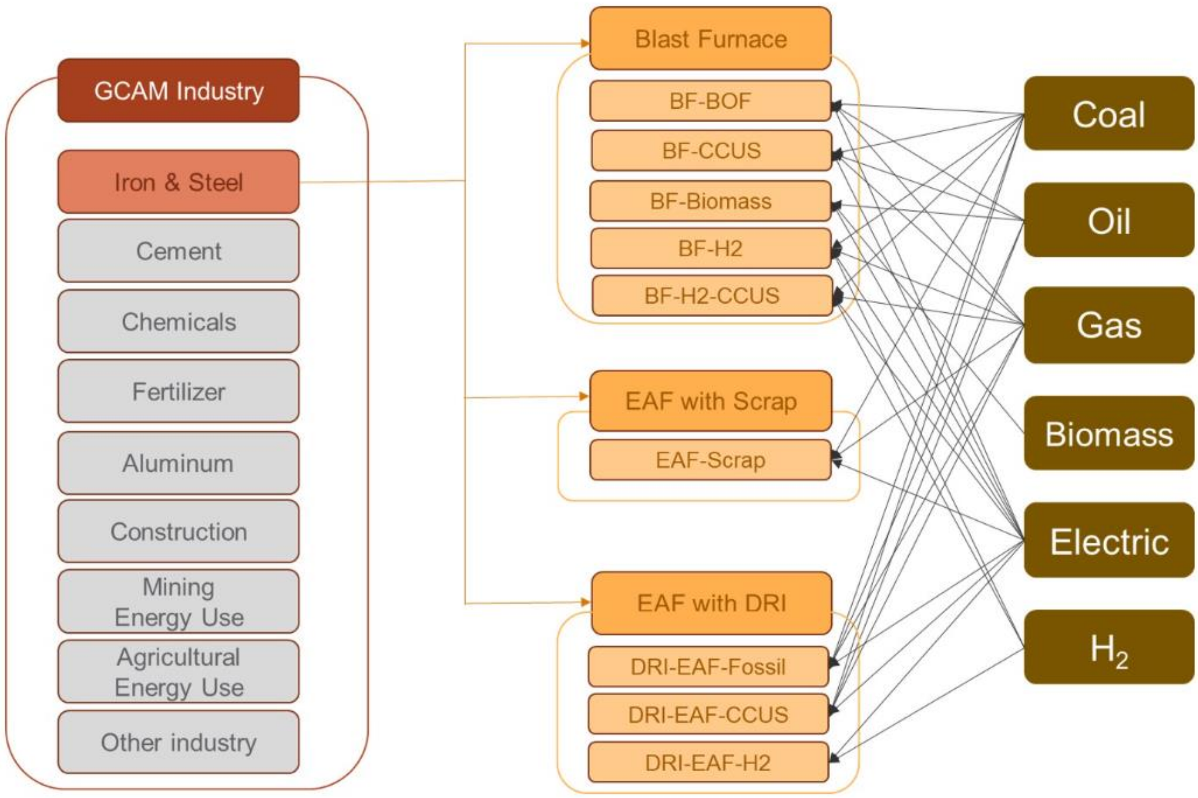
Source: Authors' compilation

Annexure 2. Example of industry sector detail in GCAM 6: Iron and Steel

One of the principal reasons for using GCAM 6 for the current study is the disaggregation of an aggregate industry sector into nine sectors. An example of the detail of the sectors, as provided in the model documentation and reproduced as is, is given below:

In the iron and steel sector, there are three different technologies represented in GCAM: Basic Oxygen Furnace (BOF), Electric Arc Furnace with scrap (EAF), and EAF with Direct Reduced Iron (DRI). Each technology has different fuels, such as coal, oil, gas, hydrogen, biomass and electricity, with and without CCS. The diagram below shows the structure of the iron and steel sector. As we can see, BOF technology can use coal, gas, oil and electricity, all with and without CCUS, whereas the EAF with scrap technology can use coal, gas and electricity.

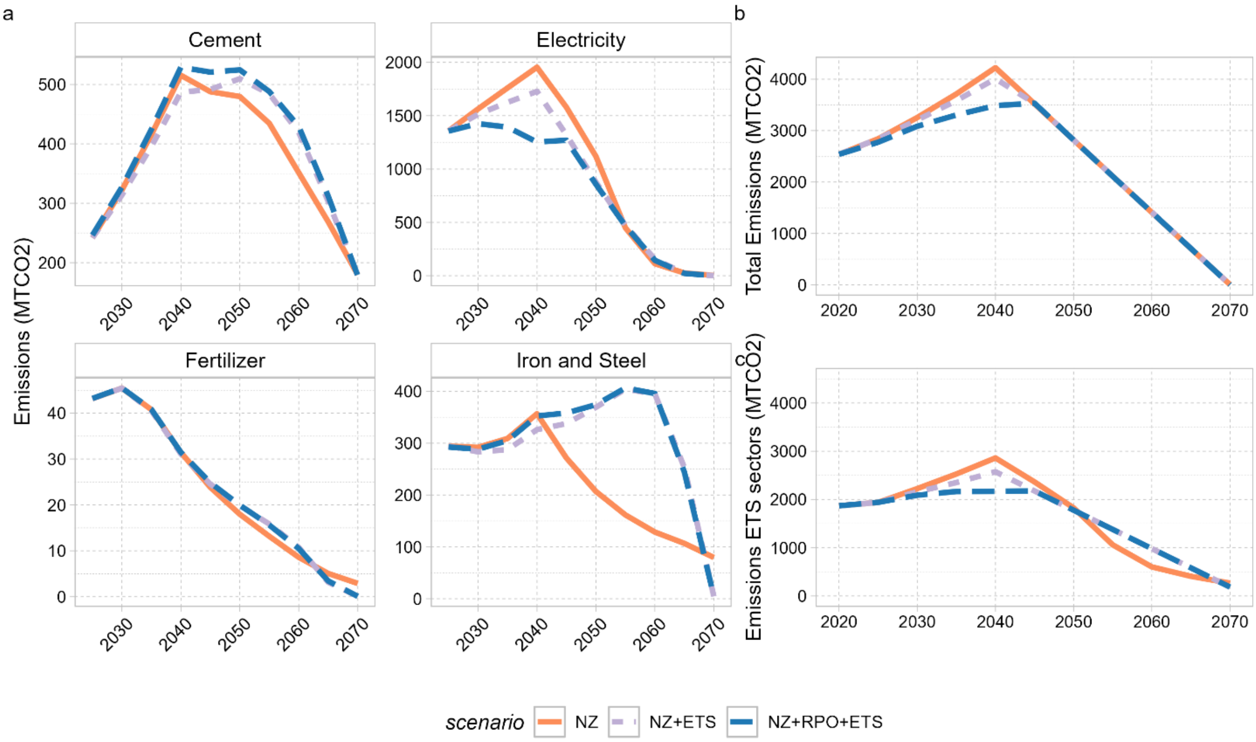
Figure A5. GCAM's representation of the existing technologies and fuels in the Iron and steel sector.



Source: GCAM Documentation 2023

Annexure 3. Sectoral and economy-wide emission trajectories

Figure A6. Emission trajectories for the – a) individual ETS sectors, (b) whole economy, and (c) combined emissions for the four sectors comprising the ETS - electricity, iron and steel, cement, and fertilizer.



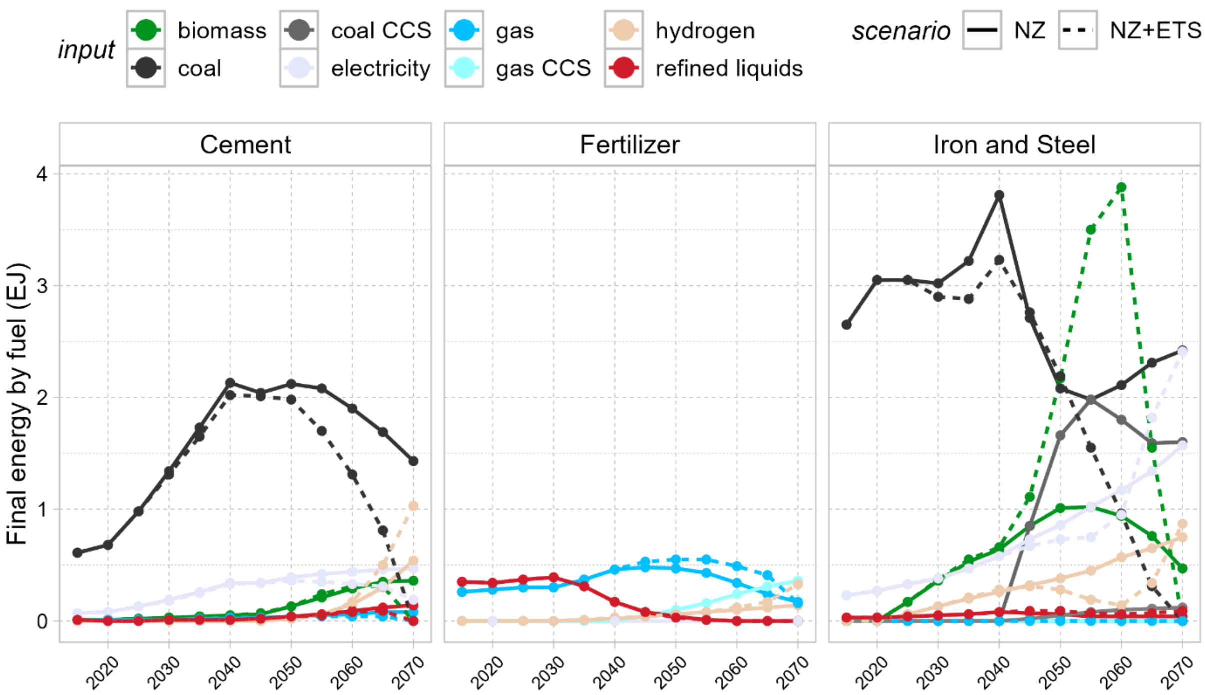
Source: Authors' analysis

We assume the overall emission trajectories across the three scenarios remain unchanged after 2040 (Figure A6, left).

For the four ETS sectors, we assume a 10 per cent decline in overall emissions compared to the baseline in 2040, after which the emissions linearly decrease to around 183 $MtCO_2$ in 2070 (Figure A6, right). We do not assume zero emissions from these four sectors because the cost of reaching net-zero without net-negative emissions from the AFOLU sector results in a fall in overall production from the high carbon price. This is particularly the case for the cement sector, where mitigation options are fewer (for example, for process emissions), and a high carbon price leads to high cement prices, affecting demand for cement. Moreover, since CCS is not assumed to have 100 per cent efficiency, some residual emissions will remain even after abatement at a high cost.

Annexure 4. Final energy by fuel in the industry sector

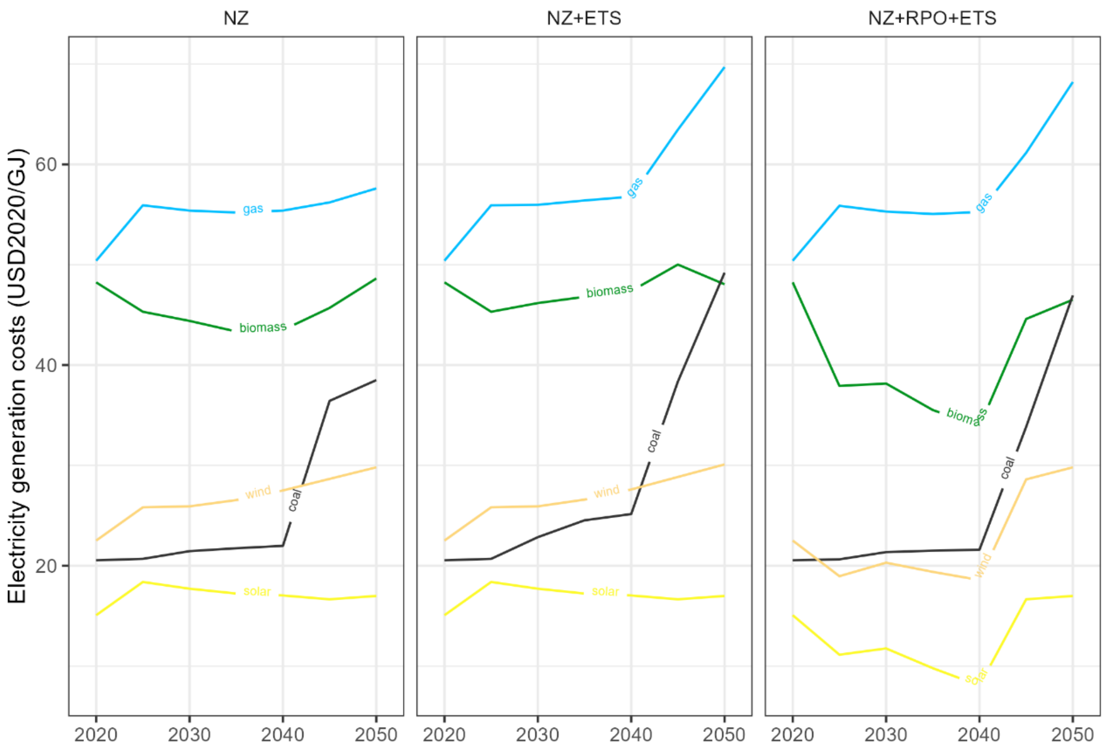
Figure A8. Absolute final energy (in EJ) for the different ETS sectors by fuel.



Source: Authors' analysis

Annexure 5. Aggregate electricity generation costs by technology

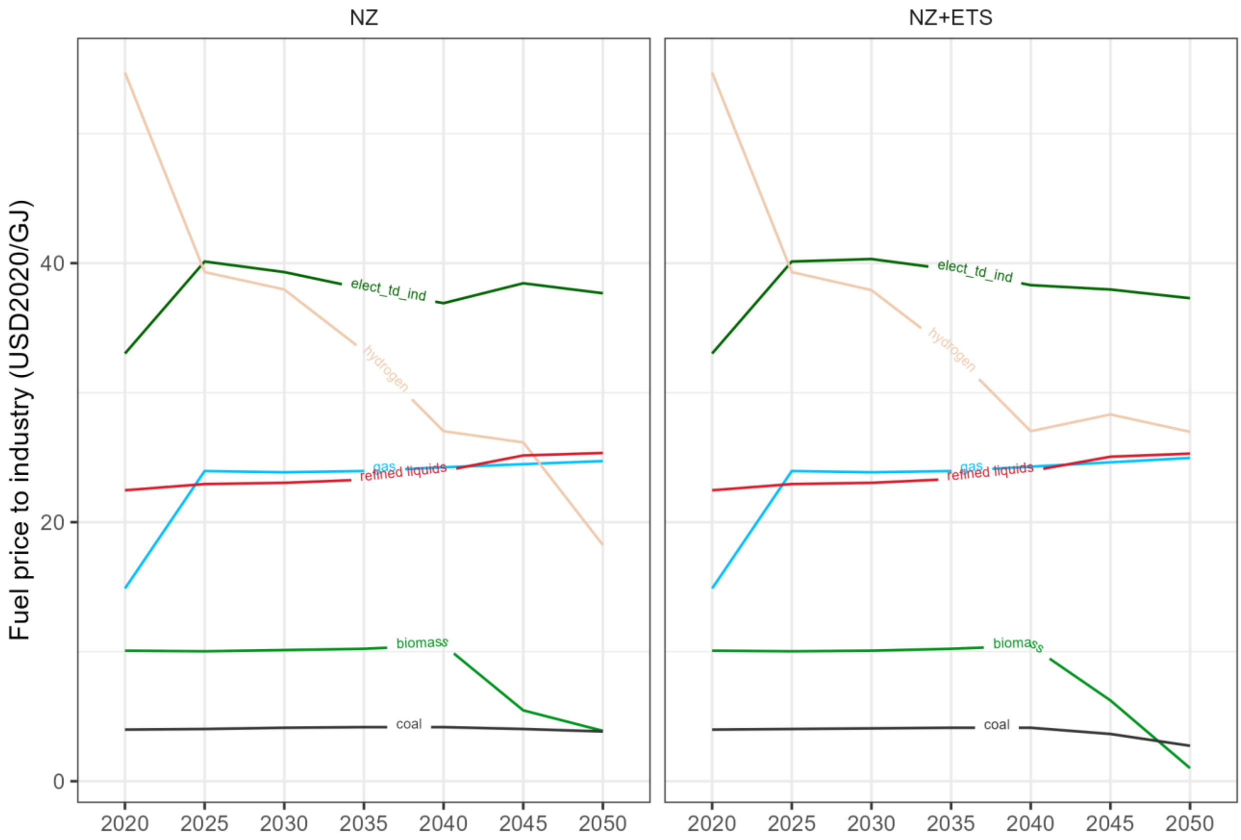
Figure A8. Aggregate power generation cost of technologies across scenarios



Source: Authors' analysis

Annexure 6. Fuel prices to industry

Figure A9. Fuel prices to industry.



Source: Authors' analysis

Annexure 7. Sector-specific emissions cap, percentage reduction with respect to BAU scenario

Table A3: Percentage reductions in the ETS sectors for the NZ + CC scenario and its scenario variants NZ+CC_v1 and NZ+CC_v2. Note that the overall emissions cap remains the same across the scenarios for a particular year.

Percentage reduction relative to BAU or baseline				
		2030	2035	2040
CC	iron and steel	-5%	-7%	-10%
CC	cement	-5%	-7%	-10%

CC	N fertilizer	-5%	-7%	-10%
CC	electricity	-5%	-7%	-10%
CC_v1	iron and steel	-1%	-5%	-6%
CC_v1	cement	-1%	-5%	-6%
CC_v1	N fertilizer	-4%	-8%	-12%
CC_v1	electricity	-4%	-8%	-12%
CC_v2	iron and steel	-5%	-17%	-20%
CC_v2	cement	-11%	-16%	-20%
CC_v2	N fertilizer	-1%	-3%	-5%
CC_v2	electricity	-1%	-3%	-6%

Source: Authors' compilation

Annexure 8. Financial transfers across scenarios

Table A4: Financial transfers across sectors in different scenario variants. A negative value denotes the sector buying permits to fulfil its emission obligation. Positive denotes that the sector sells, as it has overachieved its emission obligation.

Sector	**Year**	**CC (million USD)**	**CC_v1 (million USD)**	**CC_v2 (million USD)**
Iron and Steel	2030	-0.5	31.8	-32.9
Cement	2030	-7.6	28.1	-150.2
Fertilizer	2030	-7.4	-9.9	-2.4
Electricity	2030	15.2	-54	188.2
Iron and Steel	2035	-1.3	67.5	-345.4
Cement	2035	-100.8	-8.3	-517.3

Fertilizer	2035	-29.6	-34.1	-11.4
Electricity	2035	132.8	-63.2	916.7
Iron and Steel	2040	-66	128.2	-542.1
Cement	2040	-297.5	-16.9	-985.6
Fertilizer	2040	-36.4	-44.5	-16
Electricity	2040	398.2	-108.3	1537.9
Iron and Steel	2045	-4884.1	-4019.6	-7018.8
Cement	2045	-5179.8	-3924.3	-8258.9
Fertilizer	2045	-64.2	-96.5	31.3
Electricity	2045	7323.2	5052.2	10563.7
Iron and Steel	2050	-18885	-17682.9	-21884.2
Cement	2050	-16970.5	-15211.8	-21283.6
Fertilizer	2050	-119	-155.2	23.8
Electricity	2050	26941.3	23769.1	31498.5

Source: Authors' compilation

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