**Documentation of methodology and relevant scripts and files used to generate the add-ons for the steel decarbonization paper**

Material efficiency:

* Material efficiency calculations are included in this spreadsheet: <https://docs.google.com/spreadsheets/d/1WxOaM4EzZncMa2zlioH-cMkERBG0i2YE/edit#gid=1998695623>
* Potential % reductions in steel production (compared to the reference by 2050) are calculated for each key region by based on their existing steel market shares (buildings, transportation) and potential reduction within each market from various material efficiency strategies – see these assumptions in the “literature tab” and regional calculations on the “XXXX\_calcs” tabs (row 27 – 36). ROW calculations are calculated from a weighted average of EU and India reduction potentials, based on economic development.
* Potential reductions from material efficiency were assumed to increase linearly from 0% in 2020 to their maximum in 2050 (row 41). Regions’ annual percent reductions multiplied by the reference case steel demand projections to make demand reduction calculations (new demand in Row 41). The demand reductions were subtracted from the reference case to calculate material efficiency scenario demand (row 44)
  + For each key region reference case 2020 projection was set to match 2019 historical production level
  + Caveat: in China, GCAM reference steel demand projections already matched literature estimates for material efficiency scenario production levels, so in China calcs, the potential demand reduction is added to the reference scenario, to calculation the true reference scenario and the original reference scenario is treated as the material efficiency scenario
  + Caveat: Japan reference steel demand is adjusted; it is calculated by assuming the demand per capita decreases by 1% each year (row 12)
  + Caveat: South Korea reference steel demand is adjusted; it is calculated by assuming the demand per capita decreases by 2% each year (row 18)
* We created steel income elasticity xmls that produce steel production levels that closely match the reference and material efficiency production levels modeled in the spread sheet:
  + Material efficiency income elasticity xml: input/steel/iron\_steel\_incelas\_gssp2\_MEF\_3.xml
  + Reference income elasticity xml: /input/steel/iron\_steel\_incelas\_gssp2\_REF\_3.xml

Energy efficiency:

Relevant files:

* R script used to produce the new coefficients: *steel\_energy\_eff\_coef\_calculation\_GCAM6p0.R*
* Resulting XML for efficiency: *steel\_efficiency\_coefs\_bat\_2050\_or\_20pct\_improvement\_GCAM6p0\_final.xml*

Methodology: (methods are also described in the comments in the R script)

* Best Available Technology (BAT) assumptions:
  + For BLASTFUR and EAF-DRI, BAT energy intensities are the “world best practice” values from Worrell et al. (2008), “World Best Practice Energy Intensity Values for Selected Industrial Sectors” (<https://eta-publications.lbl.gov/sites/default/files/industrial_best_practice_en.pdf>). Values used are those that make use of the alternative casting and rolling method (thin slab casting) that has a lower energy intensity.
  + For scrap-based EAF, the BAT energy intensity is computed as the sum of the IEA’s BAT estimate for scrap-based EAF (<https://www.iea.org/articles/driving-energy-efficiency-in-heavy-industries>) and the world best practice value for casting and rolling (with thin slab casting), as the IEA data does not incorporate casting and rolling.
  + Assume that the different types of BLASTFUR and EAF-DRI all have the same BAT intensity (i.e., technologies involving CCS or hydrogen have the same BAT energy intensity as the standard version of those technologies).
* For all regions that have coefficients lower (more efficient) than the BAT in 2015 for a particular technology, assume that these coefficients are constant into the future for that technology.
* For all other regions, assume that the regional coefficients for each technology scale down from their 2015 values either to 20% more efficient values or the BAT values (whichever is less efficient) in 2050. This scaling down happens linearly over 2020-2050 (where 2020 coefficients are the same as 2015 values, and 2050 coefficients are at the BAT values/20% more efficient values). Coefficients are then constant from 2050 onwards. The 20% threshold was chosen to make sure that the energy efficiency assumptions are not too aggressive for regions that currently have much higher intensity values, and takes into account the IEA’s estimate that upgrading to best available technologies would lead to an average of a 20% energy efficiency improvement in steel production (<https://www.iea.org/articles/driving-energy-efficiency-in-heavy-industries>).
  + Assume that the relative contributions of each fuel type to the overall coefficient are constant at their 2015 values into the future, while the overall total coefficient (summed across all fuels) scales down to the BAT value/20% more efficient value.
    - For example, if the coal coefficient constitutes 75% of the total energy intensity coefficient for BLASTFUR in Africa\_Eastern in 2015, and electricity constitutes 25%, then in 2050 the total intensity coefficient for Africa\_Eastern (assuming the BAT coefficient is larger than 20% of the 2015 value) will be the BAT value, with the coal coefficient given by 0.75\*[BAT\_BLASTFUR\_intensity] and the electricity coefficient given by 0.25\*[BAT\_BLASTFUR\_intensity]

Hydrogen: (advanced hydrogen production cost assumptions)

Relevant files:

* R script used to generate the advanced hydrogen costs: *adv\_hydrogen\_xml\_generation.R*
* Resulting xml: *hydrogen\_adv\_GCAM6p0.xml*

Also see *adv\_hydrogen\_xml\_generation.R* for more details on methodology.

Only production costs were adjusted, not delivery/truck/pipeline/dispensing costs, nor compression/storage costs for forecourt production.

Methodology for global tech costs: (adapted from Patrick’s methods)

* Advanced costs = standard costs through 2020
* For the non-CCS technologies:
  + The standard improvement rate through 2040 is calculated as *(1-((2040 value)/(2015 value))^(1/5)*
  + The standard maximum improvement percentage is calculated as *1-(2100 value)/(2015 value)*
  + The advanced improvement rate is calculated as *2 \* (standard improvement rate through 2040)*
  + The advanced maximum improvement percentage is *25% + standard max improvement percentage*, unless this value would be greater than 75%, in which case 75% is used
  + These new advanced values are then used to calculate the new costs at each period from 2025 onwards: *costn+1=costn\*(advanced improvement rate)*, unless *1-(costn+1/cost2015)>= (advanced max improvement percentage)* in which case *costn+1=(1-(advanced max improvement percentage))\*cost2015*
* For the CCS technologies:
  + The costs in each period are computed from the sum of the corresponding non-CCS technology’s advanced costs (so, for example, for biomass to H2 CCS these come from advanced costs for biomass to H2) and the difference between the costs of the standard CCS technology and the corresponding non-CCS technology in each period.
    - E.g., if in 2025 standard biomass to H2 CCS cost is 3.7, standard biomass to H2 cost is 2.2, and advanced biomass to H2 cost is 2.0, then advanced biomass to H2 CCS cost will be 2.0+(3.7-2.2)=3.5

For wind and solar, global tech costs are adjusted using the above methodology, but GCAM actually uses regional costs, not global tech costs. These costs were adjusted using the advanced power sector costs, specifically the assumptions used to produce wind\_adv.xml and solar\_adv.xml (note also that these files should also be used in conjunction with the hydrogen\_adv\_GCAM6p0.xml file for consistency). The advanced stub technology costs for wind turbines and solar panels were thus obtained by running lines 246 to 273 from zchunk\_L225.hydrogen.R but with *L223.GlobalIntTechCapital\_elec\_adv* substituted for *L223.GlobalIntTechCapital\_elec*, where *L223.GlobalIntTechCapital\_elec\_adv* was obtained from zchunk\_L223.electricity.R.

Technology change: (share weight adjustments for increased steel production using scrap, hydrogen, CCS)

Relevant files:

* R script to produce the add-on xml for the advanced steel technology share weight assumptions*: scenario\_shrwt\_xml\_generation.R* 
  + \*\*note: need to manually add delete = “1” to the subsector level interpolation rules on the output xmls!\*\*
* Input csv files containing the share weight assumptions for the advanced technology scenarios: *steel\_decarb\_subsector\_shrwt\_adj.csv, steel\_decarb\_tech\_shrwt\_adj.csv, steel\_decarb\_retirement\_adj.csv*
* Resulting xmls: *iron\_steel\_techAdj\_v7.xml* (for the general advanced technology case) and *iron\_steel\_techAdj\_noCCS\_v7.xml* (for the no CCS case, same as general advanced technology xml but with 0 share weight for the CCS technologies) and *iron\_steel\_retirementAdj\_v1.xml* (to adjust the retirement assumptions for non-OECD regions, excluding China)
  + \*\*note: need to manually add delete = “1” to the subsector level interpolation rules on the output xmls!\*\*

See the input csv files for the specific assumptions. Generally, these files reduce BF-BOF share weights and increase those of alternative technologies. They also add longer lifetimes for steel facilities in India and other emerging economies.

Scrap adjustment for no CCS scenarios: (reducing scrap share weights in scenarios with no CCS, to not exceed global scrap limits)

Relevant files:

* R script to produce add-on xml to reduce scrap share weights: *eaf\_scrap\_share\_weight\_adjust.R*
* Input file: (output share weights from a run) *1p5\_no\_CCS\_scrap\_shareweights\_steel\_decarb\_run\_9-15-22\_regional\_costs\_TZ\_2019.csv*
* Output xml: *iron\_steel\_scrap\_adj\_for\_no\_CCS\_v1.xml*
  + \*\*note: need to manually add delete = “1” to the subsector level interpolation rules on the output xml!\*\*

Manually applies a reduction in the EAF scrap subsector share weight to ensure that global scrap-based production does not exceed the theoretical global scrap limit of ~1000 Mt in the 1.5C no CCS scenarios.

Scrap limitations: (constraining global scrap-based production)

Relevant files:

* Input files for standard scrap constraints (1000 Mt of scrap-based production globally): scrap\_constraint\_1000.xml and scrap\_constraint\_link.xml
* Input files for reduced scrap availability (500 Mt of scrap-based production globally): scrap\_constraint\_500.xml and scrap\_constraint\_link.xml

**Reference case notes**

Adjustments: Lower biomass-based BF share weights, lower BF-H2 share weights, BF-H2-CCS share weights set to 0 so that technology never comes in. All subsector share weights converge to 1 in 2050 onwards (except for in regions where BF share weights were < 0.5 in history – for those regions, we use the add on *iron\_steel\_ref\_adj\_v1.xml* to set the BF subsector share weights to converge to 0.5 rather than 1 in 2050 onwards).

**Run used in paper:** */rcfs/projects/comp-fe/steel\_decarb\_paper/steel\_decarb\_6p0\_runs/steel\_run\_9-7-23*