Core Model Proposal #: 374
Global Iron and Steel Trade

Product: Global Change Analysis Model (GCAM)

Institution: Joint Global Change Research Institute (JGCRI)

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Related sector: energy

Type of development: code, data, queries

Purpose: This core model proposal (CMP) enables GCAM to track the gross trade of regional iron and steel commodities. Following the logit-based Armington trade modeling framework, this CMP aims to improve the representation of physical output (Mt) flows in GCAM v6.0's iron and steel sector. In addition, the core model proposal also updates the regional steel demand and improves the representation of iron and steel technologies (and their energy coefficients) across all GCAM regions.

Description of Changes

Overview

This core model proposal updates the representation of physical material flows in GCAM's iron and steel sector and enables GCAM to track gross trade (imports and exports) of steel. While GCAM 6.0 exclusively tracks the temporal evolution of steel production by region, the *Global Iron and Steel Trade* CMP separately accounts for both regional steel production and consumption, as well as tracks the regional steel imports and exports, along with their evolution over time. In addition, the core model proposal also updates the regional steel demand and improves the representation of iron and steel technologies (and their energy coefficients) across GCAM regions.

1. Motivation

The iron and steel sector is one of the most-energy and carbon intensive industries in the world, with globally integrated commodity markets. Iron and steel commodities are vital for the economic growth of the global economies, and find important applications across end-use markets such as building and infrastructure, transportation, energy, tools and machinery and others. Globally the sector consumes 17% of industrial final energy and contributes to 8% of economy-wide GHG emissions. The iron and steel commodity markets are globally integrated, with 30% of the steel produced being traded across countries in 2015. Understanding the physical flows of iron and steel has become increasingly important in the recent decades, primarily due to the transfer of embodied carbon emissions via trade. This core model proposal will enable researchers to use GCAM for understanding the steel trade patterns across regions, along with the associated embodied carbon emissions and carbon leakages.

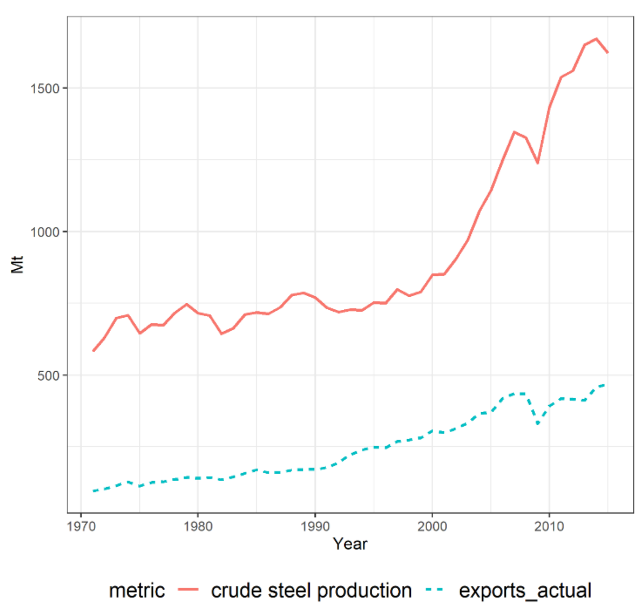


Figure 1: Global iron and steel imports and exports

Figure 2: Iron and steel trade flow (2015)

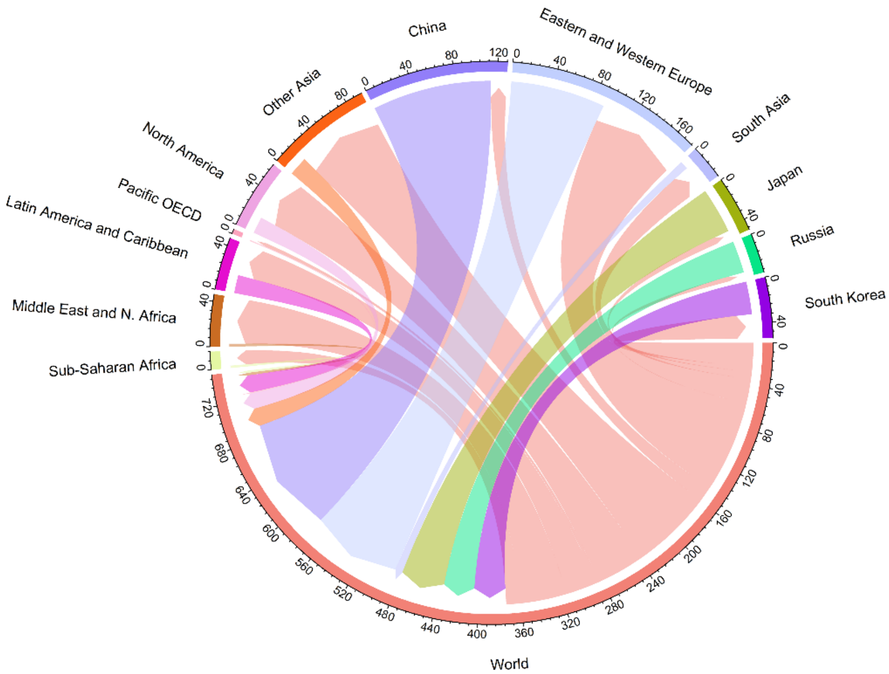
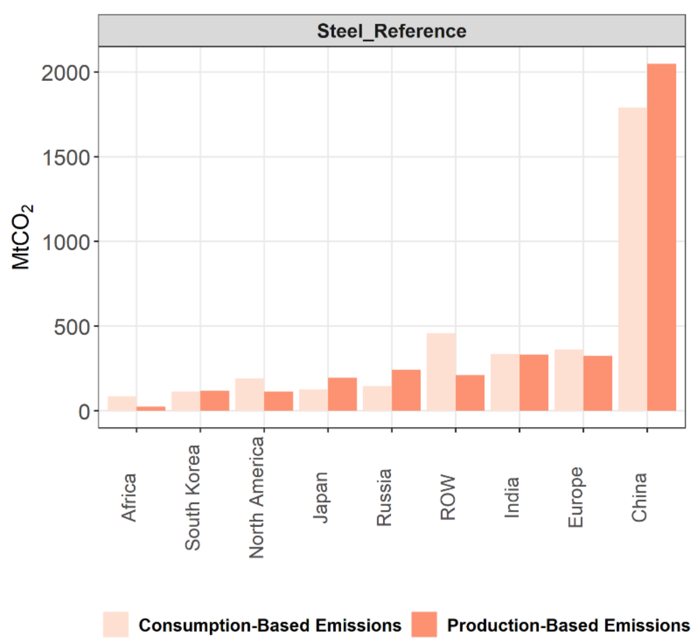


Figure 3: 2015 iron and steel CO_2 emissions for key regions



The figure above illustrates the iron and steel trade flow in 2015, along with the associated regional production and consumption-based emissions. In 2015, major net exporters of steel were China, Japan and South Korea; whereas US, EU, and Southeast Asia (included in ROW) were major net importers. This leads to net exporting regions having higher production-based emissions than consumption-based emissions (see China), and major net importing regions having higher consumption-based emissions than production-based emissions (see ROW, Europe, and North America). The discrepancy in production and consumption based-emissions lead to carbon leakages and have key climate policy implications.

2. Iron and Steel Trade Structure

Logit-based Armington trade structure is used to model steel trade. This trade structure is similar to that of the existing agricultural and fossil fuel trade in GCAM. This approach is used as it enables us to model gross trade (Mt) at the regional level. On the supply side, each GCAM region competes with each other to export steel to a global pool. This competition is driven by historical preference (captured by share weights) and regional production cost (section 3). On the demand side, each region consumes steel from a mix of domestic supply and the steel imported from the global pool. The current modeling effort captures regional gross trade with the global market. This structure can be further extended to capture bilateral trade in future GCAM modeling efforts if desired.

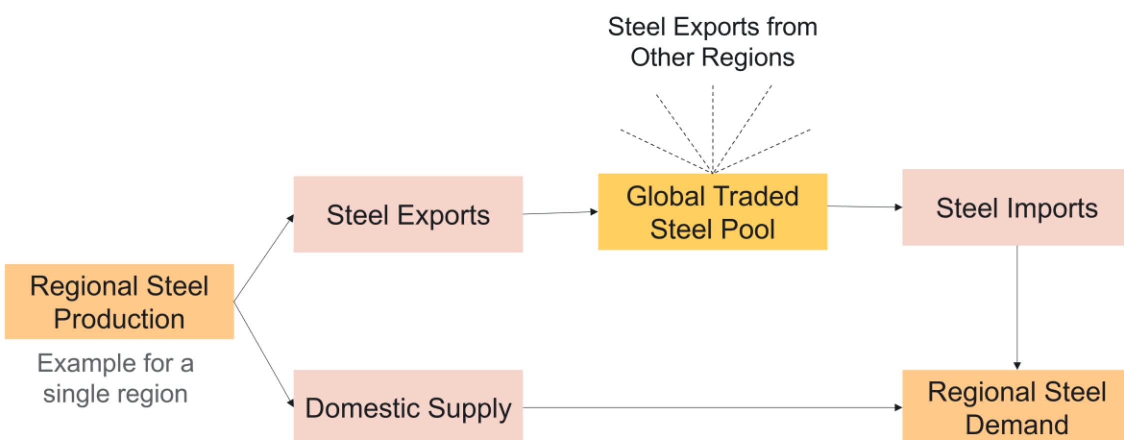


Figure 4: iron and steel trade structure in GCAM

2.1 Share weight, interpolation and logit assumptions

The share-weights calibrated in the base year are held fixed for domestic steel and imported steel through 2100 for most GCAM regions. The domestic iron and steel share weights for some regions (Africa_Northern, Africa_Southern, Africa_Eastern, Africa_Western, Indonesia, South Asia, Southeast Asia) are linearly increased to 1 by 2100, representing a gradual growth in the opportunity to expand domestic iron and steel manufacturing, when there are favorable regional production costs. These regions are assumed to have linearly increasing share weights as they experience a large increase in steel demand in the future (section 4) and currently import most of their steel. The traded iron and steel share weights for these regions also increase (to 1 by 2300 following a s-curve trajectory). This interpolation rule preserves historical trade preferences in the early years and gradually integrates them to the global markets (as their domestic manufacturing expands). The traded iron and steel share weights remain fixed for the remaining GCAM regions capturing historical preferences and existing trade barriers.

Table 1 : Explanation of logit, share weight assumptions and interpolation functions (regional markets)

Supply sector	Subsector	logit.exponent*	interpolation.function
regional iron and steel	domestic iron and steel	-3 (moderate switching behavior is observed between regional domestic supply and imported steel when costs change)	linearly increase to 1 by 2100 (Africa_Northern, Africa_Southern, Africa_Eastern, Africa_Western, South Asia, Southeast Asia, Indonesia) fixed (for all other regions)
	imported iron and steel		fixed
traded iron and steel	traded iron and steel	-6 (the logit exponent produces more aggressive switching behavior in regional trade patterns when costs change)	increase to 1 by 2300 (s-curve) (Africa_Northern, Africa_Southern, Africa_Eastern, Africa_Western, South Asia, Southeast Asia, Indonesia) fixed (for all other regions)

*Armington elasticities are selected from the GTAP Database for the ISIC codes: 241 Manufacture of basic iron and steel and 2431 Casting of iron and steel

3. GCAM implementation

3.1. Historical Calibration

No.	Metrics	Data Sources
1	Crude Steel Production; Apparent Steel Consumption (Crude Steel Equivalent); Exports of Semi-Finished and Finished Steel Products; Imports of Semi-Finished and Finished Steel Products	World Steel Association Statistical Year Books (1980, 1989, 1999, 2009, 2019) (data years: 1970 to 2018)
2	Bilateral Steel Trade (Imports and Exports)	Chatham House Resource Trade Database (2000-2015)
3	Regional Steel Production Costs	Transition Zero Database

The GCAM implementation steps for the historical calibration of the logit-based Armington trade structure are described below. First, we collect the historical steel production, consumption, imports, and exports data from World Steel Association statistical year books. Then, we harmonize the trade data to mathematically fit the trade balance equation and remove the intra-regional trade within GCAM regions. The World Steel Association data and the bilateral steel trade data are country-level data which are later aggregated into GCAM regions. The table below illustrates the data along with their sources.

Data Processing Steps

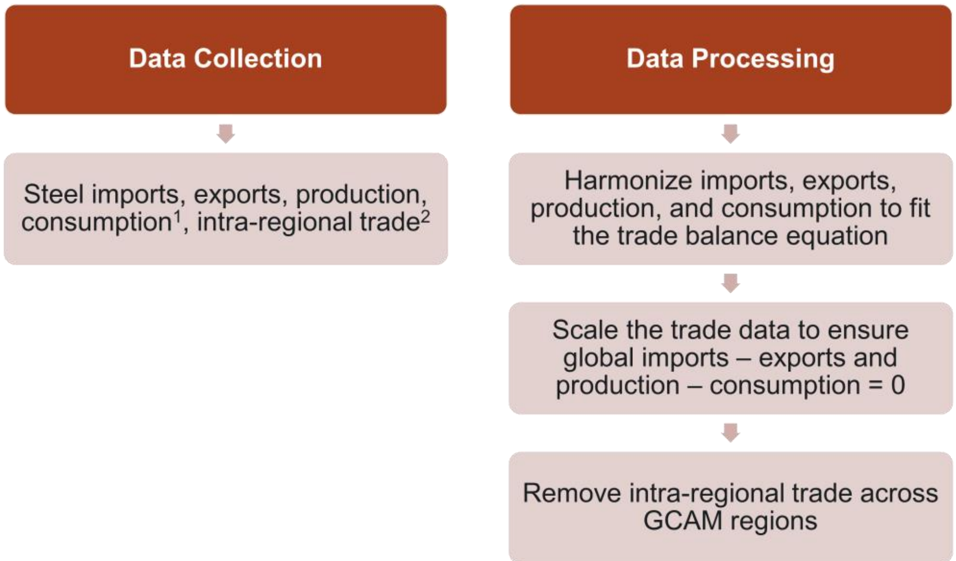


Figure 5: iron and steel trade CMP data processing steps

The figure below illustrates the data processing steps. First, we harmonize the steel production, consumption, imports and exports data to achieve the trade balance. This is required as the data reported by WSA does not always fit the trade balance equation (below) due to data reporting inconsistencies. To achieve trade balance, we adjust the steel imports and exports by a scaling factor (S) to match the reported WSA apparent steel consumption data. We set a tolerance limit (T=10%) for adjusting the scaling factor (S). This means, if the required increase/decrease in scaling factor (S) is 10% greater/lesser than the reported WSA exports/imports value, we re-calculate the apparent steel consumption numbers instead and use the reported WSA imports and exports values for GCAM calibration.

$$\textbf{Apparent Steel Consumption}_{\textbf{crude steel eq.}} = \textbf{Steel Production}_{\textbf{crude steel eq.}} - S * \textbf{Steel Exports}_{\textbf{crude steel eq.}} + S * \textbf{Steel Imports}_{\textbf{crude steel eq.}}$$

Second, we scale the re-calculated steel imports, exports, production, and consumption data such that they match at the global level. This leads to global production minus consumption and global imports minus exports being equal to zero. Finally, we remove the intra-regional trade (trade happening between countries within a GCAM region) from the aggregated WSA exports and imports data. The percentage of intra-regional trade within a GCAM region is estimated using bilateral steel trade data (2000-2015) from the Resource Trade Database (as shown below).

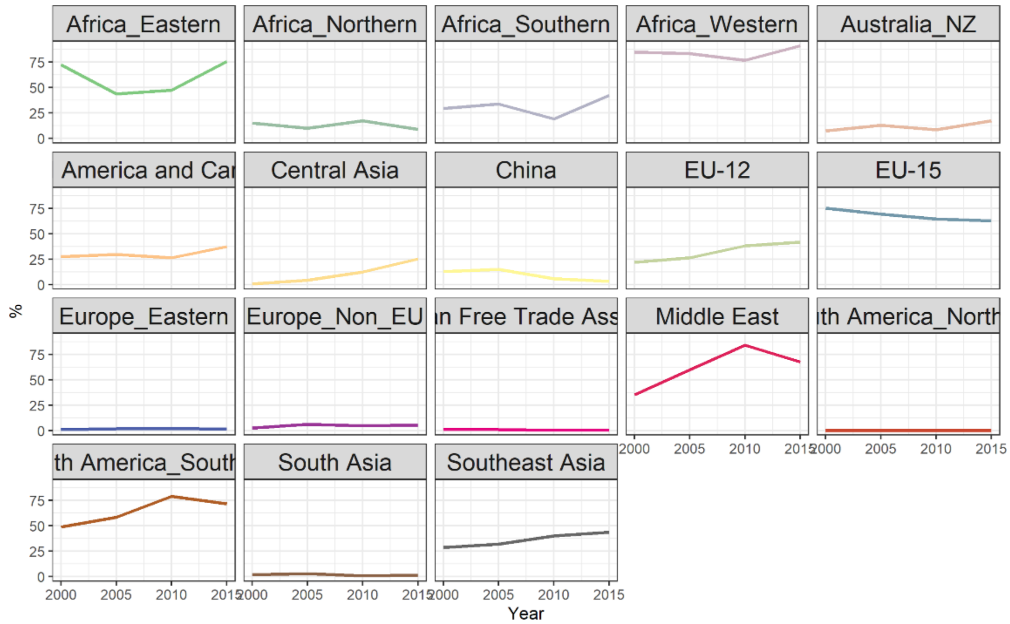


Figure 6: Intra-regional trade (2000-2015)

We also update the historical EAF-DRI based steel production values in this CMP. Country-level DRI (direct reduced iron) production, imports, and exports data are obtained from WSA statistical year books. This data is used to calculate DRI consumption (production - exports + imports). We assume that the DRI consumed by a country translates to the production of steel using EAF-DRI process.

3.2 Future Drivers

3.2.1 Steel Demand Estimation

Steel demand projections across regions are calculated using a non-linear (NLIT) model that is parameterized using historical steel consumption per capita and GDP per capita data (Figure below). This model is currently used in GCAM v6 to calculate future steel production. In this CMP, we re-parameterize the NLIT model parameters and GCAM income elasticities to estimate the future regional steel demand trajectories (instead of future steel production).

3.2.1.1 NLIT model

$$\mathbf{C = a \times e^{\left(\frac{b}{GDP_{pc}}\right)} \times (1 - m)^{(T - T_0)}}$$

The NLIT model (Van Ruijven et al. 2016) relates steel consumption per capita with GDP per capita, year, and several model constants. Here, C = steel consumption per capita, GDP_{pc} = GDP per capita, T = year, and T_0 = 1990 (base-year from which material efficiency improvements are realized). The NLIT model constants are: *a*, *b*, and *m*. The model constant *a* corresponds to the saturation level consumption per capita at high income levels. The model constant *b* corresponds to the GDP per capita at which the curve starts approaching the saturation level, and *m* corresponds to the material efficiency improvement of per capita consumption, which shifts the curve downwards as years proceed.

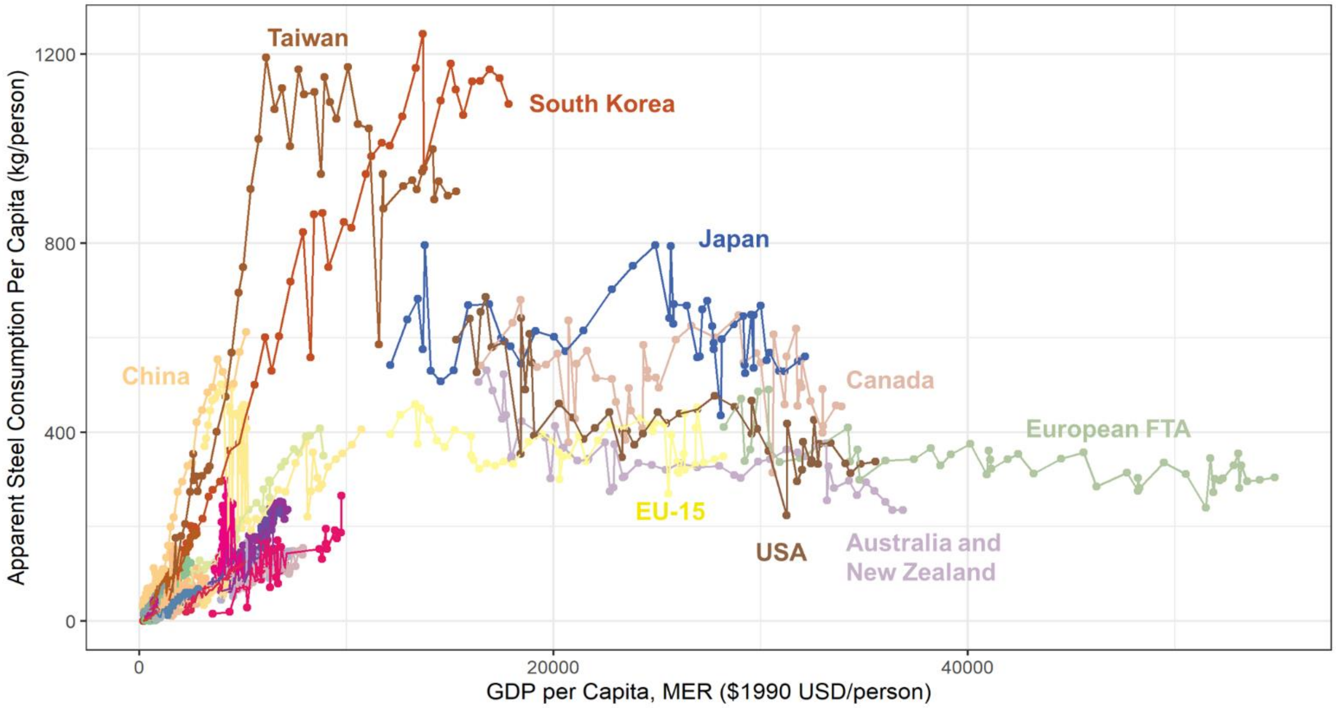


Figure 7: Historical apparatent steel consumption per capita and GDP per capita

In this CMP, we fit the global historical demand data (1990-2018) to the NLIT function to obtain the best-fit model parameters (a, b and m). The constants a, b, and m are parameterized using global regression of historical data for most GCAM regions. For some GCAM regions like China and South Korea, which have unique historical consumption trends, regional model-fitting is performed (and their data are excluded from the global model-fitting). After fitting the constants for all GCAM regions we adjust the values of the constants a and *b* to match with the 2020 historical consumption data. The final regional parameters (*a*, *b*, *m*) used in the NLIT model are tabulated in *A323.inc_elas_parameter.csv*.

3.2.1.2 Fixed Final Demand

Alternatively, If the users wish to manually specify the regional steel consumption trajectories (and bypass the NLIT model) they can use the following example XML to swap the "iron and steel" `energy-final-demand` for the `fixed-final-demand`.

```
<scenario>
   <world>
        <region name="USA">
            <energy-final-demand name="regional iron and steel" delete="1" />
            <fixed-final-demand name="regional iron and steel">
                <service year="1975">3.17207479964381</service>
                <service year="1990">4.04944185218166</service>
                <service year="2005">2.48423106976744</service>
                <service year="2010">1.726</service>
                <service year="2015">1.58964429530201</service>
                <service year="2020">2.0</service>
                <!-- note the C++ will interpolate values -->
                <service year="2100">2.7</service>
            </fixed-final-demand>
        </region>
     </world>
</scenario>
```

3.2.2 Regional Steel Production Cost Estimation

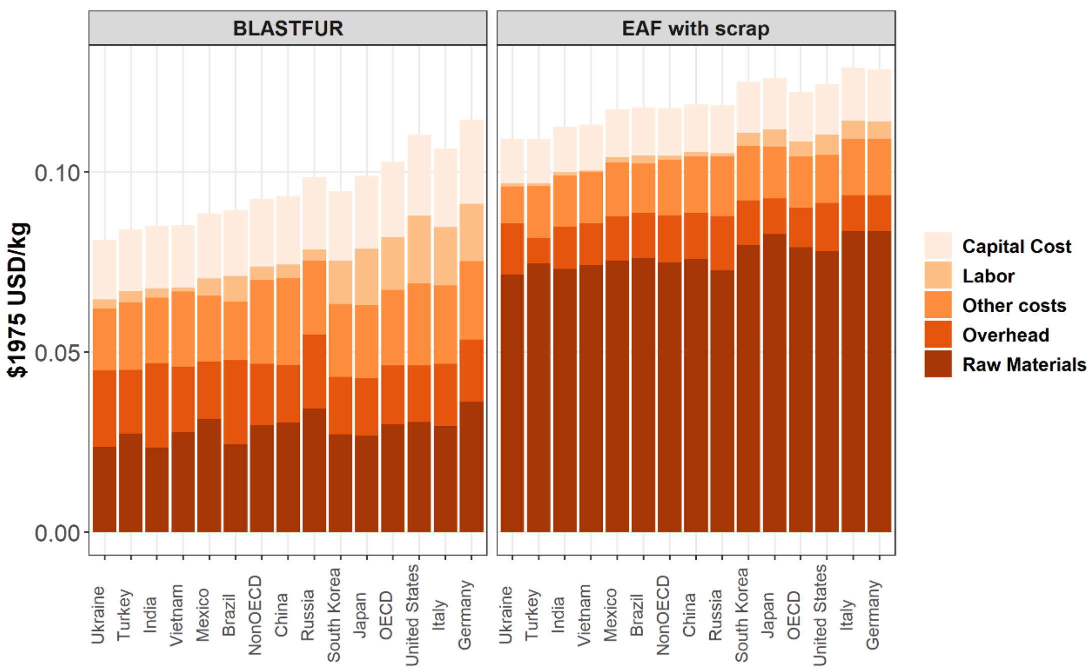


Figure 8: Regional steel production non-energy costs

In GCAM 6.0, global steel production technology costs are used to drive technological competition across all GCAM regions. In this CMP, these steel production technology costs are regionalized. We use the Transition Zero (TZ) Global Cost Tracker Database to estimate the regional non-energy costs. The TZ database provides plant-level production cost data for BLASTFUR and EAF technologies across major steel producing countries. We average these plant-level costs across the countries listed in the database and map them to GCAM regions. We use OECD and non-OCED averages for GCAM regions where direct mapping is not possible. In addition, we assume that the

EAF costs listed in the TZ database are representative of EAF-scrap technology and use global tech costs for EAF-DRI technology.

The TZ database provides a detailed breakdown of energy and non-energy costs (including labor, raw material, overhead, and other costs) associated with steel production. Since the energy costs are calculated endogenously in GCAM, we remove these costs from the database before further processing. As TZ database doesn't provide CAPEX costs, we exogenously add them to the regionalized TZ costs using adders (*A323.capital_cost_adders.csv)*, which are an estimate of the ratio of CAPEX costs to OPEX and raw materials costs from literature (IEA Iron and Steel Technology Roadmap, Vogl et al. 2018). Similarly, we also use CCS cost adders for technologies having CCS (*A323.ccs_adders.csv)*. The estimated non-energy costs are assumed to be constant into the future.

3.2.3 Global Steel Production Cost Update

In addition to regionalizing the costs, we also update the iron and steel global tech costs (although the trade model only uses the global EAF-DRI costs). The total BF-BOF, EAF-DRI, and EAF-scrap non-energy costs in *A323.globaltech_cost.csv* are the sum of the TZ labor costs and the CAPEX, non-labor OPEX, and raw materials costs from the IEA Iron and Steel Technology Roadmap, Figure 1.3. The TZ labor costs for these technologies are assumed to be the median values from the TZ database, with labor costs assumed to be the same for EAF-DRI and EAF-scrap subsectors. In addition, we assume that hydrogen-based EAF-DRI has the same non-energy costs as fossil-based EAF-DRI (in alignment with Vogl et al. 2018). Similarly, we assume that BF-biomass and BF-BOF with hydrogen have the same non-energy costs as standard BF-BOF. Thus, the only adder needed to the non-energy costs for other steelmaking technologies (beyond the conventional BF-BOF, DRI-EAF, and EAF-scrap) is for CCS. We further assume that the CCS non-energy CAPEX and OPEX costs per ton of steel are the same for BF and DRI. We obtain the adder for CCS from the same IEA Iron and Steel Technology Roadmap, Figure 2.11; the adder goes into *A323.ccs_adders.csv*.

3.2.4 Input-Output Coefficients (for regional steel technologies)

In this CMP, we improve the estimation methodology of the input-output coefficients of iron and steel technologies across GCAM regions. In GCAM 6.0 the regional input-output coefficients are calculated using the following methodology:

1. The regional steel energy use (EJ) by fuel is calculated bottom-up by multiplying the global steel intensity (EJ/Mt) values (*steel_intensity.csv*) by the WSA steel production values (Mt).
2. The estimated bottom-up steel energy use by fuel and region is then compared to the steel sector IEA energy balances data to calculate a scaling factor. Here, the scaling factor is equal to IEA energy use by fuel divided by bottom-up energy use by fuel.
3. Finally, the scaling factor is multiplied with the original global steel intensity (EJ/Mt) values to obtain the regionalized steel coefficients by technology and fuel used by GCAM

This methodology, however, did not address several data inconsistencies as listed below:

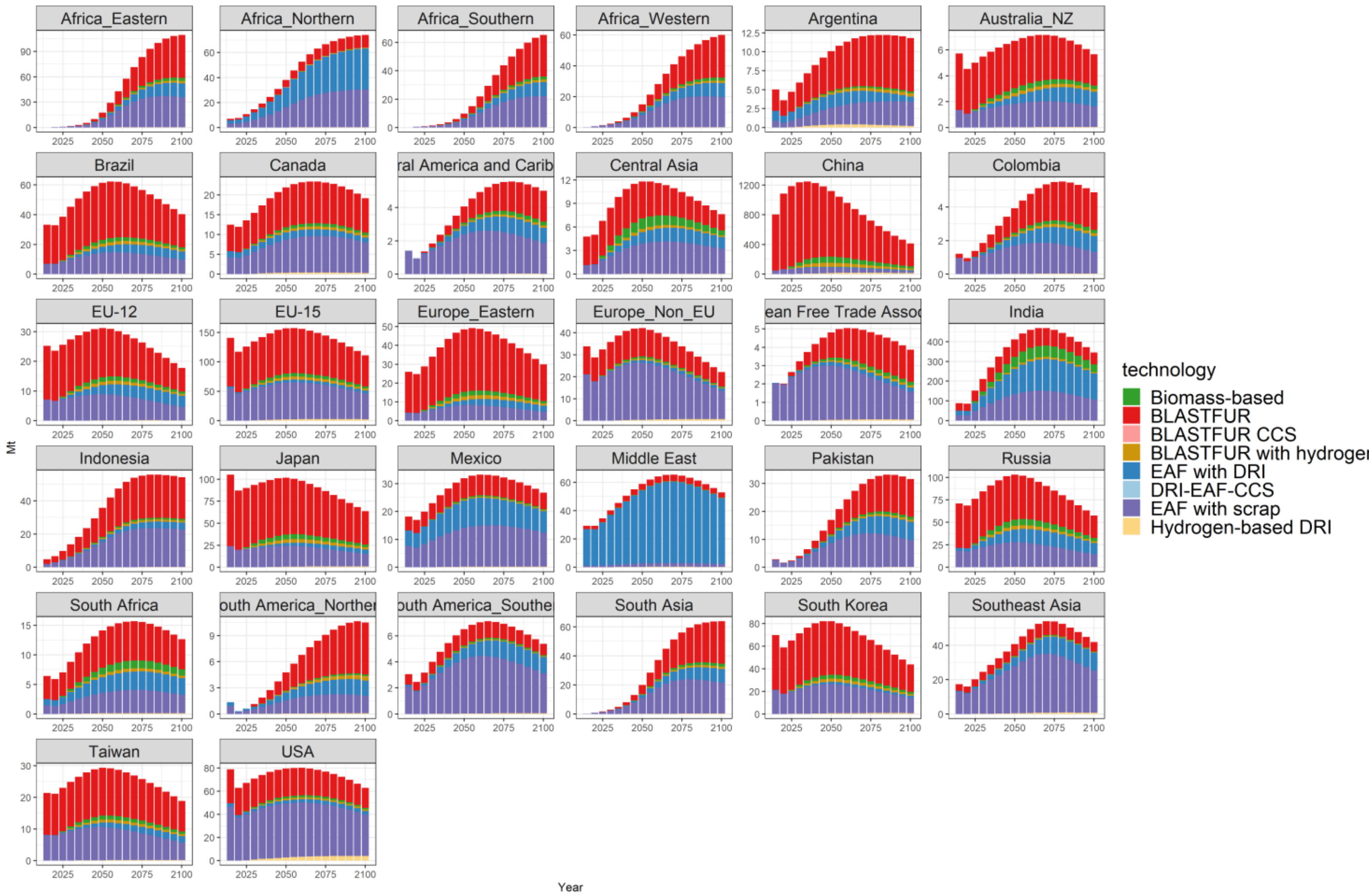
1. Several GCAM regions did not have subsectors/technologies calibrated in the base-year, resulting in zero growth for these technologies in the future years.
2. Several GCAM regions had zero energy use for certain fuels in the base-year (due to incomplete data accounting by IEA energy balances for the steel sector).
3. Several regions had technically infeasible I-O coefficients (which were incredibly high or low).
4. While the I-O coefficients for conventional technologies were regionalized, they weren't regionalized for the new technologies (e.g., BLASTFUR w/ hydrogen). This led to the new technologies outcompeting conventional technologies in some regions due to incredibly low I-O coefficients (which were lower by a factor of 2-10 in certain instances) leading to very low fuel consumption and energy costs.
5. The differences in I-O coefficients across technologies within the same subsector were incorrectly captured (for example, the electricity I-O coefficient for BLASTFUR with CCS should be higher than the conventional BLASTFUR, but in allocated as the same in GCAM 6).

In this CMP, we fix all of the above mentioned data inconsistencies using the following approaches:

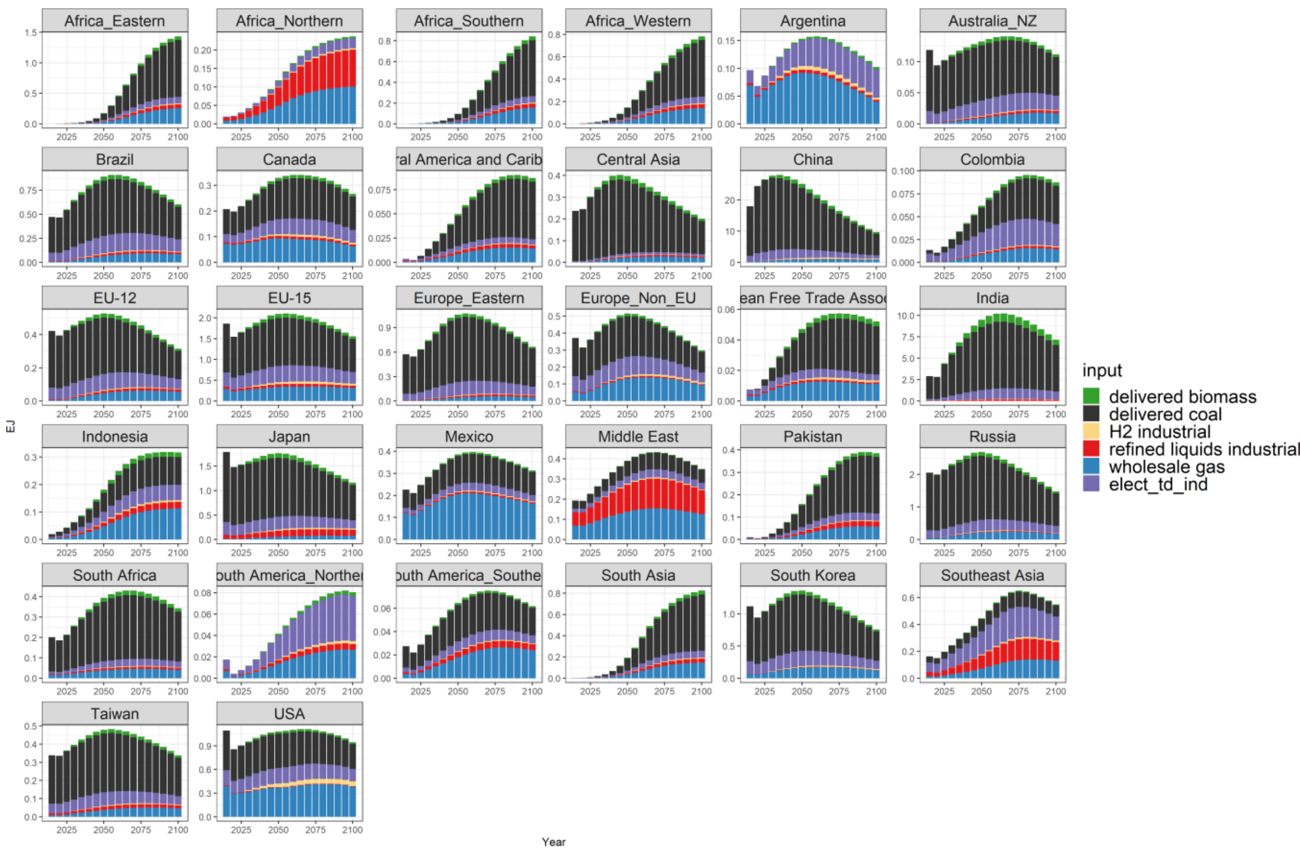
1. We add a minimum calibration value to the conventional subsectors/technologies across all GCAM regions to enable future market participation.
2. We pull energy use data from "other industry" for GCAM regions with zero energy use in the base-year.
3. We set a tolerance limit to the scaling factor. We do not scale the global intensity coefficients if that estimated scaling factor is >= 6 or <= 0.16.
4. We apply the same regionalized scaling factor as the conventional technologies to the new technologies to regionalize their I-O coefficients.
5. We modify the data pipeline to make use of the existing variations in the I-O coefficients across different technologies which were previously ignored.

4. Key Results

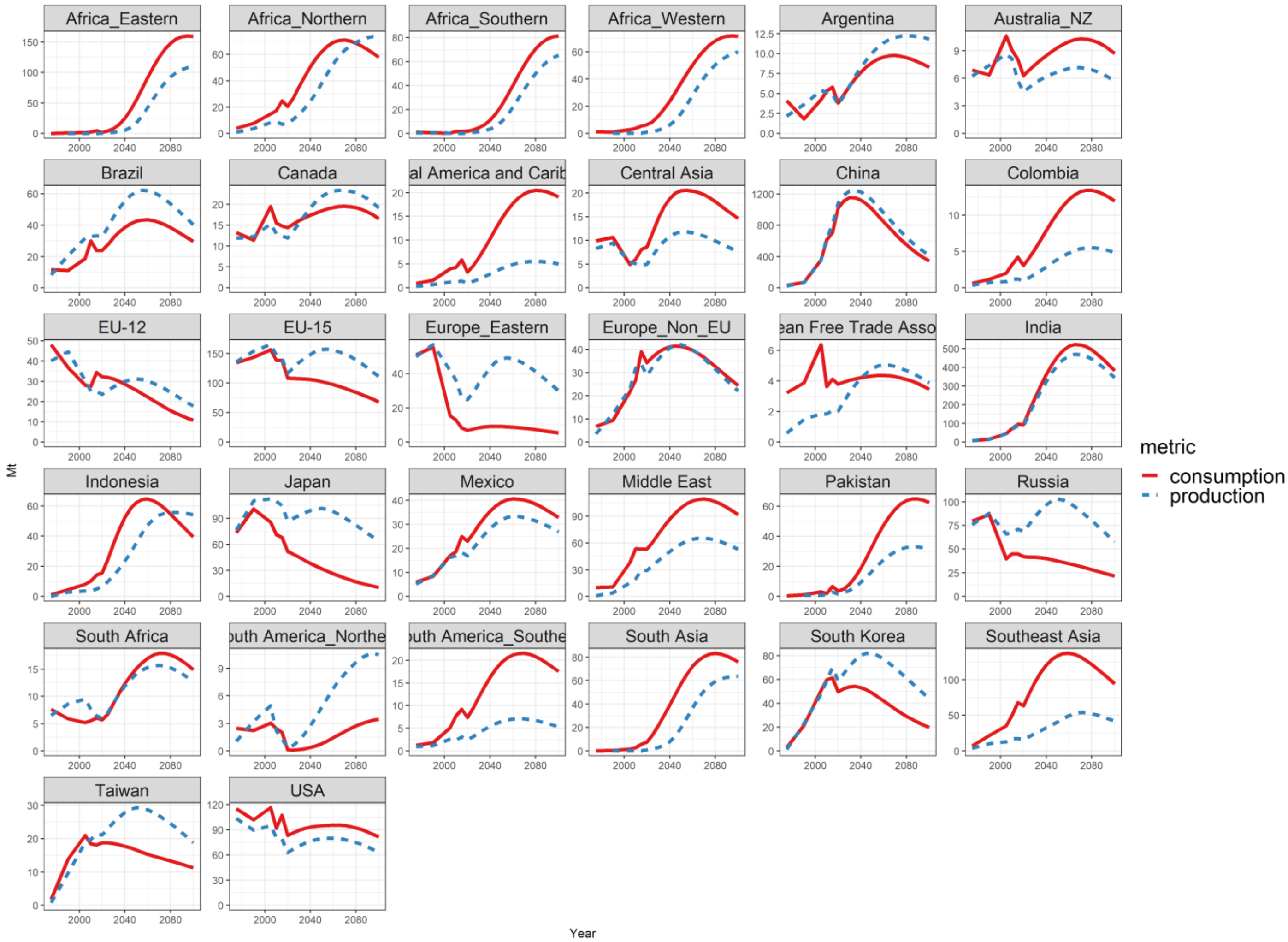
1. Steel Production by Technology



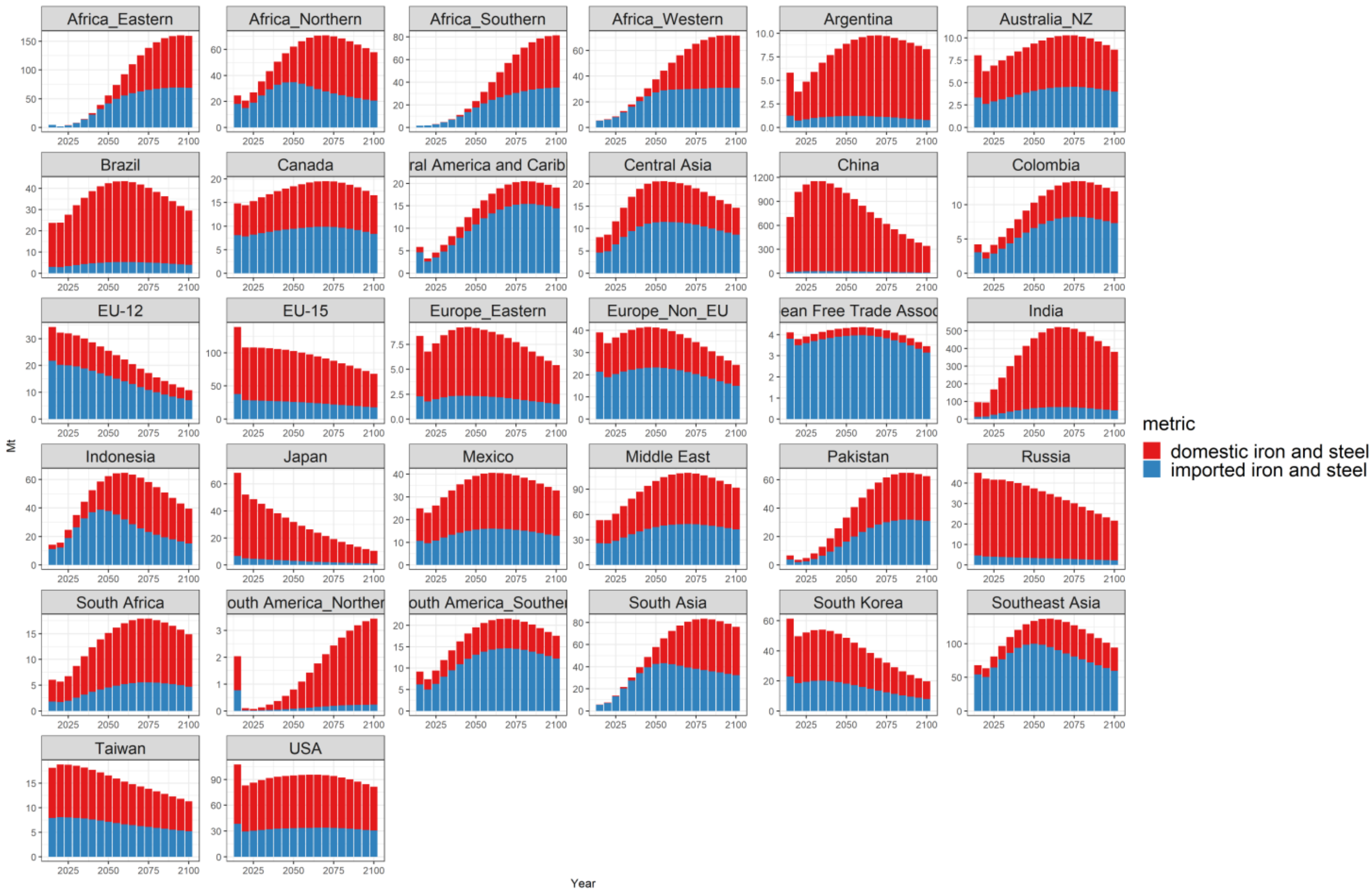
2. Iron and Steel Energy use by Fuel



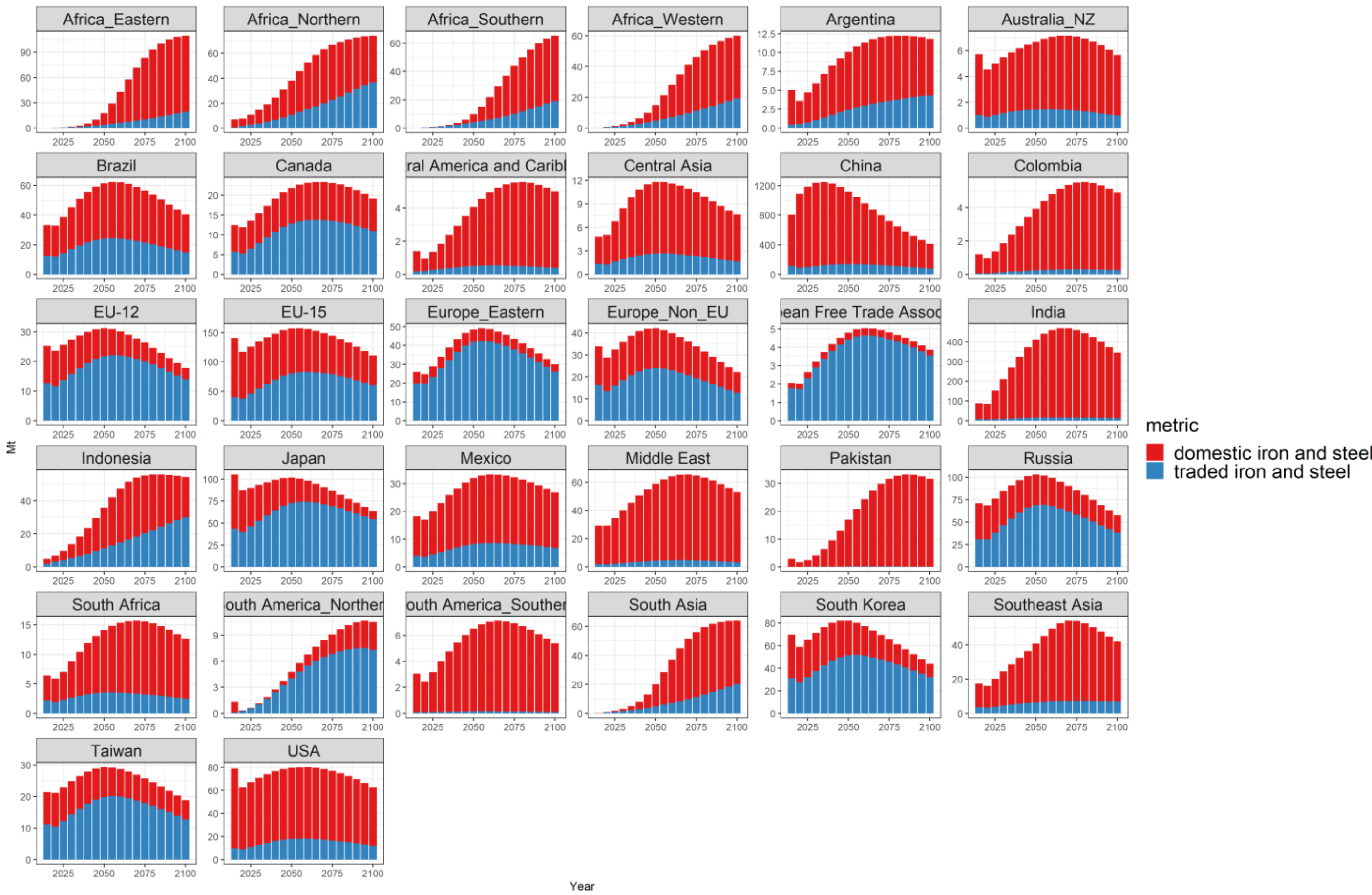
3. Iron and Steel Production and Consumption



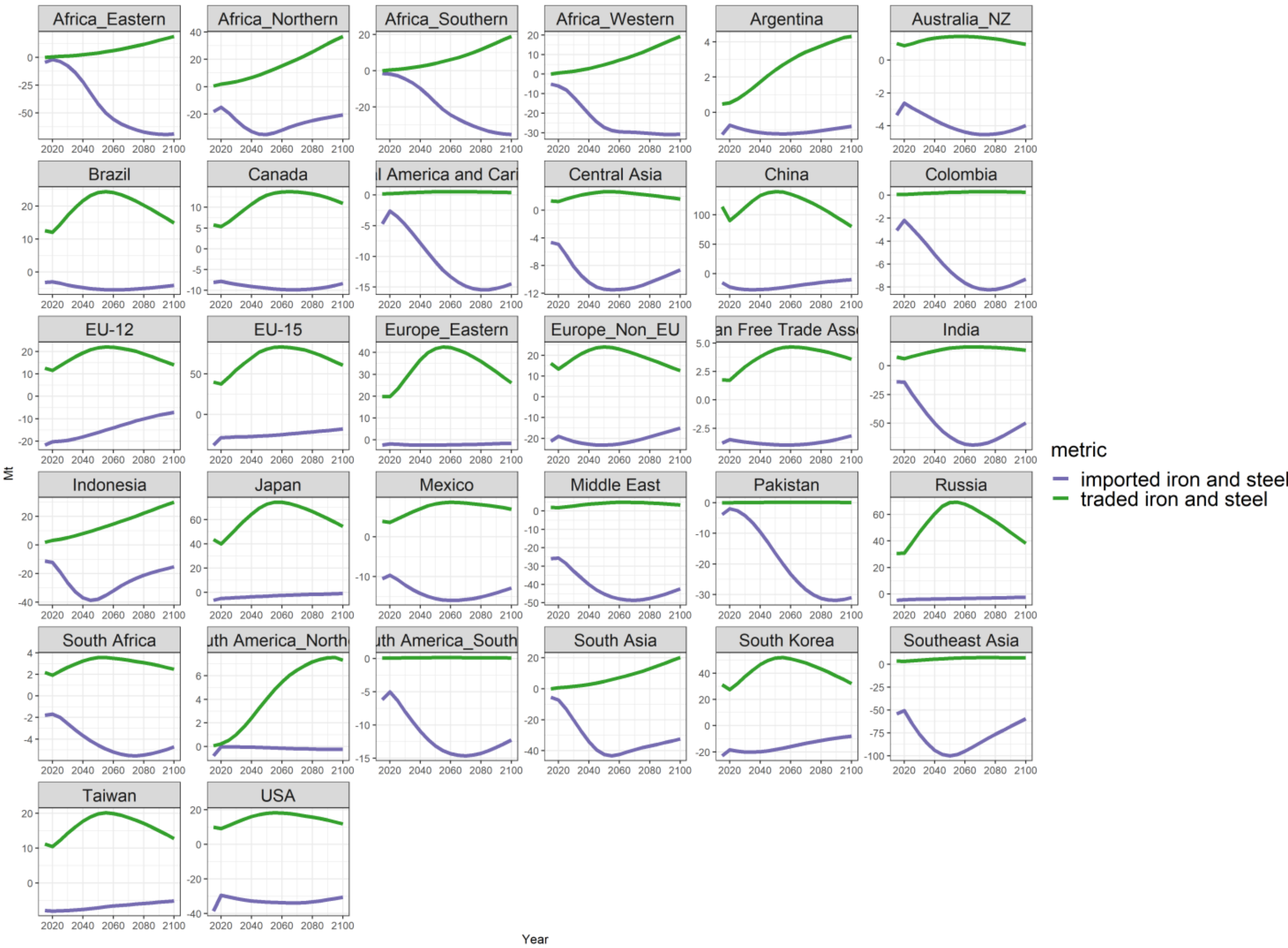
4. Steel Consumption (breakdown by gross imports and domestic supply)



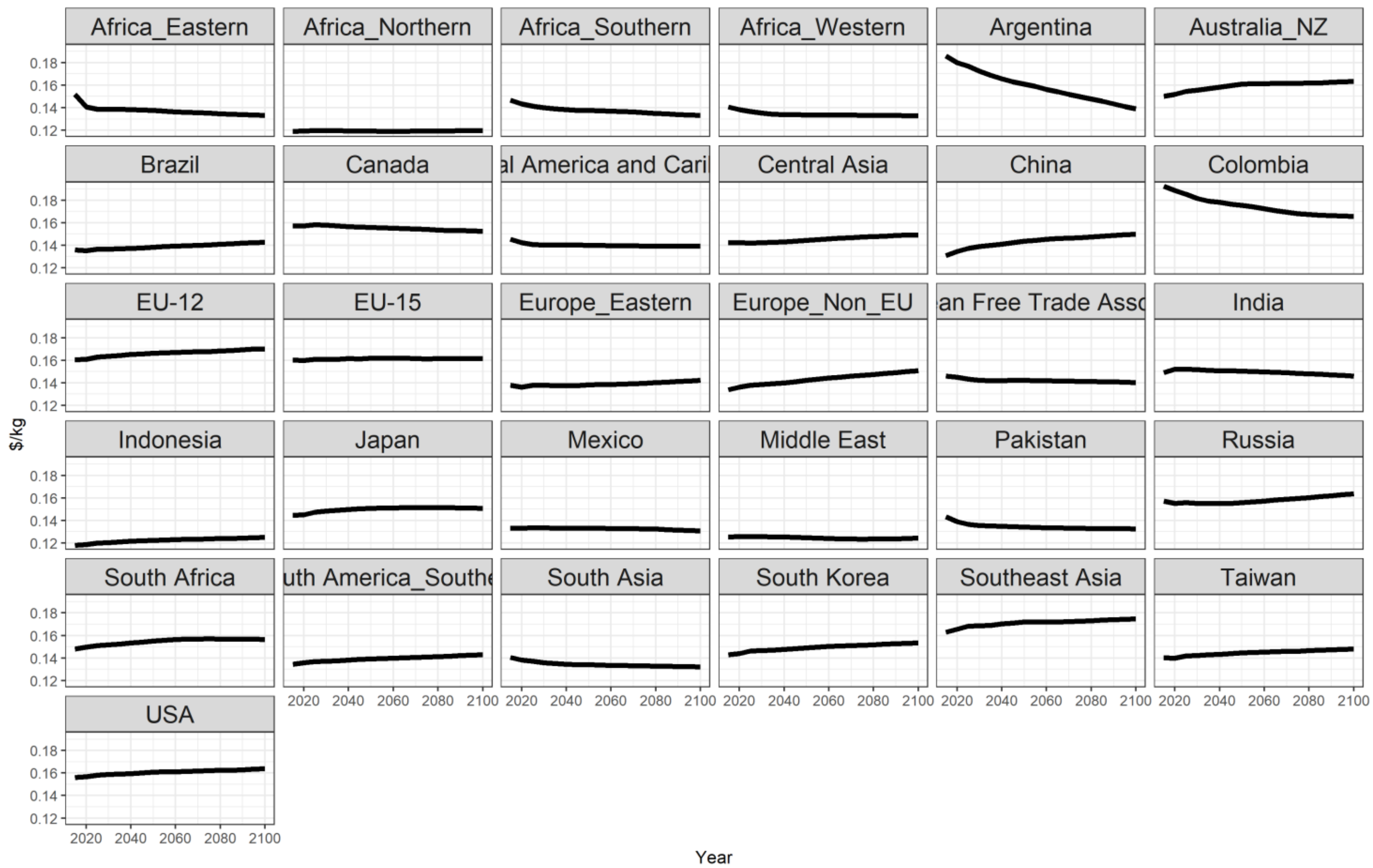
5. Steel Production (breakdown by gross exports and domestic supply)



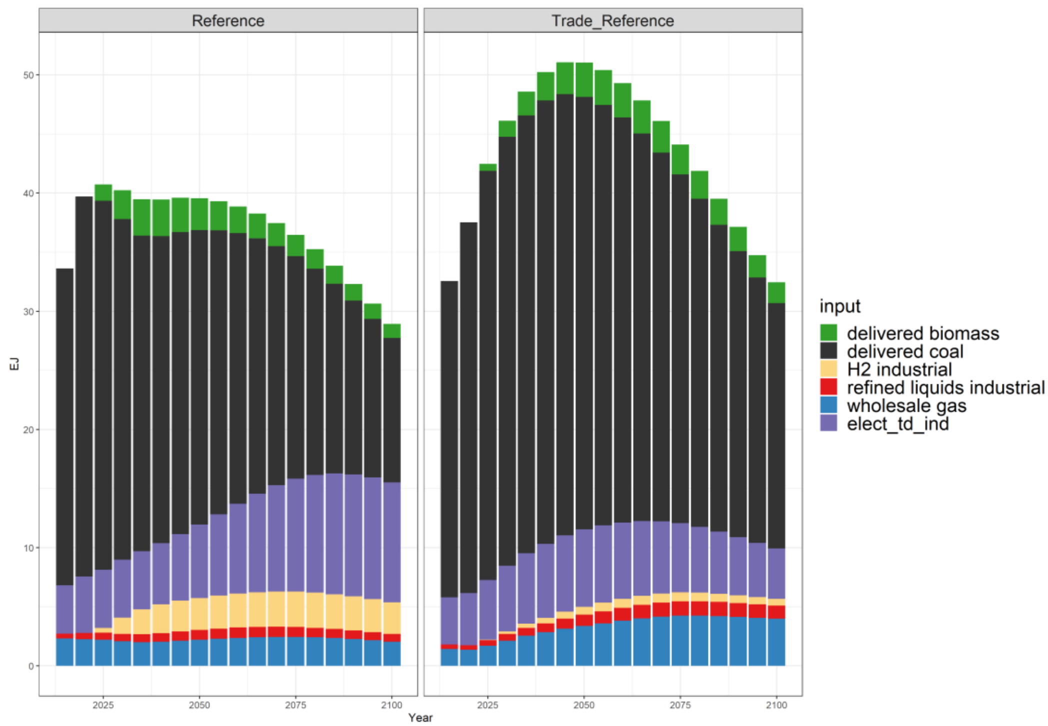
6. Gross Iron and Steel trade by region



7. Iron and Steel Production Cost by Region



8. Comparison to GCAM v6.0 (a - Iron and Steel Energy Use; b - Iron and Steel Production by Technology)



Description of code changes

This table includes only the input files that were added or modified (relative to GCAM 6.0).

Chunk	Input Files	Notes
zchunk_L238.iron_steel_trade.R	energy/irnstl_RegionalSector.csv energy/irnstl_RegionalSubsector.csv energy/irnstl_RegionalTechnology.csv energy/irnstl_TradedSector.csv energy/irnstl_TradedSubsector.csv energy/irnstl_TradedTechnology.csv	
zchunk_LB1092.iron_steel_GrossTrade.R	energy/WSA_steel_prod_cons_1970_2018.csv energy/WSA_steel_trade_1970_2018.csv energy/mappings/WSA_gcam_mapping.csv energy/Rt_iron_steel_bilateral_trade.csv	
zchunk_batch_iron_steel_trade_xml.R		

zchunk_L2323.iron_steel.R (modified)	energy/A323.capital_cost_adders.csv energy/A323.ccs_adders.csv energy/TZ_steel_production_costs.csv energy/mappings/TZ_steel_cost_gcam_mapping.csv energy/mappings/TZ_steel_cost_oecd_mapping.csv energy/A323.globaltech_cost.csv (modified)	Estimates regional steel production costs by technology Updates global steel technology costs Recalibrates base-year service output of iron and steel from steel production to steel demand Modifies code to use historical input-output coefficients for bio-based technologies
zchunk_batch_iron_steel_xml.R (modified)		Adds regional steel costs (StubTechCost)
zchunk_L2323.iron_steel_Inc_Elas_scenarios.R (modified)		Changes energy.final.demand from "iron and steel" to "regional iron and steel" Recalibrates steel production to steel demand

zchunk_LA1323.iron_steel.R (modified)	energy/steel_prod_process.csv	Conducts iron and steel trade balance calculations (consumption = production - exports + imports) Regionalizes iron and steel sector domestic supply interpolation rule Calculates EAF-DRI related steel production in historical years (2010, 2015)
batch_SSP_REF.xml, batch_SSP_SPA1.xml, batch_SSP_SPA23.xml, batch_SSP_SPA4.xml, batch_SSP_SPA5.xml, configuration_policy.xml, configuration_ref.xml, configuration_usa.xml (modified)		Adds iron_steel_trade.xml to the configuration files
energy/A323.demand.csv (modified)		changes energy.final.demand from "iron and steel" to "regional iron and steel"
constants.R (modified)		Adds the scope of iron and steel resources to be included when calculating intra-regional trade. Adds GCAM regions for which domestic supply share weights are adjusted

A323.globaltech_cost.csv (modified)		Updates global tech costs for iron and steel production
steel_prod.csv (modified)		Adds steel production by technology for Africa_Southern based on literature estimates
A323.globaltech_shrwt.csv (modified)		Lowers technology share weights for BLASTFUR with hydrogen, CCS and hydrogen, and biomass-based BLASTFUR
steel_intensity.csv (modified)		Adds global steel intensity for BLASTFUR with hydrogen and BLASTFUR with CCS and hydrogen
calibrated_tech.csv (modified)		Adds BLASTFUR with hydrogen and BLASTFUR with CCS and hydrogen to calibrated tech

zchunk_L232.industry_USA.R (modified)		Deletes traded iron and steel and domestic iron and steel in the global USA region Calibrates imported iron and steel to net imports. Where net imports = USA imports - USA exports Calibrates regional iron and steel to the calculated net imports
zchunk_batch_industry_USA_xml.R (modified)		Adds the modifications made in zchunk_L232.industry_USA.R to the industry_USA.xml