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Analysis

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Limited quantity and quality of steel supply in a zero-emission future

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Achieving a zero-emission future depends greatly on how steel production is decarbonized within a limited time frame. Here we show that the production of zero-emission steel is possible but that the quantity and quality of steel may be limited by scrap downcycling. Using Japan as a case study, our analysis shows that most steel scrap is currently downcycled into construction materials, thereby limiting scrap-based steel to only 20% of the total steel used for automobiles, compared to 60% for buildings. Under a strict carbon budget, such downcycling practices could limit the production of steel used for automobiles to ~40% of current levels by 2050, even if production technology progresses according to the roadmap. The results indicate that steel users should not take the current level of steel supply for granted in a zero-emission future. Decarbonizing the steel sector, therefore, will depend not only on stand-alone efforts by the steel industry but on joint action with steel users to enable scrap upcycling and service provision with less steel use.

The science is clear: emissions from all major sectors must be reduced quickly to zero to avoid the destructive impacts of climate change[1]. The key question is how this can be achieved. Several sectors, including electricity and road transport, already have solutions available on a commercial scale, including renewable energy and electric vehicles[2]. In contrast, such critical solutions do not yet exist at scale in the steel sector, which accounts for ~7% of global CO_2 emissions[3]. The steelmaking process involves using coke to reduce iron oxide ore and the combustion of fossil fuels to generate high temperatures, making it one of the most difficult sectors to decarbonize[4]. Thus, a critical challenge in reaching a zero-emission future centres on how to decarbonize this hard-to-abate sector within a limited time frame.

The scientific basis for the debate in this domain has been supported mainly by technology-rich integrated assessment models that explore possible technology mixes and policy options[5,6]. However, these models face two major challenges when applied to evaluations of the steel sector. First, the solutions rely heavily on innovative production technologies, including carbon capture and storage (CCS) and hydrogen-based steelmaking, due to the model structure, in which future steel demand is given as an exogenous variable in the technology selection optimization routine[7–10]. In response, the industry has increased its efforts and commitment to implement innovative production technologies to decarbonize its scope 1 and 2 emissions[11]. However, these technologies still face serious technical, economic and social challenges[12,13] and have yet to be implemented at scale. Recent studies have questioned whether their implementation can be scaled up in time[14–16]. Second, the models treat steel as a single commodity and do not consider the quality of different steel products. Steel is shipped as a variety of products with different shapes and specifications, with markedly different production processes and end-uses[17,18]. It is therefore unclear how much steel, and what quality, can be produced and used under a carbon budget that is consistent with internationally agreed climate targets. Such a lack of understanding makes it difficult to prepare for a scenario in which innovative production technologies fail to scale up sufficiently and in time.

Several pioneering efforts based on material flow analysis have sought to complement these knowledge gaps by exploring different decarbonization scenarios without resorting to the mass deployment of innovative production technologies[19–23] or by integrating quality issues in the steel recycling system[24–26]. A particularly innovative study

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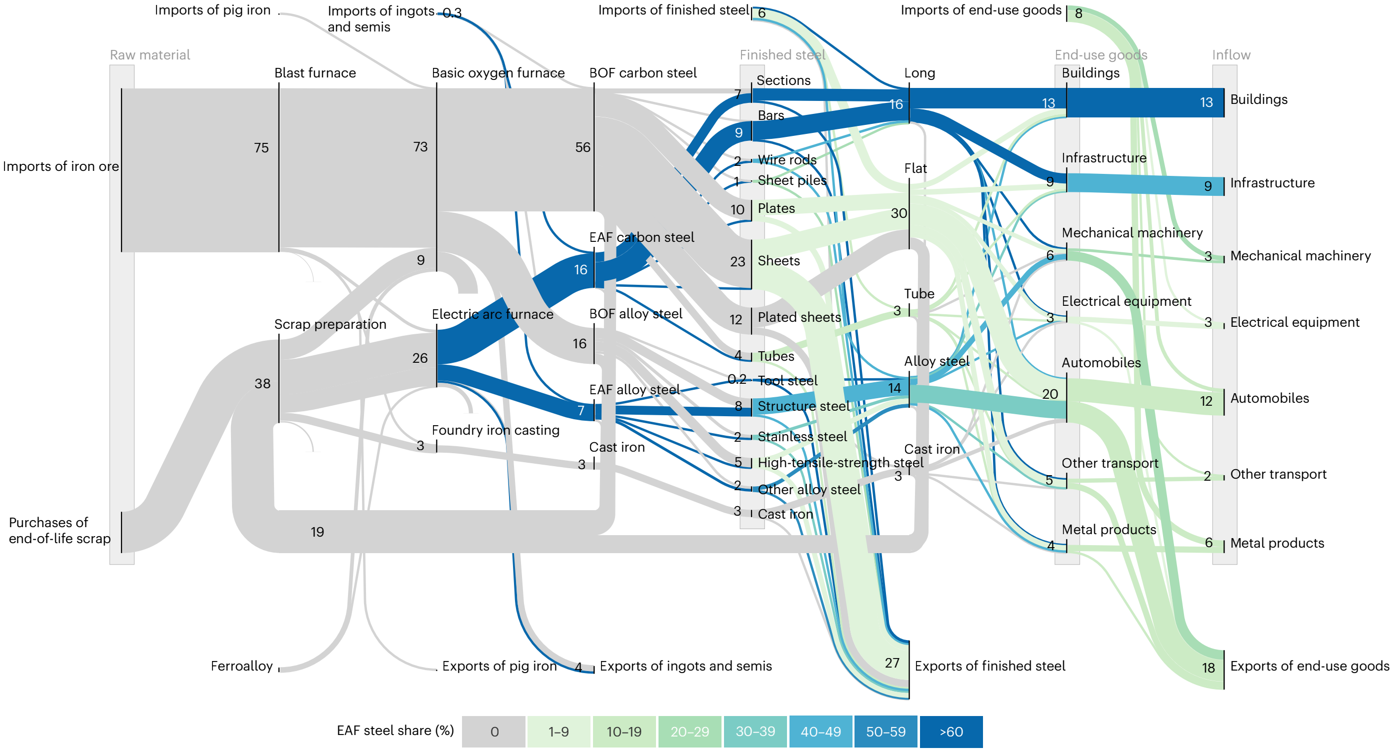

Fig. 1 | Map of steel flows from raw materials to end-use goods in Japan in 2019. The thickness of each flow reflects steel weight and the colour reflects the share of steel made from scrap-based EAF route. The iron ore flow represents the iron embedded within the ore and excludes the mass of oxygen and gangue. All flows are shown to scale in Mt yr^{-1}. The Sankey diagram was designed with floWeaver[55].

in this domain showed that impurities in scrap steel can constrain future global steel recycling[27]. The study demonstrated that it would be increasingly challenging to produce high-grade steel products with strict impurity tolerances (for example, sheet steel for deep drawing) from recycled steel. Yet, what is still missing is a link to a zero-emission context. The existing scenarios assume that future steel production will grow according to the in-use stock evolution patterns of current industrialized countries without any constraints. It is, therefore, not clear how stringent climate policies will affect future steel production and its quality or when, and to what extent, specific challenges will arise in industrialized countries where in-use stocks and demand growth have already stabilized.

Our work addresses these knowledge gaps by constructing detailed maps of current steel flows and systematically assessing the impacts of imposing a carbon budget on future steel flows. The map of current steel flows is constructed by aggregating and reconciling fragmented data on production, trade and yields in each process using a series of mass-balance equations. Future steel flows under the carbon budget are calculated using a newly constructed 'material budget model' that combines optimization techniques and a set of mass-balance equations[21]. The model derives an industrial structure that is consistent with the carbon budget under various technological assumptions by treating material flows as endogenous variables in the optimization routine. We apply the model to Japan, given the magnitude of its emissions, stock saturation trends and the availability of the necessary data sets for the modelling. Japan is the world's fifth-largest emitter[28] and the world's third-largest steel producer[29], which means that it plays a central role in decarbonizing the steel sector.

Results

Current steel flows and downcycling practices

The detailed map of current steel flows shown in Fig. 1 clearly depicts the industrial structure of mass imports and mass exports, importing all iron ore and exporting large volumes of steel products. Particularly distinctive are the categories of domestically produced sheet steel and automobiles, approximately 60% and 50% of which are exported overseas, respectively. Such an industrial structure relies heavily on the ore-based blast furnace/basic oxygen furnace (BF/BOF) route, which is considerably more carbon-intensive than the scrap-based electric arc furnace (EAF) route. Currently, the BF/BOF route accounts for ~75% of total crude steel production, while the EAF route accounts for ~25%. However, ~90% of EAF-derived carbon steel is processed into long products, such as sections and bars that are used mainly in buildings and infrastructure. Consequently, EAF-derived steels account for <10% of the total production of high-grade steels, such as sheet steel and high-tensile-strength steel, which are often used in automobiles. This phenomenon, in which material processed from waste has a lower value than the original material, is referred to as downcycling[30].

Such downcycling practices are used because tramp elements (copper and tin) mixed in scrap are difficult to remove in the current steelmaking process and nitrogen is easily mixed into liquid steel during arc melting[31–33]. Elevated contents of tramp elements and nitrogen in steel can cause various problems, including increased susceptibility to cracking at high temperatures, steel quality deterioration and strain aging, making it challenging to produce high-grade steel through the EAF route[34,35]. Consequently, the amount of EAF-derived steel contained in buildings, infrastructure and automobiles, which together account for >70% of the total finished steel, varies markedly. The building and infrastructure industries obtain about 40–60% of their total steel requirements from the EAF route. In contrast, EAF-derived steel accounts for <20% of all of the steel inputs into the automotive industry, highlighting a high reliance on more carbon-intensive steel. Such a phenomenon is indicative of the high requirement for high-grade steel in the automotive industry and the emission-intensive nature associated with downcycling of scrap steel.

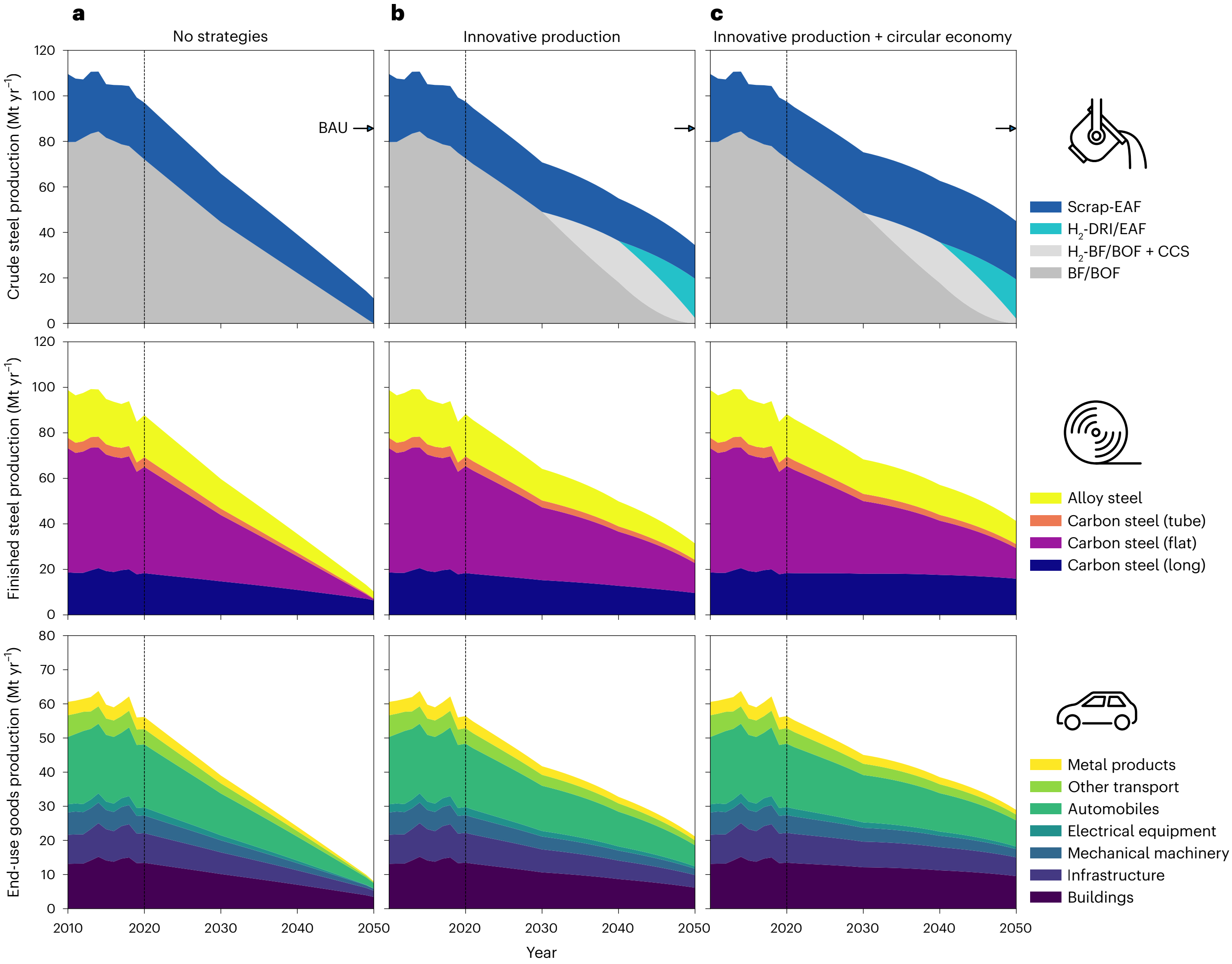

Fig. 2 | Production of crude steel, finished steel and end-use goods, available under the carbon budget in Japan, 2010–2050. a–c, Three scenarios are considered here: no strategies (**a**), innovative production (**b**) and innovative production + circular economy (**c**). The vertical dashed lines mark the year in which the future projections begin (2020). The data for 2050 business-as-usual (BAU) crude steel production are from a national energy modelling study[36].

Future steel flows under a carbon budget

The key question is how much steel and what quality, can be produced and used under a carbon budget if current downcycling practices continue. This question essentially depends on the extent to which the steel sector takes responsibility for a zero-emission future and how production technology and the circular economy progress. Our central assumptions are that the steel sector has a responsibility to meet national targets as well as the commitments set out in the industry's technology development roadmap. We assume that emissions from the steel sector are regulated according to a carbon budget that is set on the basis of the national target of a 46% emissions reduction by 2030 (compared to 2013 levels) and reaching carbon neutrality by 2050. In this case, the 2050 carbon budget is deducted from the findings of indepth national modelling study[36], which considered carbon uptake by forests and other sinks and is used as a boundary value to ensure consistency with global commitments. Advances in production technology and in the circular economy can manifest as one of two scenarios. The first is the no strategy case, where all modelling parameters are held constant over the course of the scenario. The second case is where there are ambitious changes in production technology and the circular economy, with rates and levels of implementation based on industry roadmaps and scientific literature (Supplementary Table 11 and Figs. 5–8). Specific interventions include decarbonizing the electricity supply, improving energy efficiency, replacing coke with hydrogen in BF with CCS, producing hydrogen-based direct reduced iron (H_2-DRI), increasing domestic recycling capacity and extending product life, while excluding the adoption of any carbon offsetting scheme. The model solves for a steel flow structure that maximizes the available in-use steel stock within the imposed carbon budget while respecting a series of mass-balance constraints. The underlying logic is that our demand for services is not met by steel production but by the in-use steel stock accumulated in society as products and infrastructure[37].

The model reveals that the production of steel available under the carbon budget would be far more limited compared to the current production capacity (Fig. 2). This result reflects the limited resource availability. The zero-emission compatible production technologies currently being pursued by the industry are mainly H_2-DRI and scrap-based EAF, both of which are linked to non-emitting electricity. Thus, steel production in a zero-emission future essentially depends on the availability of three resources: electricity, hydrogen and scrap.

In the most pessimistic case, where emissions from the steel sector are regulated to stay within the carbon budget without progress in production technologies and the circular economy, the BF/BOF route will need to be phased out by 2050, with crude steel production

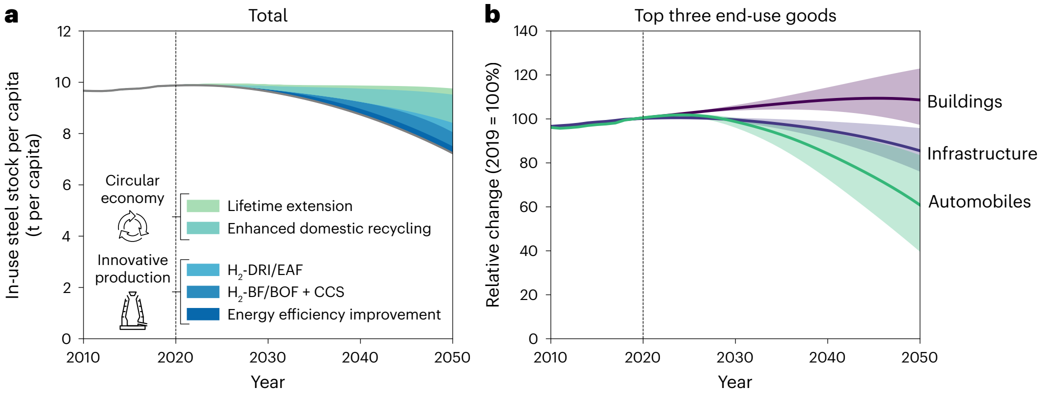

Fig. 3 | In-use steel stocks available under the carbon budget in Japan, 2010–2050. a, Total per capita in-use stock. **b**, Relative change in top three end-use goods. **a** depicts the increase in available in-use stock within the carbon budget as a result of advances in production technology and the circular economy. In **b**, the coloured bands around each line show the maximum and minimum values of the estimates, which depend on the degree of advances in production technology and the circular economy. Solid lines represent the means of scenarios. Vertical dashed lines mark the year in which the future projections begin (2020).

limited to ~10% of current levels (Fig. 2a). By extension, the production of finished steel and end-use goods in 2050 would likewise be limited to ~10% of current levels. If production technology developments progress according to the industry roadmap, then the available production of crude steel in 2050 could increase to ~35% of current levels (Fig. 2b). However, the non-emitting electricity, and thus green hydrogen, available to the steel sector is not infinite; even if the H_2-DRI/EAF route were deployed at a scale that increases the non-emitting electricity that is available to the industry and fuel production sectors, production capacity would still fall far short of current levels. This trend holds true even if the H_2-DRI/EAF route is implemented much faster than the uptake of non-emitting electricity, for example, by reducing electricity demand in other sectors or by importing hydrogen from overseas (Supplementary Fig. 9). These results clearly illustrate the difficulty in expecting the H_2-DRI/EAF route to make up for all of the current production capacity by 2050. The remaining option for increasing production capacity under the carbon budget is to expand the scrap-based EAF route. Instead of exporting scrap overseas, enhancing domestic recycling capacity could increase the available production to ~45% of current levels or ~45 Mt by 2050 (Fig. 2c). Yet, due to limited scrap availability (partly because of extended product life), the available production is far from reaching the same scale of production capacity as today (~100 Mt) or 2050 business-as-usual production (~86 Mt)[36]. Taken together, these results suggest that maintaining current levels of steel production capacity by 2050 will be challenging under the carbon budget. Thus, zero-emission steel production is possible by 2050 but in limited quantities relative to current production levels.

Notably, such steel supply constraints might not be uniform for all end-use sectors. If current downcycling practices continue, then the production of high-grade steel could be more severely constrained compared to long products as the BF/BOF route shrinks. Specifically, the available production of long products could be constrained to ~90% of current levels, while flat products could be more severely limited to ~30%. Consequently, the steel available to the building industry could be ~70% of current levels, while the automotive industry, the current primary user of high-grade steel, could face steel supply constraints as severe as ~40% of what it is today by 2050. These results suggest that steel supply in a zero-emission future could be limited not only in quantity but also in quality due to the downcycling practices of scrap steel.

Evolution of in-use steel stock

Along with such supply constraints, the steel that is accumulated as products and infrastructure (in-use stock) in society could be far less by 2050 than it is at present (Fig. 3). If no progress is made in production technology and the circular economy, then the in-use steel stock available under the carbon budget could decline from the current level of ~10 t per capita to ~7 t per capita by 2050 (Fig. 3a). This decline means a transition to a society living on fewer steel products than at present. Such a transition to a society with constrained steel stocks could be mitigated by the progress of production technologies and the circular economy as per the industrial roadmap. However, the key point here is the difference in the level of constraints imposed by the types of end-use products. A closer look at the per capita stock levels for specific end-uses shows that buildings and infrastructure could maintain levels that are similar to current levels, even under the carbon budget (Fig. 3b). In contrast, the per capita steel stock as automobiles could decrease to 40–80% of current levels by 2050, depending on advances in production technology and the circular economy. This is due to higher requirements for high-grade steel and shorter product life spans compared to construction applications. The results show that our demands for goods and services in a zero-emission future, especially those related to automobiles, will need to be met using less steel than is currently used.

Discussion

Overall, the key message of our analysis is that while zero-emission steel could be produced through the efforts of the steel industry, this would only be possible in limited quantities for steels of certain quality if current downcycling practices continue. This perspective is not unique to Japan and could become apparent at a global level as downcycling of scrap steel increases[27,34]. Despite the potential for such steel supply constraints in a zero-emission future, the Japanese government and industries are currently leaving the decarbonization of the sector entirely to innovative production technologies[38,39]. Relying solely on innovative production technologies is equivalent to society completely entrusting the steel industry with finding a solution. Now that climate change is essentially an issue of timing, steel users should not assume that they will be guaranteed the same level of steel supply as they have today in a zero-emission future. Instead, they should look now for ways to provide the same services while using less material inputs. Decarbonizing the steel sector will therefore depend not only on stand-alone efforts by the steel industry but also on joint action with steel users.

So what action is required from steel users? What is clear is that a business model should be developed that provides the same services with less material use by improving material efficiency[40]. Technologies and systems for achieving this would include improvements in product longevity (through reuse, repair and remanufacturing), goods sharing, lightweight design, material substitution and process yield improvement[41]. One pioneering study in 2010 argued that even a 50% emission cut by 2050 would require substantial reductions in steel demand through improved material efficiency[23]. The limited quantity and quality of steel supply, as indicated in this study, urgently reinforce this previous message that material efficiency must be a fundamental component of mitigation strategies. The automotive industry in particular, which may be subject to severe steel supply constraints, will need to rethink its current business model. Instead of selling consumers lots of large and heavy electric vehicles, they can provide mobility services to consumers in the form of small and light electric vehicles[42]. Evidence already exists that focusing on 'service provision' rather than 'ownership' through car-sharing and ride-sharing can almost halve the need for automobiles while meeting our mobility needs[19,43–45]. Looking at a wider range of steel products, multiple lines of evidence show that the same level of service can be provided at half the level of in-use steel stocks currently used by high-income countries[19,21,46]. It is therefore possible to meet our service demands in a world of constrained steel supply if technologies and systems to improve material efficiency are placed at the heart of the decarbonization plan. In this case, given the steel-intensive nature of the technologies necessary for climate change mitigation and adaptation, such as renewable electricity, railways and flood protection infrastructure[47], a balanced plan will be crucial for reducing total steel use while building and managing these essential infrastructures.

Another critical measure is to promote upcycling to produce high-grade steel using the scrap-based EAF route. This measure is particularly important from two perspectives: to increase the steel supply to industries that are dependent on high-grade steel and to keep the steel industry profitable in the face of declining total production. While promoting upcycling may reduce the available supply of construction-grade steel, whether this will be a serious issue needs to be considered in conjunction with other construction materials. A recent study suggested that a substantial reduction in the construction of buildings and infrastructure is required to achieve zero emissions in cement and concrete production[48]. Further, a movement exists to use engineered timber instead of steel and concrete to reduce emissions from building construction[49]. While this study does not capture such material linkages and therefore cannot provide any clear insights into the extent to which steel will be needed for future construction, producing high-grade steel by upcycling rather than producing construction-grade steel is clearly in line with these future narratives. Given the relatively high prices of high-grade steels, this strategy will also directly benefit the steel industry[34]. The key challenge is how upcycling can be realized. Previous studies have demonstrated that, even in a future of increasing steel production, extensive dilution of recycled steel with ore-based steel is needed to deal with copper contamination[27]. However, as indicated in this study, such a strategy will become increasingly challenging in a future of limited production growth. What will be urgently needed, therefore, is collective action between the steel industry and steel users to implement the technologies and systems necessary to cope with impurities; such processes would probably include changes to product design, advanced sorting, alternative shredding and processing and composition manipulation[50,51]. The various private partnerships that have been recently established to close the loop in the automotive industry (for example, between BMW Group and Salzgitter AG) are important initiatives in this domain. Given that innovative ore-based steelmaking can be constrained by the limited availability of non-emitting electricity, and thus green hydrogen, joint action between the steel industry and steel users is crucial for promoting upcycling.

Looking closely at the Japanese steel industry, it is clear that the current industrial structure of mass imports and mass exports is incompatible with a zero-emission future. This is because the imported ore-based BF/BOF route, which currently accounts for the production of nearly all high-grade steels, is inconsistent with a zero-emission future. Thus, if the government and industry stick to the current decarbonization plan, Japan could lose its international competitiveness in response to the growing need for zero-emission steel. Instead, a shift to an industrial structure based on the production of high-grade recycled steel should be investigated, taking advantage of the high levels of scrap availability and recycling infrastructure. According to detailed furnace-level data, Japan's aging blast furnaces will be phased out by 2038 if they are not refurbished[52]. Japan, therefore, has an important opportunity to move from the BF/BOF route to the EAF route without creating stranded assets. A key prerequisite for such a shift, however, is to revisit the assumption that innovative production technologies will automatically decarbonize the sector and to place upcycling at the heart of future industrial strategies. It is important to note here that Japan has an industrial structure with more stringent impurity requirements than most countries. For example, copper tolerances, which are the main impediments to upcycling, are considerably stricter in sheet steel for deep drawing ($\leq 0.06\ \mathrm{wt\%_{Cu}}$), mainly used in the transport sector, than they are for construction bars ($\leq 0.4\ \mathrm{wt\%_{Cu}}$)[25]. The Japanese transport sector currently uses 42% of the total steel supply, which is much higher than the United States (26%)[18], the United Kingdom (23%)[53], China (12%)[54] and the global average (13%)[17]. Japan is therefore more vulnerable to copper contamination than other countries, making the establishment of upcycling systems particularly important and urgent.

Overall, our analysis suggests two key innovation opportunities that are currently underemphasized in the steel sector decarbonization plan: (1) improving material efficiency to provide the same level of service with less steel use and (2) upcycling to produce high-grade steel via the scrap-based EAF route. Our analysis does not negate the need for investment in innovative production technologies, such as hydrogen-based steelmaking or CCS. Rather, what this study emphasizes is that the arsenal required to decarbonize the steel sector should include far more strategic options, instead of simply relying on silver bullet production technologies. Placing material efficiency improvements and upcycling at the heart of the decarbonization plan will decrease the likelihood of an overreliance on innovative production technologies and allow us to prepare for the risk of failure to scale up these technologies sufficiently in time.

Methods

Constructing a steel flow map

A detailed map of current steel flows is constructed by aggregating and collating fragmented data using a series of mass-balance equations. The starting point of steel flows is the procurement of raw materials: iron ore and scrap. Iron ore is fed into BF along with limestone and coke, where it is reduced to pig iron. Most of the pig iron is decarburized in the BOF by injecting oxygen to produce liquid steel, while some of the pig iron is also used for iron casting. In this process, scrap generated from continuous casting and rolling is also fed into the BF/BOF route, absorbing the exothermic oxidation heat of carbon and contributing to furnace cooling. Scrap that is treated on the market—called fabrication scrap and end-of-life scrap—is fed mainly into the EAF, where it is melted by arc discharge heat to form liquid steel. Globally, some iron ores are reduced directly at low temperatures using a reducing agent such as natural gas but this is not currently done in Japan. Liquid steel produced by the BF/BOF route and the EAF route is transformed into semifinished products such as slabs, blooms and billets by continuous casting. Semifinished products are then processed into finished steel products such as plates, bars and wires through rolling. At this point, finished steel products can be divided into carbon steel, in which carbon is the main alloying element and alloy steel, in which manganese, nickel, chromium, molybdenum and other elements that are added to improve performance. Finally, finished steel products are shipped to various industries and manufactured into end-use goods, such as buildings, infrastructure, machinery and automobiles.

The steel flow from raw materials to finished steel products is structured on the basis of industry shipment data, trade statistics and furnace-specific material supply and demand data. In this study, reflecting the difference in the data structure between carbon steel and alloy steel, carbon steel flows are categorized by shape (for example, bars and sheets), while alloy steel flows are structured by type (for example, stainless steel and high-tensile-strength steel). The steel flows from finished steel products to end-use goods are linked by an allocation matrix and a fabrication yield matrix, as reported in a previous study[17]. These matrices describe the allocation from each finished steel product (14 rows) to each end-use good (7 columns) and the resultant yield. Please see Supplementary Tables 1–4 for detailed calculations and data.

Exploring future steel flows

Future steel flows under the carbon budget are estimated using a so-called 'material budget model', which combines a series of mass-balance equations with optimization routines[21]. The objective is to maximize the in-use steel stock within the scenario period under the carbon budget and the objective function is formulated as an intertemporal linear programming model. The main feature of the model is that it derives a steel flow structure that is consistent with the carbon budget under various production technology and circular economy assumptions, while ensuring dynamic mass-balance in the system. In this case, the level of implementation of both production technologies and the circular economy is predetermined on the basis of industry roadmaps and academic findings. The concept is the opposite of the general integrated assessment model, which explores a production technology structure that satisfies specific carbon emission constraints given future steel flows based on cost considerations[7]. The procedures used in this model allow us to identify which, how and to what extent steel flows need to change if innovative production technologies cannot be scaled up in time and to explore key intervention opportunities from a material flow perspective. The carbon budget is based on a national target of a 46% reduction by 2030 (compared to 2013) and carbon neutrality by 2050. In this case, the 2050 carbon budget is deducted from an indepth national modelling study[36], which takes into account carbon uptake by forests and other sinks and is applied as a boundary value to ensure consistency with global commitments. Detailed formulations and data can be found in the Supplementary Information.

Considering that the future is uncertain, the following three scenarios are envisioned for the future development of production technologies and the circular economy. It should be noted that all of these scenarios are subject to the carbon budgets described earlier.

(1) No strategy: all modelling parameters are held constant during the scenario period. This scenario is regarded as a benchmark for exploring the effectiveness of each intervention measure.
(2) Innovative production: the development of the production technologies currently on the table progresses according to the industry roadmap. Specific technologies include energy efficiency improvements in both BF/BOF and EAF routes, substitution of coke with hydrogen in BF with CCS, H_2-DRI and decarbonization of the electricity supply.
(3) Circular economy: the transition to a circular economy progresses as steel is used longer and more cyclically in society. Specific measures include increasing domestic recycling capacity and extending product life (through measures such as reuse, repair and remanufacturing).

Detailed assumptions are shown in Supplementary Table 11 and Supplementary Figs. 5–8. It is important to note that some key assumptions, such as the supply of non-emitting electricity available to the H_2-DRI route, are based on the national modelling study that does not assume a major transformation of the steel industry[36]. In practice, industrial transformation has a substantial impact on the energy supply sector but such feedback is not considered here. As discussed in the detailed literature review[5], linking the transformation of the steel industry, as described in this study, to national models is clearly the next important research step for capturing more holistic impacts.

Reporting summary

Further information on research design is available in the Nature Portfolio Reporting Summary linked to this article.

Data availability

The input data and model results of this study have been deposited on GitHub (https://github.com/takumawatari/material-budget-steel). Source data are provided with this paper.

Code availability

The full model code is available on GitHub (https://github.com/takumawatari/material-budget-steel).

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Author contributions

T.W. designed the study. T.W. performed the analyses. T.W., S.H., K. Nakajima and K. Nansai prepared the manuscript.

Competing interests

The authors declare no competing interests.

Additional information

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