Opportunities and roadblocks in the decarbonisation of the global steel sector: A demand and production modelling approach

Kimon Keramidas, Silvana Mima, Adrien Bidaud

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ABSTRACT

The steel sector represents a growing share of global carbon dioxide (CO_2) emissions and is perceived as a hard-to-abate sector in the drive towards economy-wide decarbonisation. We present a model detailing steel demand and multiple steel production pathways within a larger global multi-regional energy system simulation model, projecting material, energy and emissions flows to 2100. We examine decarbonisation levels and options under different assumptions on climate policy, technologies and steel demand patterns, and study low-carbon options in the production of hydrogen as a steel decarbonisation vector. Global steel demand increases at a decelerated pace compared to the past two decades (+65% in 2050 compared to 2020), driven by substantial increases in the underlying socio-economic conditions. Climate policies lead to a limited positive feedback effect on steel demand (+21% in 2050) due a faster equipment turnover and higher electrification, which could be overcompensated by energy saving and material efficiency measures. Increased recycling and strong electrification (up to 63% of production in 2050) are projected as key levers towards decreasing emissions, made possible thanks to the increasing availability of steel scrap. Strong climate policies would be needed to push the steel sector to decarbonize fully, with electrification, carbon capture, biomass and hydrogen all contributing. Carbon capture would be necessary to reach net-zero emissions in the second half of the century.

KEYWORDS

Iron and steel; climate mitigation; industry decarbonisation; energy system model; integrated assessment model

1. INTRODUCTION

With nearly all states having signed the United Nations international climate treaty of the Paris Agreement since 2016, collective efforts are needed to "holding the increase in the global average temperature to well below 2°C above pre-industrial levels and to pursue efforts to limit the temperature increase to 1.5°C above pre-industrial levels"[1]. According to literature synthesized by the Intergovernmental Panel for Climate Change's (IPCC) Special Report on 1.5°C[2], there is high agreement among the scientific community that global anthropogenic emissions of carbon dioxide (CO_2) need to be reduced to net-zero by around mid-century in order to be consistent with the more ambitious Paris Agreement target. Accordingly, significant efforts to reduce emissions have to be pursued by all world countries and across all sectors of the economy. However, countries and sectors would differentiate their contribution in the overall reduction depending on cost-efficiency and other considerations. Thus, a net-zero global target does not necessarily coincide with a similar target for all sectors. In particular, heavy industry has been identified as a challenging sector to decarbonize, along with aviation, shipping and agriculture[3]; this is due to a combination of sector-specific factors: high projected activity growth, comparatively costlier emissions abatement options and slow capital turnover.

The iron and steel industry is responsible for a sizeable share of the world's CO_2 emissions: around 7.4% of energy and industry emissions in 2021 with 2.70 $GtCO_2$; the volume and share of these emissions grew rapidly over 2000-2015 (from 1.33 and 5.5% to 2.76 $GtCO_2$ and 8.0%, i.e. +5.0%/year) and remained relatively stable since[4]. This is mainly due to an increase in demand for steel and steel products, from 860 to 1960 Mt over 2000-2021, mainly coming from China and India, while the emissions intensity has decreased slowly (-0.6%/year over 2000-2021).

Without additional effort, the demand for steel and the sector's emissions are projected to increase, in particular due to economic growth and increasing living standards in developing economies[5], [6].

Historically, higher income levels and well-being have been correlated with an increase in the demand of material goods, and of steel in particular: over 2000-2021, steel demand grew by 3.4%/year while global GDP grew at 3.3%/year. The challenge then becomes to reconcile continued increase in well-being for all (and associated steel demand increase) with the aspirations to decarbonize the world economy. Quantitative tools that are able to create multi-sectoral sectoral decarbonisation pathways are particularly suited for this task.

A number of private sector announcements have placed the objective of net-zero emissions in 2050 or earlier as something achievable for the iron and steel sector but provide little information in the means to achieve this: Baowu[7], POSCO[8], ArcelorMittal[9], TataSteel[10], ThyssenKrupp[11]. Privately-funded think tanks have produced a quantitative basis for the net-zero objective with a techno-economic evaluation of options (see the study of the business coalition Net-Zero Steel Initiative[12]). Other studies have focused on static assessments of options[13], [14].

Techno-economic modelling of steel demand and production is thus a prerequisite for constructing pathways for the future of this sector. Modelling is an important tool in making informed and quantitative estimates of the future needs of the energy sector[15], and has been used by researchers, public planners and private investors alike. Energy system models and integrated assessment models (IAMs) are prominently used to inform the IPCC's working group on mitigation options. Several of these models represent the iron and steel sector independently of the rest of industry; however, its representation is done in a stylized manner. Several models do not represent the iron and steel sub-sector separately from other industrial sub-sectors[16]; few models represent steel demand by end-use (as opposed to a using a single type of demand[17]), few represent physical production of steel (as opposed to using a single economic activity indicator as a driver[18]) and few represent specific production processes (as opposed to a single value of energy efficiency for the entire sector); see a comparison of several IAMs[19]. Moreover, industrial ecology and material flow models have worked on representing steel stocks and annual steel demand by end-use, as well as estimating scrap made available for recycling, but do not represent the steel production side[20], [21].

The main goal of this study is to chart a way forward for the iron and steel industry in a context of energy transition as required by the regional and global effort of decarbonisation to limit climate change. We propose to tackle these issues of steel demand and supply in an integrated way within an energy system model. The resulting projections of steel flows, energy needs and greenhouse gas emissions are more self-consistent.

We first provide information on the methodology to project steel demand and production; we then describe the scenarios that we assessed (section 2); we present and discuss results for steel demand and trade, for the steel production mix, emissions and investments, and for overall mitigation options (section 3); finally, we conclude on main findings and open issues (section 4).

2. METHODS: MODELLING WORLD STEEL DEMAND AND SUPPLY

2.1. The energy system model POLES

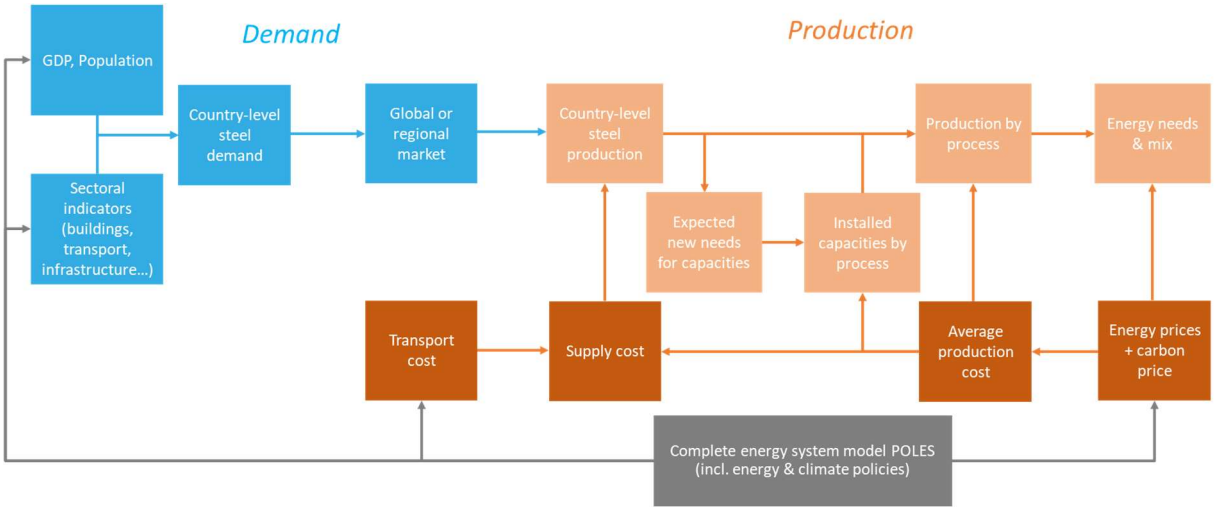
Prospective Outlook for Long-term Energy Systems (POLES) is a global multi-regional energy system model that has been used extensively in global and regional climate policy studies[22]–[24]. POLES is a 66-region multi-sectoral partial equilibrium simulation model with an annual time step, with endogenously calculated energy prices (including electricity and hydrogen prices with multiple production technologies) and lagged adjustments of energy demand. Demand for energy services is derived from existing equipment and macroeconomic indicators; following equipment depreciation, choice across fuels or technologies is made with a logit distribution function using total costs and preference factors. All greenhouse gas emissions are represented.

2.2. Steel module overview

We modified the POLES model by integrating different aspects for decarbonizing steel demand and production. This is a significant evolution of a previous POLES steel module[25], which had not been used since 2003.

The overall scheme of the materials demand and production module enriched and developed in this work is given in Figure 1. A general description is provided below, with more information in the following sections and more detail in supplementary information (SI). See SI section 7 for a comparison of key results with the previous model version.

Figure 1: Schematic view of the steel demand and production modules of POLES for this work



Top left: for each region, annual demand for steel is determined based on material intensity per end-use , which are associated to stocks and flows of equipment, ultimately relying on macro-economic development and living standards. For each end-use, steel scrap is released at the end of the lifetime of the associated equipment; a scrap collection rate determines quantities of scrap available for recycling.

Top right: demand is met by production at the global level, with allocation based on production and transport costs and self-sufficiency constraints. Annual production is distributed across several production processes based on their costs and existing capacities; planning for new capacities is based on anticipation of future production needs and on costs. Cost-based competition within each process determines final energy consumption by fuel; energy- and process-related emissions are then calculated.

Bottom: energy and climate policy acts on the prices for energy fuels, including secondary fuels (electricity, hydrogen). Demand for steel can change as a result of the adaptation of the energy services and of the technologies mix to the policy; regional production allocation and the processes mix can change as a result of the policy directly impacting production costs.

2.3. Steel demand

Total apparent steel consumption by region was reconstructed from domestic production[26] and net trade[27].

Time series for steel demand by end-use are difficult to obtain. News reports from the industry provide the decomposition of steel demand by end-use for select regions[28]–[31]: construction ranged from 35% (EU) to 68% (China) and automotive from 8% (China) to 26% (USA). However, the sectoral decomposition differs across sources and only select years are available; therefore, a top-down decomposition of total consumption would necessitate many assumptions.

For this work, demand was estimated for certain end-uses in a bottom-up manner (specific material content per sector times an activity indicator), leaving a residual category when compared with annual apparent consumption time series. Three main demand sectors were singled out: buildings construction, road transport and power. See SI sections 4 and 5 for detail.

Buildings construction

Buildings construction (residential and commercial) is the single largest consuming sector for steel, estimated in this work at 32% of total global steel demand in 2015. Although "construction" is estimated to be the largest end-use by industry reports, it encompasses not only buildings but also other infrastructure; in this modelling, demand for buildings construction is separated from demand for other infrastructure, which is in the residual category.

A specific steel demand per floor area surface is associated with projections of new constructions of floor surfaces. Steel demand per surface were adapted from [20]. No strong correlations were found with macroeconomic indicators (GDP/capita, urbanization rate, population density); differences appear to be related to regional construction practices. They were kept constant in the projections.

Road transport

The automotive sector is one of the main consuming sectors, estimated in this work at 12% of total global steel demand in 2015, and growing strongly at 10%/year. It encompasses the production of light (private cars, vans) and heavy (trucks, busses) duty vehicles for road transport.

A specific steel demand per vehicle type from [32], [33] is associated with projections of vehicle fleets.

Power sector

This work estimates that the power sector absorbed 4% of total global steel demand in 2015. Steel demand for power generation and for the power grid were distinguished.

Specific material consumption per power generation technology (kg/kW) was obtained from [34]–[37]. New annual installations per technology are produced by the power sector module of the POLES model endogenously, on the basis of equipment lifetime, total costs and bottom-up electricity demand projections. Power generation capacities lifetimes differ depending on the technology; they range from 20 (wind) to 50 (hydro) years.

Specific steel consumption for the power transport and distribution grid (kg/GWh) was derived from [38]. New needs for the grid arise from the projections of power generation and a grid equipment lifetime. Grid equipment is considered to have a 40 year lifetime.

Infrastructure and other

The remaining demand pertains to the construction of public works and other infrastructure (roads, rail network, oil and gas and mining extractive industries, manufacturing industries), to machinery and equipment (mechanical engineering, maritime vessels and other transport vehicles, containers and packaging, tubes, domestic appliances, and other uses). This work estimates that in 2015, it corresponded to 52% of global steel demand. Given the diffuse nature of this demand category and the lack of specific drivers to associate it with in the energy system model for a bottom-up estimation, this remaining demand was projected as a constant percentage of total demand. In projections, the aggregate changes in the three bottom-up end-uses above drive the evolution of the residual demand.

2.4. Steel production

Currently, three main processes dominate world steel production. The blast furnace followed by a basic oxygen furnace (BF-BOF, 72% of world production in 2020) makes use of coking coal as a reduction agent for the iron oxide in the ore; steel plants can also include facilities to convert mineral coal into coke. The electric arc furnace (EAF, 22% of production) is a form of recycling, it melts scrap metal into new steel items. The direct reduction with EAF process (DRI, 6%) does away with coking coal and uses a mix of hydrogen and carbon monoxide (as syngas derived from methane or coal) as reduction agents, producing sponge iron, which is fed into an EAF to produce steel. Market shares have been mostly stable over the past 30 years, with direct reduction gaining importance at the expense of electric arc.

Production processes considered for the modelling were limited to those with a technology readiness level today that have a reasonable chance to represent a sizable share of production capacities in the time horizon of the study. The Technology Readiness Level (TRL) of production processes were taken from [39]–[42]; technologies with a TRL above 5, i.e. from demonstration level to mature, were selected to be modelled. They were: BF-BOF; EAF; DRI using fossil gas followed by EAF (DRI-NG); DRI using hydrogen directly (DRI-H2) followed by EAF; smelting reduction followed by BOF (Smelt); low-temperature electrolysis (electrowinning, E-winn); as well as 3 carbon capture options (BF-BOF+CCS, DRI-NG+CCS, Smelt+CCS). Technologies still at a research level, such as high-temperature electrolysis, were excluded.

Process efficiency and investment costs for new installations are set exogenously (from [12], [39], [43]–[46], the assumptions are presented in SI section 6). Historical statistics on energy[47] and capacities[48], [49] are used to set up process efficiency and fuel mix for existing equipment. Coke ovens were not accounted in the iron and steel sector but in the energy transformation sector.

Investment in new production capacities is calculated based on the growth of production in past years. The choice among capacities is made using a logit distribution with total costs and preference factors. Total costs consist of capital expenditure (CAPEX) and a number of operational expenditures (OPEX):

- CAPEX: overnight investment costs annualized over the lifetime of the equipment with a discount rate;
- raw material costs: iron ore (driven by international maritime transport cost), steel scrap (availability influences the steel scrap price), coking coal (endogenously calculated), oxygen (constant);

- energy input costs (endogenously calculated, with upstream production costs and trade for fossil fuels and multiple production technologies for electricity and hydrogen, which are purchased by the steel sector);
- CO_2 price (exogenously defined);
- CCS transport and storage cost (constant) and carbon credit from biomass-CCS (determined by the carbon content of biomass and can cover, at most, the energy input costs and CO_2 price);
- revenue from by-products (slag produced in basic oxygen furnaces is sold at a constant price).

CCS technologies include a fixed CO_2 capture rate (BF-BOF: 65%; DRI: 55%; Smelt: 80%, from[39], [50], [51]).

Preference factors represent the factors that influence the choice that are unrelated to pure economics, reflecting country specificities observed on the historical mix such as inertia in choosing existing technologies (the weight of past capacities, its effect is phased out by 2035), or technological availability for new technologies (CCS availability and electrowinning maturity grows over time; a shortage in global scrap curtails investments in new electric arc capacities). In addition, there is the possibility to retrofit certain processes into others (in particular for retrofitting CCS).

The choice among fuels within each process is made using a logit distribution with user costs, including efficiency and carbon pricing and any process-specific constraints (such as a specific reduction agent). Biochar being a less energy dense fuel than coal and traditionally used in smaller furnaces, the use of biochar as a coke substitute was capped at 50% of the energy consumption of furnaces.

Regional allocation of global production is done on the basis of the region's average production cost and a transport cost (cost of exporting towards net importers, weighted average over importers' market share in global trade) under the constraint of available capacities per region.

2.5. Scenarios

In order to take into consideration several uncertainties in how the energy system as a whole, as well as steel demand and steel production technologies more specifically, might develop, we considered multiple scenarios that were quantified with the POLES model.

The scenarios are driven by macroeconomic projections (GDP, population) that are defined exogenously as model inputs; energy prices, technological development and emissions are calculated endogenously under scenario-specific constraints and parametrization. Scenario rely on historical statistics for energy demand and steel production, which extend to the year 2020.

We assessed the following contrasted scenarios:

A Reference (*Ref*) scenario: existing policies related to energy supply and demand policies and targets, as well as legislated emissions policies and targets that are backed by supporting energy-sector policies, are enacted. No additional policies are considered compared to what had been legislated as of June 2022 (see Annexes of [52] for the list of policies considered). Accumulated net CO_2 emissions over 2020-2100 amount to 3070 Gt, resulting in a global mean temperature increase at the end of the century of 3.0°C (median probability), as calculated by the online MAGICC tool[53].

Several scenarios compatible with the Paris Agreement goal of limiting climate change to 1.5°C above pre-industrial levels: they differ in several dimensions related to technological availability and maturity, and in the socio-economic implementation of the climate policies necessary to reach the temperature objective. They consist in:

(i) *15C_ CCS* with an earlier availability of carbon capture across the entire economy, to study a steel sector that might continue its reliance on technologies that involve combustion;
(ii) *15C_ Elec* with more ambitious technological learning for new direct and indirect electrification technologies, to study a steel sector that might move more towards a new paradigm;
(iii) *15C_ LD* with lower energy service demand and lower material demand, resulting in fewer emissions to decarbonize on the steel production side, to study a steel sector where sobriety, efficiency and circularity are more important;
(iv) and *15C_ Opt* which combines elements of all of the above, to study a best-case scenario for the degree of economic effort to obtain a decarbonized steel sector.

The specific levers that were used to parameterize these scenarios are presented in Table 1 and are detailed below.

Table 1: Parameter matrix for the scenarios in this study

	Climate policy	*CCS availability*	*Bioenergy availability*	*New electricity costs*	*Energy demand adaptation*	*Steel demand adaptation*	*Steel plant lifetime*
Ref	Current adopted policies	Default	Conservative	Pessimistic	Default	Default	Default
15C_ CCS	Global carbon price	Default	Optimistic	Pessimistic	Default	Default	Reduced
15C_ Elec	Global carbon price	Delayed	Conservative	Optimistic	Default	Default	Reduced
15C_ LD	Global carbon price	Default	Conservative	Pessimistic	Energy conservation measures	Material efficiency measures	Reduced
15C_ Opt	Global carbon price	Default	Optimistic	Optimistic	Energy conservation measures	Material efficiency measures	Reduced

Climate policy: For each 1.5°C scenario, a carbon price is applied to all regions and all sectors of the economy. The carbon price follows a sigmoid curve starting from 2022, with an inflection in 2040 and a saturation level in 2100; it is adapted for each 1.5°C scenario for a peak-temperature budget (i.e., at the year of global net-zero CO_2 emissions) of 650 $GtCO_2$ from 2020, which is compatible with a 1.5°C global mean temperature increase compared to pre-industrial levels at the end of the century. 2100 prices are 0, 880, 1130, 795 and 750 $\$/tCO_2$ for the scenarios listed above.

CCS availability: availability for installing CCS options and CCS infrastructure is determined by a multiplying factor to the technology's cost, uniformly across all regions, with a duration of 50 years from zero (first-of-a-kind) to one (pure cost-competition); first-of-a-kind from 2020 (default) or from 2050 (delayed).

Bioenergy availability: lignocellulosic biomass availability is determined by supply costs; higher costs result in total global bioenergy demand not exceeding 170 EJ/year (conservative) and lower costs result in 200 EJ/year (optimistic). A cap for bioenergy penetration in steelmaking processes was set at 50% (conservative) and 75% (optimistic). As a convention, solid biomass energy use is considered carbon-neutral (compensated by carbon absorbed in the growth of new biomass in a sustainably managed cycle); and biomass with carbon capture and sequestration (BECCS) is considered as carbon net-negative.

New electricity costs: investment costs for the electrowinning furnace for steel differ, with optimistic costs a third lower than pessimistic costs. Hydrogen electrolyser costs decrease, reaching 480 \$/kW, as per[54] (pessimistic), and to 98 \$/kW in 2050, as per[55] (optimistic); see SI section 7 for a complete view of hydrogen production pathways and costs. In addition, in the pessimistic case the steel sector is provided by the average hydrogen considering all production pathways plus a transport and distribution duty; the optimistic case sees green hydrogen production taking place close to the steel plant, resulting in a price driven only by wind and solar electrolysis technologies, without a transport and distribution duty.

Energy conservation measures: building surfaces and vehicle stocks are related to demography, economic growth and occupancy rates. Residential surfaces are capped to a maximum value of 50 m^2/cap (default: no cap; the region with the highest level, the USA, reaches 108 m^2/cap in 2100). The car ownership ratio is capped to a maximum of 0.4 car/cap (default: values are capped by 0.6 car/cap); in addition, we assume a modal shift from private transport to public transport and soft modes, maintaining the total passenger mobility compared to the default case.

Material efficiency measures: specific material demand per floor surface area for buildings decreases over time (to 67% of its initial value by 2050) and specific material demand per vehicle for road transport decreases over time (to 50% of its initial value by 2050), uniformly across all regions, with 2050 values following the ambitious scenario in[56]. Steel scrap recycling increases to a maximum recovery rate (from an estimated 80% of end-of-lifetime scrap collection rate in 2020, to 90% in 2030, accounting for 10% considered unrecoverable).

Steel plant lifetime: the default value (35 years) for renewing the stock of steel production capacities was reduced in the 1.5°C scenarios (23 years) to reflect increased pressure to renew the stock towards more low-carbon processes. See SI sections 6 and 8 for more details.

3. RESULTS AND DISCUSSION

Scenarios were executed to 2100; results are presented for the world and key regional aggregates; more granular results are provided in SI spreadsheets.

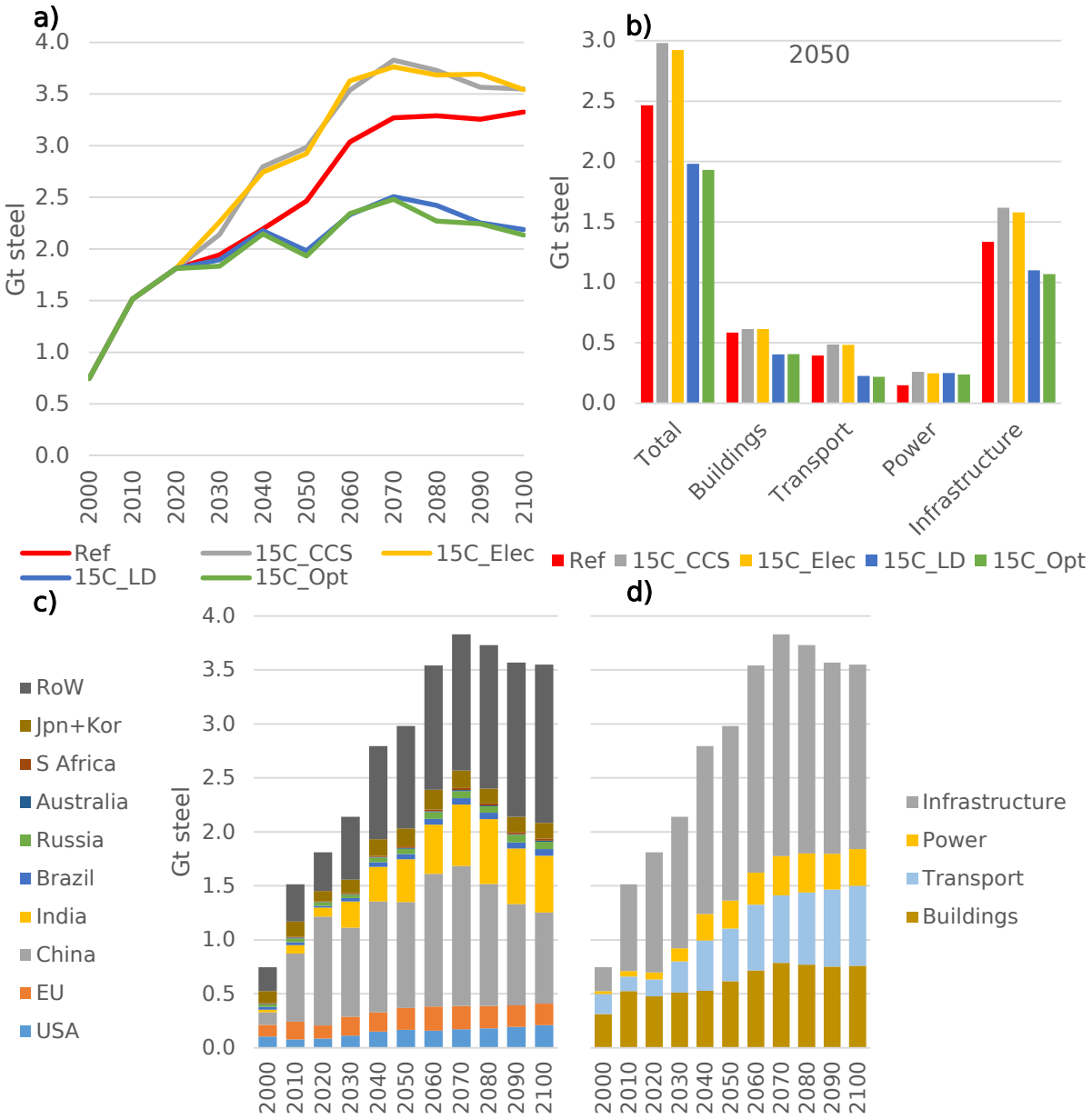
3.1. Growth of world steel demand to decelerate

Global steel demand is projected to continue to increase in the coming decades, but at a decreasing rate of growth with a stabilization in the second half of the century (Figure 2). Demand is projected to reach 2.98 Gt in 2050 (65% above the 2020 level) peak in 2070 and reach 3.62 Gt in 2100 (15C_CCS). Annual demand growth decreases from 4.4%/year over 2000-2020 to 1.7%/year over 2020-2050 and 0.4%/year over 2050-2100. This is driven by a strong demand increase in India and the Rest of the world, while demand in China stabilizes to 2050 and increases again thereafter.

Total steel demand evolution is due to an increase of demand over all uses. In terms of volume, most of the increase to 2050 comes from infrastructure, followed by road vehicles, power and, finally, buildings construction. A second wave of buildings construction in China in the 2070-2090 period, roughly 70 years after the first wave over 2000-2020, results in global steel demand for buildings increasing again, while demand in most other regions increases or stabilizes. Demand for the other uses increase moderately throughout the end of the century.

These increases are driven by the underlying socio-economic conditions. Demand for buildings (+29% over 2020-2050) is driven by an increase in global floor surface area (+66%). Demand for transport (+214% over 2020-2050) is driven by an increase in global passenger (+46%) and goods (+65%) traffic volumes, with corresponding increases in vehicles stocks. Demand for power (+302% over 2020-2050) is driven by an increase in global power production (+180%) (15C_CCS).

Figure 2: Global steel demand (a) across scenarios; (b) by end-use sector in 2050, all scenarios (c) by region, 15C_CCS scenario; (d) by end-use sector, 15C_CCS scenario



Source: POLES model. "Jpn+Kor": Japan and South Korea. "RoW": Rest of the world.

The implementation of climate policies leads to a positive feedback effect on steel demand. This amounts to 19-21% higher steel demand in 2050 and an additional 16-17% of accumulated demand over 2020-2050 (15C_CCS and 15C_Elec compared to Ref). This is brought about by an increase in demand for transport and for power, and to a lesser degree for buildings. This feedback would result in an increase in emissions in order to produce this extra steel; however, in all cases, this increase is smaller than the emissions savings brought about by the new low-carbon equipment and infrastructure built with this extra steel.

In buildings, climate policies accelerate the renovation rate in order to achieve higher buildings shell insulation levels, resulting in more steel needs. Over the 2020-2050 period, accumulated renovated surfaces are 29-32% higher (15C_CCS and 15C_Elec vs Ref), and accumulated steel demand is 4-5% higher compared to Ref. The production-side increase in emissions induced by this higher steel demand (about 0.9-1.0 $GtCO_2$, accumulated) are more than compensated by the emissions savings brought about by more energy-efficient buildings and the accompanying switch to low-carbon fuels in buildings energy use (which were at 3.0 $GtCO_2$/year in 2020).

In road transport, similarly, climate policies induce a faster stock turnover in order to achieve decarbonisation faster; in addition, climate policies induce a certain reduction of overall passenger mobility as well as a certain modal shift from private cars to busses. These effects combine to result in 2020-2050 accumulated steel demand 20-23% higher (15C_CCS and 15C_Elec) compared to Ref. This considerable increase would result in more emissions

from steel production (about 2.3-2.7 $GtCO_2$, accumulated); however, they would amount to the equivalent of less than the year 2020's total road transport energy use emissions.

In power, climate policies push towards higher electrification and a shift towards lower-carbon power sources. As the power sector is progressively decarbonised, electricity becomes a lower-carbon energy vector and power demand becomes higher. While low-carbon technologies require less steel than fossil fuel technologies per unit of installed capacity on average, some of them, such as wind and solar, have a low load factor and more units would need to be built to replace the equivalent fossil fuel unit with the same nameplate capacity. Over the 2020-2050 period, the average steel intensity of newly installed capacities is 7% lower in 15C_CCS compared to Ref (106 kg/kW vs 115 kg/kW) while accumulated installed capacities are 65% higher, resulting in an accumulated steel demand that is 53% higher (55% for 15C_Elec). Again, this feedback would result in additional emissions in steel production compared to Ref (approximately some accumulated additional 2.4 $GtCO_2$); however, these would be much smaller than the emissions saving brought about by the decarbonisation of the power sector (from about 12 $GtCO_2$/year in 2020 to net-zero in 2050).

In infrastructure and other uses, resulting from the combined behaviour of the above end-uses, steel demand is also higher than in the Ref (17% accumulated).

As a direct result of the energy and material savings and efficiency measures, the steel demand in 15C_LD is lower. The climate policies feedback on steel demand could be contained and even overcompensated, resulting in total steel demand that is slightly lower than in Ref (-4% accumulated for 15C_LD, -5% for 15C_Opt). The effect is larger in the specific sectors where measures were implemented, buildings (-15%) and road transport (-18-20%). Demand in power is little different to the other 1.5°C scenarios (+44-48%), with differences mostly due to the feedback of lower steel production on electricity demand itself. The difference becomes more pronounced after 2050, when the measures have been fully phased in; total steel demand peaks in 2070 but at a much lower level (2.54 Gt in 15C_LD compared to 3.80 Gt in 15C_CCS), a level that is exceeded already in the 2020s in the other 1.5°C scenarios. Thus, these savings and efficiency measures would provide a longer time for the steel production industry to respond to an increasing demand while simultaneously meeting the decarbonisation challenge. Indeed, it could be realistically expected that the higher costs of producing low-carbon steel would be passed down to the end-users, which would result in a demand level responding accordingly; while a steel price elasticity on demand was not included in this modelling, its effects are here approximated by the adoption of such savings and efficiency measures.

3.2. Steel production mix to diversify

Steel production mix

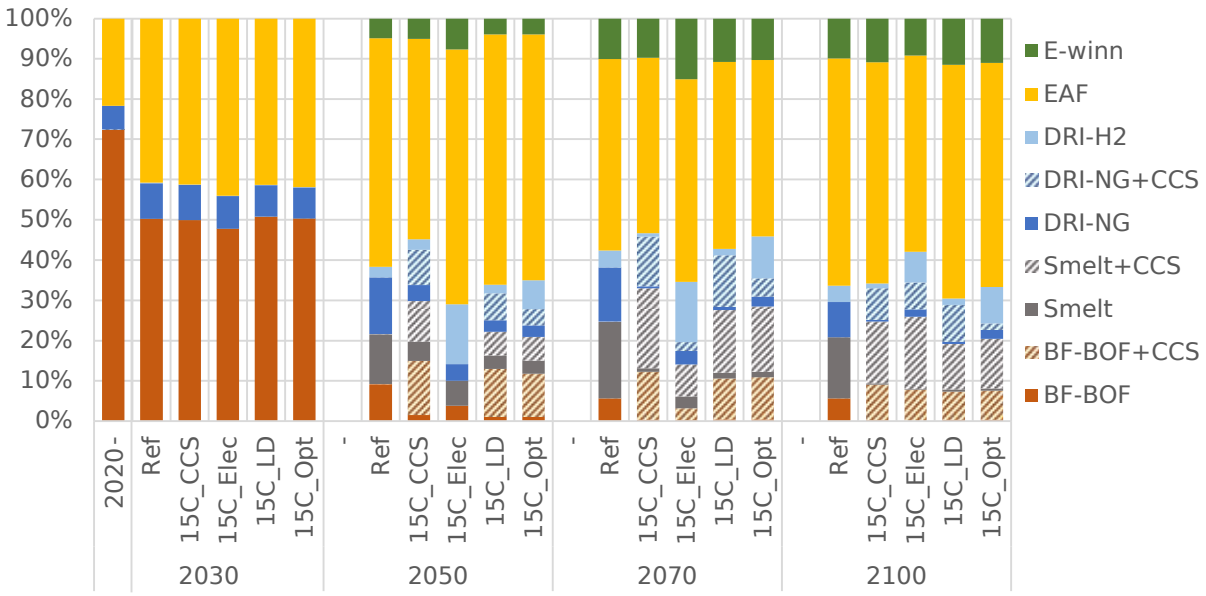
Recent industrial-scale innovation and investment projects are focusing on DRI-H2 and DRI-NG-CCS solutions[57], which might prove to be decisive for the medium term. We offer here a longer-term view that takes into account a wider range of options that might be available to the sector. The production mix in the projection evolves from the current situation. Figure 3 presents the world production mix, including the substitution process that takes place over part of the stock once older equipment is retired and the effects of retrofitting CCS onto existing capacities.

Without strong climate policies (Ref), there is a strong increase of electrification (EAF) and a progressive penetration of direct reduction and, to a lesser degree, of smelting reduction, at the expense of BF-BOF. EAF covers 57% of production by 2050, up from 22% in 2020. Indeed, the scrap available for recycling (recovered from equipment reaching the end if its lifetime as well as new scrap produced in steel plants) more than doubles over 2020-2050 (+116%), allowing this considerable expansion of secondary steel production. Primary steel makes up 43% of total production, which is sufficient to provide for specialty steel products for which secondary steel is not of high enough quality.

With strong climate policies (15C_CCS), the mix is much more diversified: CCS technologies emerge (taking up 32% of the market by 2050) and direct reduction decreases (however, direct reduction using hydrogen remains approximately the same at 2-3%). These effects are more noticeable with more optimistic assumptions on electricity (15C_Elec), where CCS is substituted by more EAF (63%), more hydrogen and more unabated technologies, resulting in higher emissions.

DRI-H2 production over all scenarios increases over time in the first half of the century and reaches 2% (15C_LD) to 15% (15C_Elec) share of global steel production of in 2050, the latter amounting to 40 MtH_2/year. In the second half of the century, the comparatively cheaper CCS options result in that share decreasing. This low share for DRI-H2 is consistent with other studies where this technology was included in economic competition with other production routes[12], [58].

Figure 3: Global steel production mix



Source: POLES model.

These changes in production mix are due to several factors. The climate policy effort distorts the competitiveness of different options. Fossil fuel-based technologies without CCS become non-competitive from around 50 $/tCO$_2$. The use of biomass coupled with CCS in BF-BOF and smelting reduction result in carbon credits that decrease OPEX (up to covering all of the expenditure for energy and coke inputs) and decreases net emissions further. Steel production using the smelting reduction and direct reduction processes have the comparative advantage of not needing coking coal and can become more competitive than the BF-BOF process. As the CO_2 price increases, the direct reduction process using hydrogen gains advantage over using natural gas and partly capturing the CO_2 emissions with CCS.

The OPEX of EAF is driven upwards partly due to the impacts of the decarbonisation effort on the electricity price, but also due to the higher price for scrap, due to a higher demand for scrap globally.

The extended use of BF-BOF, Smelt and DRI technologies with CCS at the expense of EAF results in an increase of energy intensity, either after 2050 in 15C_CCS or after 2070 with the delayed implementation of CCS in 15C_Elec.

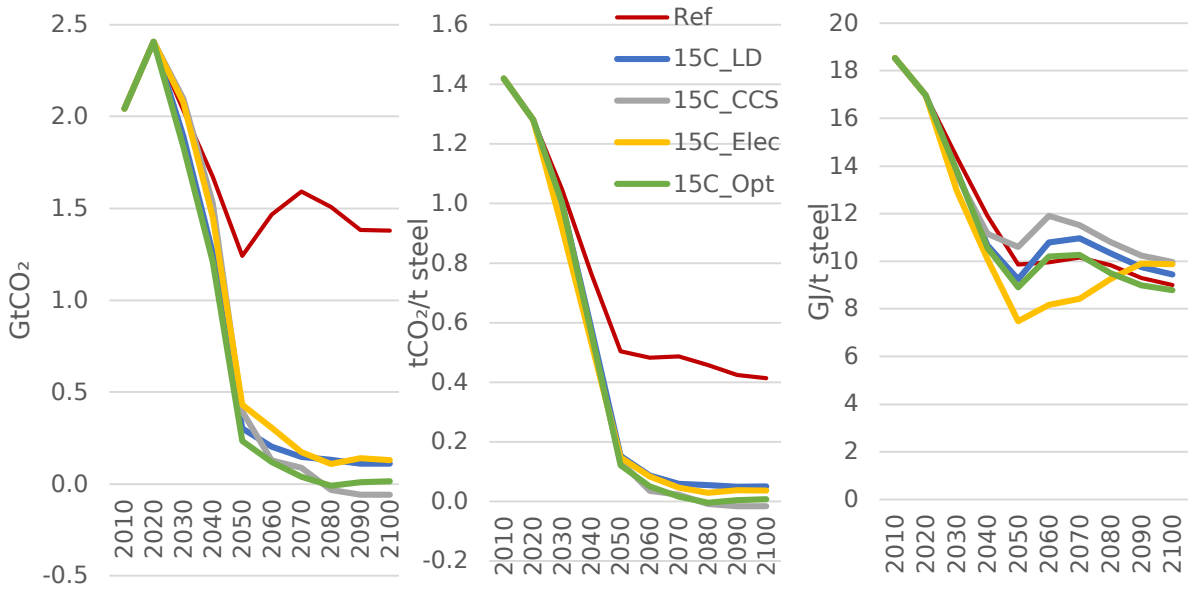
Steel sector emissions

The resulting CO_2 emissions of the steel sector are presented in Figure 4. Steel sector emissions in 2020 are estimated at 2.4 GtCO$_2$. Even without strong climate policies (Ref), emissions peak in the 2020s decade, decrease significantly and stabilize after 2040 to around 1.5 GtCO$_2$, with the CO_2 content of steel decreasing from 1.3 tCO$_2$/t in 2020 to 0.5 tCO$_2$/t in 2050.

With strong climate policies, the steel sector emissions decrease dramatically to around 0.3 GtCO$_2$ in 2050; the CO_2 content of steel reaches 0.1 tCO$_2$/t in 2050 for all 1.5°C scenarios, under an average carbon price in 2050 of 800 $/tCO$_2$. Net-zero emissions are reached in the second half of the century only thanks to the contribution of CCS technologies and biomass (during the 2070s for 15C_CCS and 15C_LD, not reached by the end of the century for 15C_Elec).

As evidenced by the 1.5°C scenarios, the carbon price, CCS availability and plant lifetime are the most important drivers for emission reductions (see also the sensitivity analysis in SI section 8). The shortening of lifetimes in the 1.5°C scenarios to allow a faster turnover is a significant contributing factor to the production mix change and fall in emissions. However, this presents the risk of considerable sunk costs in processes with unabated emissions.

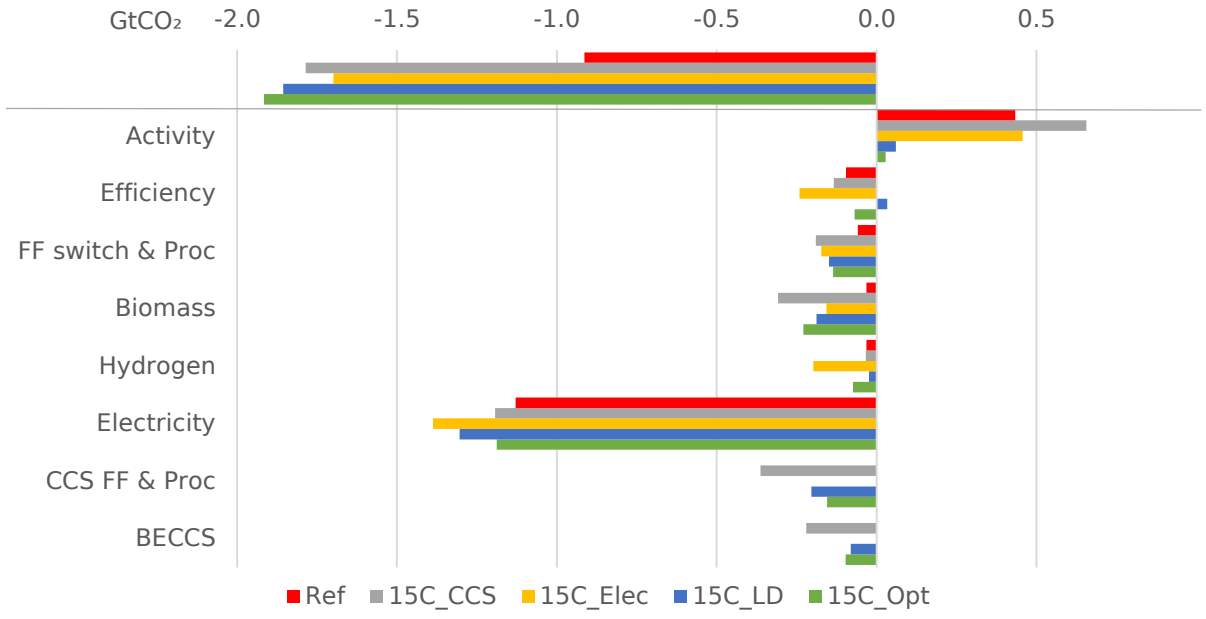
Figure 4: Global steelmaking emissions (left), emissions intensity per ton of output (middle) and energy intensity per ton of output (right)



Source: POLES model.

Overall, following the logarithmic mean Divisia index (LMDI) method[59], the main decarbonisation options expressed as a decomposition of emission differences between 2020 and 2050, averaged over the four 1.5°C scenarios, are (Figure 5): electricity (70%), biomass (12%), CCS (10%, most of which with fossil fuels), fossil fuel switch from coal to gas (9%), process efficiency (6%), hydrogen (5%). The increase in tons produced counts as an additional constraining factor for decarbonisation as it would otherwise lead to additional production-side emissions (activity, -17%).

Figure 5: Emissions reductions in 2050 compared to 2020 and distribution of decarbonisation options from 2020 to 2050



Source: POLES model. "Mitig vs 2020" refers to total emissions reductions in 2050 compared to 2020, decomposed in options below. Sector efficiency has been distributed across the "Efficiency" and "Electricity" options, given the large difference in energy use of the EAF process compared to all others. Hydrogen is sourced outside of the steel facility (green hydrogen is not accounted in electricity).

Steel sector investments and production costs

Investments to support the supply of steel (overnight investment costs of production capacities), both to replace ageing equipment and for greenfield plants, are considerable. They amount to an average of 11 G$/year over the

2021-2050 period in Ref, which are considerably lower (-54%) than the estimated investments over 2001-2020 of 25 G$/year as a result of demand growing much slower. Investments are higher in 15C_CCS (22 G$/year, +94% compared to Ref), given the costlier technologies chosen, the retrofitting towards CCS, but also the higher capacities installed (+24%) due to an even higher demand. This is mitigated by demand-side savings and material efficiency measures (15C_LD and 15C_Opt), where average investments are lower (14 G$/year, +19% compared to Ref).

As a result, taking into account the total costs (investment, raw materials, fuels cost, carbon price), the average ton of steel produced in the world becomes costlier. In Ref, the increase is small (+7% over 2020-2050); in 15C_CCS, steel is more than half as much (+67%) more expensive to produce in 2050 compared to 2020, from about 650 to 1080 $/t. If these costs were entirely passed down to the final consumer, this would make an average car (using 900 kg of steel) some 390 $ more expensive (or 1.4% more expensive considering 28,000 $/car); this is higher than in [60] (<1%) but consistent with the more ambitious climate target of 1.5°C in this study. This anticipated low-carbon premium can be a limiting factor in the expansion of clean steel production for first movers, and innovative solutions will be needed to decrease the risk for investors (such as rules to access public finance, purchase contracts for low-carbon products, group investments around industrial clusters) [61].

Whether costs would be passed down, especially the costs related to the carbon price, would be a policy-making question related to consumer protection and purchasing power beyond the scope of this study, as well as a matter of climate policy. With rising steel prices, it could be expected that the demand would adjust accordingly: this is indeed reflected in 15C_LD, which sees a steel demand that is 19% lower than Ref and a steel cost that is rises by 61% by 2050 (i.e., 50% higher than Ref in 2050). By comparing Ref and 15C_LD in 2050, the implicit price elasticity of steel demand is -0.54, which is within the range of values observed for long-term elasticities for energy products[62]. The steel saving measures could, however, be implemented by behaviour change and policy intervention with tools other than just pricing, such as building codes or equipment standards.

Of note, most of the production costs of steel are operating costs rather than fixed costs: the share of operating costs increases from 79% in 2020 to 87% and 90% in 2050 in Ref and 15C_CCS, respectively.

Hydrogen supply for steel

It then becomes an issue on how to supply the steel sector with sufficient quantities of low-carbon energies in a timely manner. This would be particularly challenging for new fuels that do not yet have a production, transport and distribution infrastructure in place, such as hydrogen.

Hydrogen production would have to move away from the current processes dominated by unabated fossil fuels (steam methane reforming, coal gasification) towards lower-carbon solutions, at a considerable cost (see SI section 7).

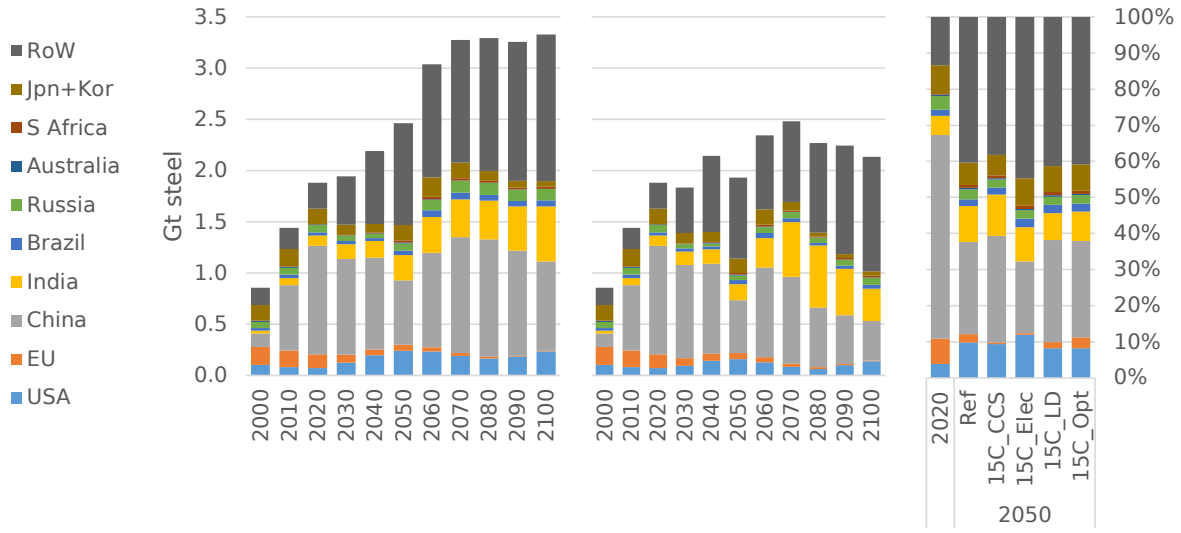
Our results show that hydrogen demand for steelmaking is projected to make up a relatively small share of overall hydrogen demand (as much as 6% of total hydrogen demand, in 15C_Elec in 2040), taking into account non-energy uses such as hydrogen as an intermediate product in nitrogen-based fertilizers, in oil refineries and other chemical processes. Other emerging uses, such as hydrogen fuel cells in transport and the use of hydrogen as an input to the production of synthetic hydrocarbons, consume larger amounts of hydrogen; in decarbonisation scenarios, they are projected to be the dominant uses of hydrogen worldwide[52], [63]. Thus, the steel sector is likely to not be a driving force in shaping the hydrogen production industry and its market price, and it is likely to be a price taker of hydrogen produced for multiple purposes. For the current most advanced pilot DRI-H2 projects, the same entity will be producing the hydrogen on-site using low-carbon grid electricity specifically, relying on other actors to expand grid capacity[64], [65]. However, DRI-H2 projects' electrolyser capacity is a small share of the overall hydrogen projects underway in Europe[61]. This raises questions as to whether self-production of hydrogen would be the most likely configuration for the steel sector, or whether the business model that would dominate would be hydrogen produced in a variety of ways and transported to the steelmaking site where it would be consumed.

3.3. Steel trade patterns to reorganize

The regional distribution of steel production, dependent on production capacities, production costs and transport costs, remains concentrated around China in the projections (Figure 6). The production over-capacity in certain regions resulting from changing demand patters redraws the map of potential importers/exporters (Figure 7). In the medium term, with standing capacities and a decreasing domestic demand, China could become a major net exporter. Certain regions change their trade status, from net importers to net exporters (USA, South Africa) at the expense of other exporters that reduce their exports (Russia, Brazil, Australia). The EU moves towards relying

massively on imports, while the Rest of the world moves from relying significantly on imports toward self-sufficiency.

Figure 6: World steel production by region, Ref (left), 15C_Opt (middle) and 2050 for all scenarios (right)



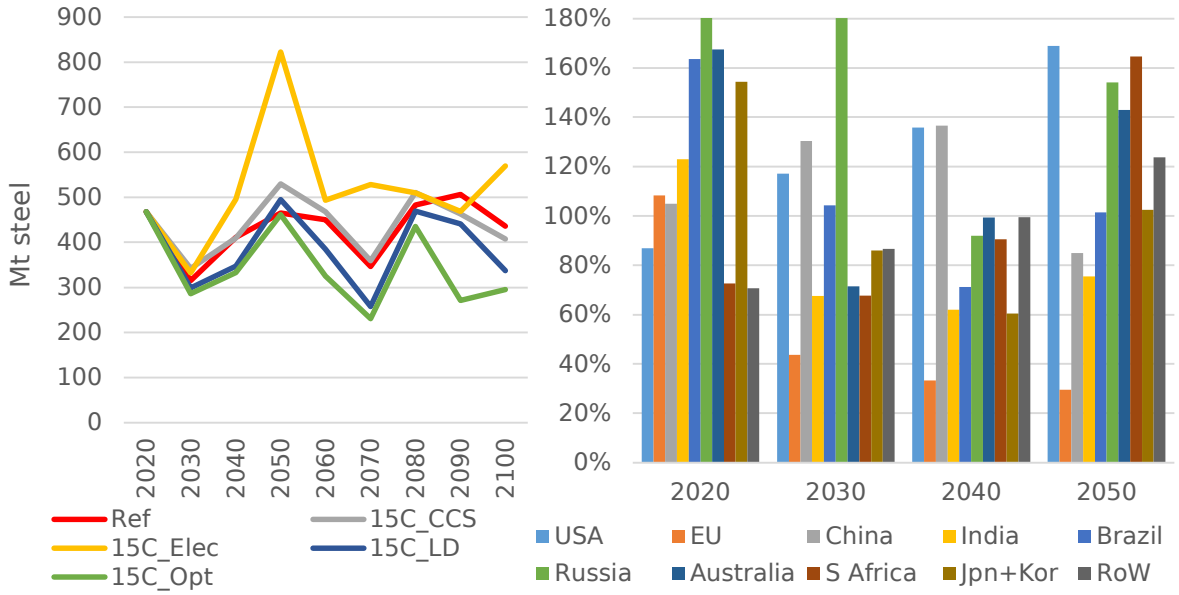
Source: POLES model.

In the longer term, the increase in transport costs becomes an important component of traded steel cost: on world average, from 6% to 11% and 15% in 2050 in Ref and 15C_Opt, respectively, resulting in more self-sufficient supply on average.

The implementation of climate policies usher small changes in the market shares of regions in the world steel production mix compared to Ref: in 15C_CCS, China +4% market share at the expense of EU, India and the Rest of the world; in 15C_Elec, China -6% at the benefit of the USA and the Rest of the world (15C_LD and 15C_Opt similar to 15C_CCS). Broadly, countries with a prevalent production mix based on EAF (e.g., USA) are better equipped to reduce emissions if CCS is unavailable and gain market share in 15C_Elec, while those with a predominantly BF/BOF-based mix (e.g., China) lose market share.

These relatively small changes in market shares are due to the uniform implementation of the carbon price in the 1.5°C scenarios in all regions; a fragmented climate policy with differentiated levels of decarbonisation effort across regions would result in a greater cost diversity and adjusted trade patterns.

Figure 7: Global steel trade (left) and regional independence rate (right) in the 15C_Opt scenario



Source: POLES model. Estimated 2020 value for Russia is 240%.

As global patterns of demand shift and production capacities adjust, steel trade (global net imports with the model's regional disaggregation) experiences changes in the coming decades, with less trade in the lower steel demand scenarios and overall volumes similar to the recent past (Figure 7). While traded volumes increased over the past decades and reached an all-time high in 2016, exports as a share of total production have actually been decreasing since 2000 (from 39% to 23% in 2020[48]), which is extended and accelerated in the projections (19% and 23% in 2050 in Ref and 15C_Opt, respectively). 15C_Elec shows a notable increase in trade by mid-century as the delay of CCS increases residual emissions in BF/BOF-rich countries and changes the regions' ranking of production costs.

These results have to be put in a wider context of country-level industrial policy. Additional non-cost deciding factors might contribute to the decision to relocate production or not. Given the importance of the steel sector in direct and indirect employment, EU policy has regulation to mitigate relocation risk and prevent carbon leakage (EU emissions trading scheme[66], carbon border adjustment mechanism[67]). Other factors include innovation and strategic concerns, as per the EU's proposed Net-Zero Industry Act to maintain or increase domestic production. Conversely, low-carbon steel producers might position themselves as exporters towards leading consumers that value low-carbon products (e.g., South Africa to EU[68], Emirates to Japan[69]).

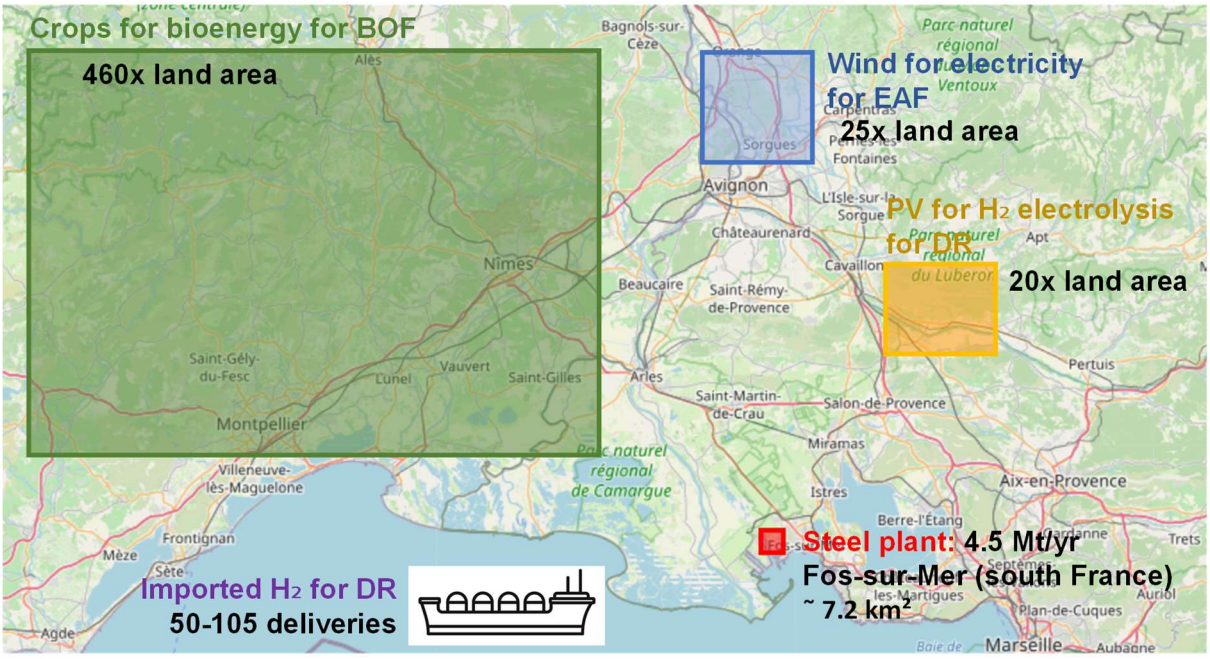
Moreover, in addition to new steel trade, the increase in electrification would also be enabled by recycling and large amounts of scrap trade worldwide.

3.4. Wider impacts

The supply of energy fuels, including hydrogen, to support the needs of the steel industry come with wider impacts on the energy system and on other sustainability indicators such as land use and water use.

In terms of land use (Figure 8), the low-carbon alternatives come at a significant premium, compared to a 1.6 km^2/Mt production capacity for a typical BF-BOF steel plant today[70]. A plant supplied entirely by hydrogen produced by electrolysis using solar power would require 20 times more surface (considering a 80 MW/km^2 land use for utility-scale PV[71]); importing the hydrogen by ship would require some 50 deliveries (considering an ammonia tanker carrying 1300 TJ/trip of NH3 similar to a long range oil tanker of 110,000 deadweight tons [72] and an 74% H_2-NH_3-H_2 round-trip efficiency[73], [74]) to 105 deliveries (considering a liquefied hydrogen tanker carrying 500 TJ/trip similar to an 125,000 m^3 LNG tanker[75] and 4% of losses[76]). In addition, a BF-BOF plant that would switch entirely to biochar and biomass would require 460 times more surface (considering 200 GJ/ha of bioenergy crops yield[77]), while a switch to EAF with zero-emissions electricity would require the power grid to install for instance wind capacities occupying the equivalent of 25 times the area of the BF-BOF plant (considering 8 MW/km^2 for onshore wind[78]). Positioning the energy production on a remote site would increase issues of supply logistics and transport losses. Given that steel plants are often located on shorelines to ease the import and export of feedstocks and products, and that steel plants are often in industrial areas where land already has competitive uses, there are significant challenges in low-carbon energy supply to enable low-carbon steel.

Figure 8: Indirect land requirements for different steel processes options



Map source: OpenStreetMap.org

In terms of renewables deployment rate, the expansion of low-carbon hydrogen would further burden the power system to install sufficient capacities of renewables to supply both electricity end-uses and hydrogen electrolysers. The decarbonisation of electricity poses significant administrative, investment and supply chain challenges already; wind and solar installation rates globally would need to increase by a factor of 11 in the 2040s compared to the 2015-2020 period (from 160 GW/year to 1,800 GW/year). Adding capacities for green hydrogen on top of that, as much as 35% additional by 2050, would raise that factor to around 16 (2,670 GW/year, 15C_Elec).

In terms of water consumption, if the above maximum of 15% of steel tons produced with the DRI-H2 process in 2050 are supplied by hydrogen produced with electrolysis, this would require 0.36 Gm^3/year of water (considering 9 L/kgH_2 stoichiometrically; 2.4 Gm^3/year for all steel production, 3.8 Gm^3/year for all hydrogen production). However, these volumes are small when considering the larger consumers of water such as agriculture (2,900 Gm^3/year in 2019[79]) or withdrawals for energy production mainly for power plant cooling (338 Gm^3/year in 2016[80]). While volumes are small, regional heterogeneity on water resources could raise local concerns of water scarcity. Furthermore, water could be recuperated from the DRI furnace shaft and recycled to produce hydrogen[40].

In terms of CO_2 flows, the carbon captured in steelmaking and other sectors (hydrogen production, power generation, other) would need to be transported with dedicated infrastructure to the point of sequestration. While the costs are estimated to be low on a per ton basis (around 10 $/t$CO_2$[81]), the infrastructure remains to be built entirely, or use repurposed fossil fuel infrastructure, with few actual projects for country- or continental-scale transport materializing as of 2023[82]. The world average steel plant of 2.3 Mt/year[83] would produce some 4.2 $MtCO_2$/year in the case of a BF-BOF plant equipped with carbon capture. This is comparable to the mass transiting through international gas pipelines (e.g., the Algeria-Tunisia-Italy TransMed pipeline capacity of 30.2 Gm^3 of natural gas over two lines, amounting to 11.6 Mt/year[84]), which underlines the scale of the effort required to put this infrastructure in place.

4. CONCLUSION

This paper presents work that gives new quantitative insights in the complex decarbonisation challenge of a sector perceived as "hard-to-abate"[42]. This work enriches the representation of industry sub-sectors in energy system models and consists in the state of the art in the way these issues are captured in energy system models. It provides an explicit picture of steel demand and its drivers, of steel production investment needs and of the effects of policy levers that are of interest to both policymakers and investors.

In this paper, we presented a new model detailing steel demand and multiple steel production pathways within a larger global multi-regional energy system simulation model. In order to assess the decarbonisation potential of the

steel sector in interaction with the rest of the economy, we built several scenarios of the future energy system with different sets of assumptions on policies, technologies and steel demand patterns. We examined to what extent and at what pace the iron and steel sector can reduce its emissions and the contribution of each decarbonisation option. Finally, we broadened the scope to some additional challenges in the provision of low-carbon energy to fuel the cleaner production of steel.

This study adds an original set of projections for steel demand to the literature. Without additional climate policies, we project global steel demand to increase at a decelerated pace compared to the past two decades, reaching a plateau from 2070 at nearly double the level of 2020. This is calculated in a bottom-up manner due to substantial increases in buildings floor surfaces, road transport fleet, power production system and infrastructure, all of which are ultimately driven by the underlying socio-economic conditions, if material used per unit of activity remain the same.

This study differentiates drivers for steel demand increase and savings, with a decomposition of effects that is new to the literature. The implementation of climate policies leads to a positive feedback effect on steel demand due to a faster equipment turnover and higher electrification; however, this increase would result in new low-carbon equipment and infrastructure that would yield large emissions savings. Introducing energy saving and material efficiency measures, which could be expected given the projected increase in steel production costs, would overcompensate this increase. Our demand projections in 2050 range from to 2.0 to 3.0 Gt. Overall, these projections are comparable to those of other studies: e.g., for 2050, 2.0-2.6 Gt in [85], 2.0-3.4 Gt in [86], 1.5-2.5 Gt in [87] and 1.7-5.2 Gt in [88].

We provide "what-if" projections of decarbonizing steel supply based on technology availability and production costs, as opposed to normative scenarios of technology substitution[89] or potentials assessments[13]. The CO_2 emissions of the steel production sector are projected to decrease even without strong climate policies: with increased recycling thanks to the higher availability of steel scrap, electrification increases at the expense of the currently dominant blast furnace process and thereby yields important energy efficiency gains. Strong climate policies would be needed to push decarbonisation further. In the context of a full decarbonisation of the economy compatible with a 1.5°C climate change target, steel sector emissions would decrease by nearly 90% in 2050 compared to 2020. This achieved with the use of hydrogen in direct reduction but especially thanks to CCS technologies, increased recycling and electrification and use of biomass. The steel sector could reach net zero as early as the 2070s; however, a delay in the availability of CCS technologies would make this unfeasible.

The costs of material efficiency measures are difficult to quantify; however, the economic assessment hints at their attractiveness as emission mitigation measures. In all decarbonisation scenarios, the steel production cost is projected to increase by half over 2020-2050, mainly driven by the price of energy inputs (including carbon pricing), thereby providing a strong impetus for the implementation of the savings and efficiency measures as an economically efficient option for decarbonisation.

The geographical distribution of steel production as well as the importer/exporter status of world regions are projected to experience in-depth changes. However, as a result of increasing transport costs, global steel trade volumes are projected to stabilize over time.

Although the hydrogen route has gathered significant investments for electrolysis and steel production in recent years[65], [90], [91], we project it to make up only a small part of the solution for steel due to its high supply cost. Direct reduction using hydrogen is projected to produce, at most, 15% of global steel throughout the century and across all scenarios, with a wide diversity across regions. The above share is reached in an optimistic configuration (green hydrogen produced in proximity to the steel plant, ambitious electrolyser cost decreases). Hydrogen demand for steelmaking is projected to make up a minority share of total hydrogen demand. This would put the steel sector in a position of price taker and raises questions as to which business model is likely to materialize, one of steelmakers purchasing hydrogen on the market or one where hydrogen and steel production is co-located.

Furthermore, the provision of large enough quantities of low-emissions energy to the steel sector would pose significant challenges in many fields. The indirect land use would increase severalfold to provide renewable electricity, green hydrogen or biomass. The pace of installation of renewable electricity capacities would need to increase by as much as 16 times compared to the recent past. The carbon transport and sequestration infrastructure remains to be built.

This study confirms the considerable multi-sectoral challenges related to the decarbonisation of the steel sector. Although policymaking and private sector interest in this issue has increased in recent years, more needs to be done in multiple fronts: adapt climate policy to align investments in clean technologies, mitigate bottlenecks in clean

energy supply and CO_2 transport infrastructure and anticipate potential adverse effects in land use, water use and employment.

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