

What bulk material production is possible on a transition to net zero emissions by 2050 with limited zero emissions resources?

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ARTICLE INFO

Handling Editor: Yang Liu

Keywords:

Bulk material production
Zero emissions resource
GHG emissions mitigation
Industrial emissions
Net zero production

ABSTRACT

Global production of bulk materials such as steel, paper, and aluminium has tripled over the past three decades and decarbonising their production is a difficult challenge. The transition to net zero emissions depends on three key zero emissions resources, non-emitting electricity, biomass, and carbon storage. This paper develops a model to anticipate how likely deployment of these three resources will constrain bulk material production on the transition to net zero emissions by 2050. The results predict that 2050 supply of steel, paper and aluminium will be up to 40% lower than demand. To address this shortfall, policy should promote a more rapid deployment of zero emissions resources in parallel with the strategies of material demand reduction.

Synopsis: This paper quantifies potential production levels of aluminium, steel and paper on a trajectory that achieves net zero emissions by 2050 given constraints on zero emissions resources.

1. Introduction

The production of steel, aluminium and paper contribute significantly to global GHG emissions due to their high specific energy demands and high levels of production. It is possible to produce all three materials with low to zero emissions. Bataille et al. (2018), for instance, conclude that reducing industrial GHG emissions to levels compatible with the Paris Agreement may be technically possible using renewable energy sources and hydrogen. Both the European Union and the United Kingdom have recently announced strategies for decarbonising industrial production systems using hydrogen (BEIS, 2021) and carbon capture and storage (European Commission, 2018). However, despite these intentions, the IEA finds that industrial production is currently not on track to meet the goals of the Paris agreement (IEA, 2021a).

Rissman et al. (2020) review integrated assessment models and scenarios and compare hydrogen demand and CCS rates across these scenarios, alongside emissions. Despite including only direct process emissions, residual emissions are at least 2 Gt in 2050 across all considered scenarios. Similarly, Wang and Chen (2019) estimate residual (industrial) emissions of up to 2 Gt in 2050 for China, India, and Western Europe using TIMES. A broad range of related models have been used to estimate the energy demands of decarbonisation. For example, use a TIMES model to estimate that renewable electricity demand in Europe in 2050 will be around 5500 TWh, if zero emissions

targets are met. For Europe, a model with high shares of renewables is provided by the JRC (European Commission, Joint Research Centre, 2018). Commercial tools like EnergyPLAN (Lund and Thellufsen, 2022) or PLEXOS (Plexos, n.d.) are also used for assessing country-level and European electricity systems. These types of model, comprehensively reviewed by Ringkjøb et al. (2018) come from the tradition of economics modelling and are rooted in cost optimisation, based on adjusting technology preferences and capacity at various timescales. The work of this paper, in contrast, comes out of the tradition of Mass Flow Analysis and is rooted in physical flows of materials and resources and the capacity of the processes that transform them.

Material production is expected to increase over the next three decades. Watari et al. (2021) anticipate that demand for major metals will increase significantly until 2100, while the OECD (2019) note that resource demand is expected to double by 2060. IEA (2021b) also assumes significantly increased material production in the roadmap “Net Zero by 2050”. A few studies consider material demand reduction, depending on direct linkages between physical demand and use rather than simply economic flow (Bataille et al., 2018). However, as Papadis and Tsatsaronis (2020) argue, decarbonisation pathways usually assume material demand will increase with population growth, without considering other options.

Decarbonisation pathways vary for each material. For steel, Wang et al. (2021) demonstrate that the carbon budget for steel production up

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<https://doi.org/10.1016/j.jclepro.2023.138346>

Received 4 January 2023; Received in revised form 6 July 2023; Accepted 4 August 2023

Available online 18 August 2023

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to 2050 could be exhausted by 2035 due to growing demand. They also find that meeting the 1.5DS target is only possible with a radical and immediate intensity reduction at an average rate of 0.85 tCO_{2e}/t steel per decade or demand reductions of 34%. [Fan and Friedmann \(2021\)](#) claim that biomass, renewable hydrogen and CCS are the most cost-effective solutions for decarbonising steel production. However, a third of steel-making countries rely on coal for electricity, non-emitting electricity generation is constrained ([Arens et al., 2021](#)) and is expensive so drives up prices ([Ren et al., 2021](#)). In parallel, the energy required to make paper and aluminium challenges net zero targets: paper production requires energy for steam and drying ([European Commission, 2015](#)) typically supplied from biomass combustion or natural gas, which may cause emissions to continue increasing ([Van Ewijk et al., 2021](#)). For aluminium, reducing specific emissions below 5 kgCO_{2e}/kg aluminium, half of today's average emissions, depends on inert anodes and decarbonised electricity generation ([Pedneault et al., 2021](#)).

Many countries have now legislated net zero emissions by 2050. The production of bulk materials with net zero emissions depends on the three “zero-emissions resources”: non-emitting electricity, carbon capture and storage (CCS) and biomass. Some studies have considered part of the reality of these constraints, including the impacts of limited non-emitting electricity and biomass supply in the EU ([Herbst et al., 2021](#)) and the challenges of switching fuel before 2030 ([Rehfeldt et al., 2020](#)). However, previous sectoral analyses have taken material demand as an external input to the model. So far, no quantified estimate has been made of the resources required to produce bulk materials with net zero emissions in 2050 and recognised that shortage of these resources must constrain supply, regardless of demand. This paper therefore addresses the question: What bulk material production is possible on a transition to net zero emissions by 2050 with limited zero-emissions resources?

2. Methodology

The paper proposes a model to predict how realistic deployment rates of the three zero emissions resources described in the introduction (ZERs) will constrain production of steel, aluminium, and paper on a trajectory to zero emissions by 2050. The model is developed based on the schematic of [Fig. 1](#) which illustrates how the three zero-emissions resources (left side), constrain material production (with processes for steel, aluminium, and paper) delivering materials, emissions, by-products and waste.

2.1. The production model

The objective of the model developed in this paper is to maximise overall production of materials under a given carbon dioxide emissions

budget, subject to constraints on the availability of the zero emissions resources and secondary materials.

The model is based on the approach of [Gast et al. \(2022\)](#) to assess the potential for industrial symbiosis. In this model the system of net zero material production transforms resource inputs into outputs y . These outputs can be grouped into materials z , other outputs b , and carbon dioxide emissions g . There are i resources in the model (inputs or outputs of the processes with one of them being electricity). Material production is characterised by a set of processes. Each of the P processes (indexed by j , with j in $\{1, 2, \dots, P\}$), operates at rate r_j . The coefficients of the production processes are stored in matrix A , with entries a_{ij} .

The model estimates material production every five years until 2050 denoted with T (with T in $\{2020, 2025, \dots, 2050\}$). When process j operates at rate r_j , it causes an exchange of substances x_i in the period T . Overall, the process rates for every time period must be positive ($r_T \geq 0$). The production of any substance in the system can be calculated with:

$$\frac{\Delta x_i}{\Delta T} = a_{ij} r_j \quad (2-1)$$

The model includes constraints. Total GHG emissions g_T must stay below a budget for that time period, $g_{max,T}$, leading to net zero emissions by 2050. They are calculated as:

$$g_T = a_{CO_2} r_T \quad (2-2)$$

Stylised production processes lead to output y containing all substances, calculated with equations (2-1), as the product of the row of the process matrix a_i and the column vector of process rates. To illustrate this, the amount of primary paper leaving the production system is,

$$y_{p_paper} = a_{p_paper} r \quad (2-3)$$

The total paper produced is the sum of primary and secondary production,

$$y_{paper} = y_{p_paper} + y_{s_paper} \quad (2-4)$$

The overall production output z_T of every period T is the sum of primary and secondary production of aluminium, steel, and paper. This can be calculated with eqs. (2-1) and using the process rates for that period r_T :

$$z_T = a_{p_alu} r_T + a_{s_alu} r_T + a_{p_steel} r_T + a_{s_steel} r_T + a_{p_paper} r_T + a_{s_paper} r_T \quad (2-5)$$

To avoid one-sided optimisation results, it is assumed that the relative production rates of the three materials (represented with $\beta_{steel-to-alu}$ and $\beta_{steel-to-paper}$) remain constant at 2019 levels (1878 Mt for steel ([World Steel Association, 2021](#)), 97 Mt for aluminium ([World Aluminium, 2020](#)) and 423 Mt for paper ([FAO, 2021](#)) i.e.:

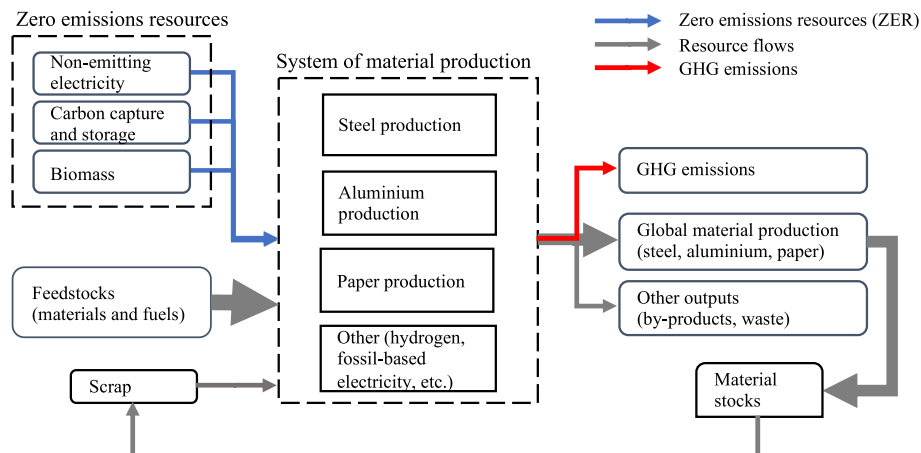


Fig. 1. Overview of the model and the production system.

$$\beta_{\text{steel-to-alu}} = \frac{y_{p_steel} + y_{s_steel}}{y_{p_primary_alu} + y_{s_alu}} = \frac{(a_{p_steel}r + a_{s_steel}r)}{(a_{p_alu}r + a_{s_alu}r)} = \frac{1878}{97} \quad (2-6)$$

$$\beta_{\text{steel-to-paper}} = \frac{y_{p_steel} + y_{s_steel}}{y_{p_paper} + y_{s_paper}} = \frac{(a_{p_steel}r + a_{s_steel}r)}{(a_{p_paper}r + a_{s_paper}r)} = \frac{1878}{423} \quad (2-7)$$

ZER production processes are indexed with c , and their rates (r_c) constrained by an upper bound $r_{c_{\max}}$ estimated using deployment rates from literature.

The production levels for the three bulk materials (given by z_T) are maximised, under constraints of the emissions trajectory ($g_{\max}$, T), availability of constrained resources ($r_{c_{\max}}$) and constant relative production levels (β). Production output for 2020 to 2050 is found with the optimisation:

$$\begin{aligned} & \text{find } r \\ & \text{Max}_{z_T} = a_{p_alu}r_T + a_{s_alu}r_T + a_{p_steel}r_T + a_{s_steel}r_T + a_{p_paper}r_T + a_{s_paper}r_T \\ & \text{Subject to : } a_{CO_2}r_T \leq g_{\max,T} \\ & \quad r \geq 0 \\ & \quad r_{c,T} \leq r_{c_{\max},T} \\ & \quad \frac{(a_{p_steel}r + a_{s_steel}r)}{(a_{p_alu}r + a_{s_alu}r)} = \beta_{\text{steel-to-alu}} \\ & \quad \frac{(a_{p_steel}r + a_{s_steel}r)}{(a_{p_paper}r + a_{s_paper}r)} = \beta_{\text{steel-to-paper}} \end{aligned} \quad (2-8)$$

2.2. Processes compatible with net zero emissions

“Net zero processes” are those that can operate without any direct or indirect emissions so depend on the three ZERs: non-emitting electricity, biomass, and CCS. The model attempts to deploy best available production technologies, derived from a range of sources:

- Steel production coefficients were taken from Bhaskar et al. (2020), Vogl et al. (2018), and Hybrit (2021) for direct reduced iron (DRI) with hydrogen. The process for electric arc furnace steelmaking from DRI and scrap with the use of coal or biomass, and the associated emissions, are taken from the European Commission et al. (2013) and Demus et al. (2012). The EC’s Best Available Technologies (BAT) processes for blast furnace and EAF steel production were used as representative technologies for current production processes (European Commission et al., 2013).
- Net zero aluminium production is discussed by the International Aluminium Institute (2021) and World Economic Forum (2020). Residual emissions are mitigated by CCS technologies. (Although the mitigation potential of inert anodes is significant, the estimated maximum potential market share in 2050 is expected to be less than 3% (Daehn et al., 2022) so they were excluded from the analysis.)
- For paper production, the process chains in Rogers et al. (2018), European Commission (2015), and Van Ewijk et al. (2018) are used. For net zero production, steam could be provided from biomass combustion and electricity-powered boilers.

2.3. Developing trajectories for the resource constraints

The deployment of zero emissions resources has large uncertainties; resource availability will depend not only on technical constraints but also on the levels of ambition in climate policies, and on socio-economic factors affecting competing demand from other sectors. No previous model estimates total availability of these resources, which hampers validation. To address this, a Monte-Carlo simulation was used to find a range of likely outputs based on several combinations of resource

availability.

2.3.1. Greenhouse gas emissions budget

GHG emissions are assumed to reduce every five years to achieve net zero production by 2050. Current total emissions from producing aluminium, paper and steel are approximately 5.1 Gt CO₂ as discussed in the supplementary material with a trajectory to 2050 shown in Fig. 2–(A). The trajectories for non-emitting electricity, biomass, and CCS (B-D) are described in the following sections and are allocated to the production sectors on the current share of global emissions (15%).

2.3.2. Zero-emissions resources

Global renewable generation in 2020 was approximately 7500 TWh (IEA, 2021a) and 2500 TWh electricity from nuclear energy (IAEA, 2021). 15% of new non-emitting electricity generation is allocated to material production based on the current fraction of global CO₂ emissions caused by these three materials (5.1 Gt out of 35 Gt). The non-emitting electricity comes from various renewable sources, which could be owned by the industrial company or other utility providers. Three scenarios of future generation are considered: a linear increase from current generation extrapolated to 2050 based on current deployment rates; the IRENA energy outlook estimate; accelerated deployment beyond that anticipated by IRENA. The model assumes that electricity can be used without considering geographical variations and the additional infrastructure needed to generate, transport and store intermitting electricity. The trajectory is summarised in Fig. 2-2 (B).

Global CCS capacity of 40 Mt in 2020 (from IEA, 2021a; Global CCS Institute, 2020) has grown at around 2 Mt per year over the past decade. Accordingly, the IEA’s estimates of 2050 capacity which was 10 Gt in 2010 reduced to 5 Gt in the 2018 report. This estimate was used in the recent IEA scenarios (IEA, 2021b) but still appears optimistic, given historical deployment. There are many risks in CCS deployment including containment, performance, public perception and market failure (Pawar et al., 2015) and availability of permanent storage (Lane et al., 2021). As a result, two trajectories are used for the lower and upper bounds of CCS technology availability: a continued linear increase of 2 Mt per year, and a more optimistic trajectory, reaching a total of 1 Gt in 2050 of which 15% is allocated to the processes included in the analysis.

Biomass is used in the model both for wood-based paper production and for heat. Global biomass availability difficult to predict due growing demand, and other sustainability concerns including biodiversity, ethics, and food security (IEA, 2017). Lenz et al. (2020) also describe technical challenges related to biomass quality. Current demand for pulp production is estimated by multiplying the average wood demand for pulp with the annual virgin pulp production of 263 Mt (Statista, 2020) giving a lower boundary of approximately 550 Mt (dry weight). International Energy Agency (2021) estimates current use of bioenergy at about 63 EJ or 4200 Mt of dry biomass threefold by 2050 (International Energy Agency, 2021). If all bioenergy is allocated to production processes based on current emissions, 220 Mt are available in 2020 with increments of 32 Mt of bioenergy every five years. Hence, the upper bound for biomass in production in 2050 is estimated at 960 Mt.

2.3.3. Provision of scrap

Scrap from manufacturing which depends on current production rates while scrap from resource recovery depends on previous production and product lifespans. A stock model is developed to estimate both flows from the four stages of production, manufacturing, material stocks and end-of-life (EOL) recovery. The model is summarised in Fig. 3 for a single material m and its mass flows along the production cycle.

The mass flows leaving the production system (m_1) are.

$$m_1 = m_{\text{primary}} + m_{\text{secondary}} \quad (2-9)$$

The flow entering the material stock (m_2) is calculated from the average production and manufacturing yield (ρ_{yield}) of the materials.

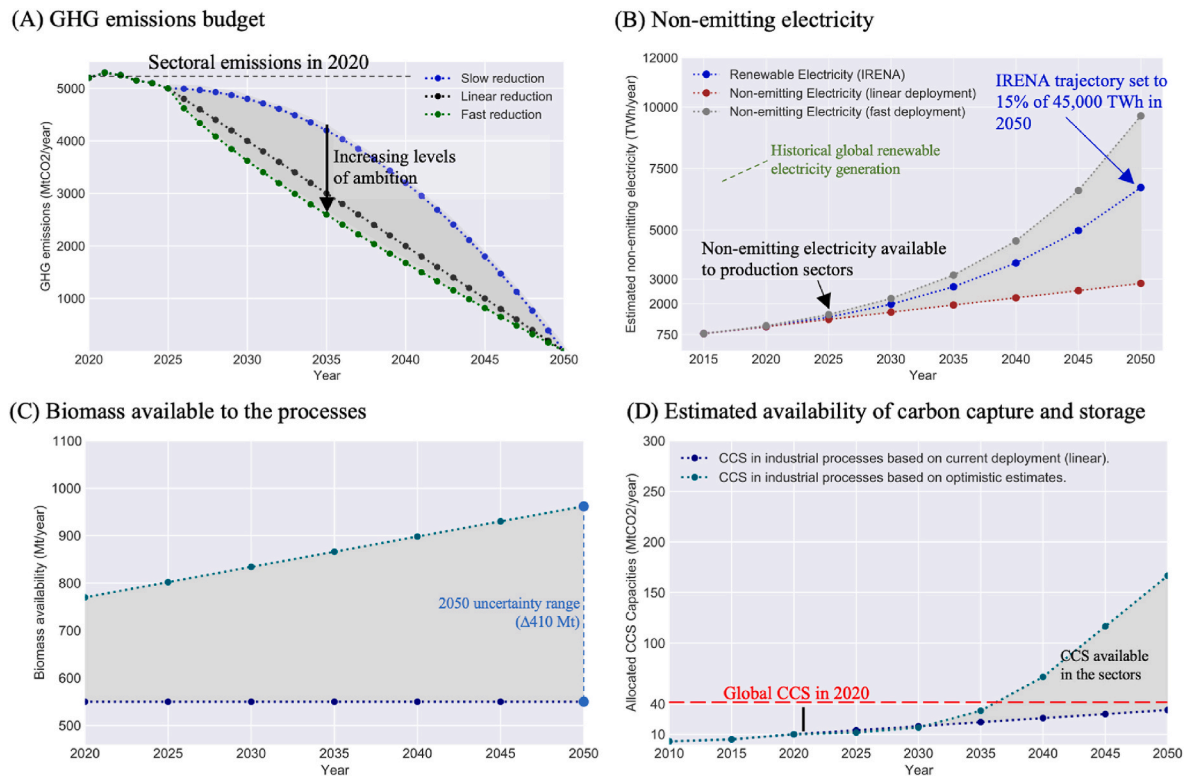


Fig. 2. Overview of the parameters of the model: (A) GHG emissions budget set to achieve net zero emissions in 2050 with three trajectories; (B) non-emitting electricity estimated based on current deployment rates and allocated to the industrial processes based on the current share of carbon dioxide emissions; (C) biomass available to the processes based on biomass availability and estimated biomass supply to industrial production in report by [IEA \(2021\)](#); (D) estimated availability of carbon capture and storage (CCS) in the industrial production sectors.

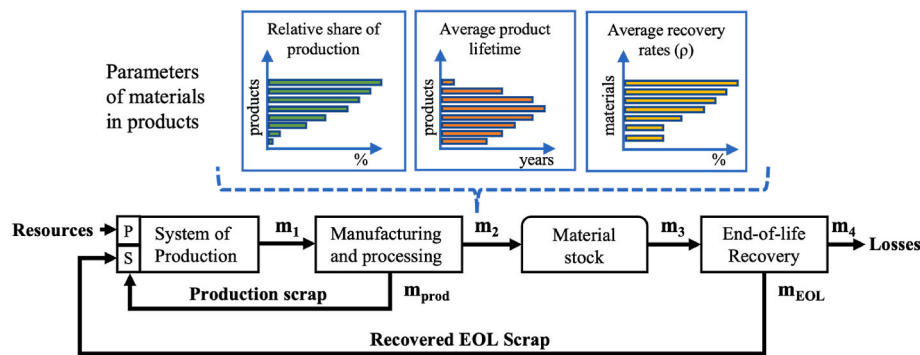


Fig. 3. Model for estimating flows of secondary resources.

$$m_2 = m_1 * \rho_{\text{yield}} \quad (2-10)$$

$$m_{prod} = m_2 * (1 - \rho_{yield}) \quad (2-11)$$

After use, materials are recovered at rate ρ_{EOL} enter secondary production and are used for producing new materials:

$$m_{EOL} = \rho_{EOL} * m_3 \quad (2-12)$$

$$m_4 = (1 - \rho_{EOL}) * m_3 \quad (2-13)$$

Historical material production from 1970 to 2020 was used to estimate current stocks of materials. Product life spans and recovery rates for steel and aluminium were taken from [Cooper et al. \(2014\)](#) and for paper from [Van Ewijk et al. \(2021\)](#). It is assumed that relative shares of production (i.e., product categories) and product life spans remain constant over time, that production yield is similar for primary and

secondary production and that it remains unchanged to 2050.

The upper bound of scrap available for secondary production is therefore,

$$m_{scrap} = m_{prod} + m_{EOL} \quad (2-14)$$

2.4. Addressing uncertainty in the trajectory

The production trajectory estimated by the model has two categories of uncertainty arising from the assumptions and structure of the model, and the data used.

In their review, [Spiegelhalter and Riesch \(2011\)](#) assess five sources of uncertainty related to future events, parameters, model structure, known inadequacies and unknown inadequacies. Those uncertainties are addressed in this model by use of a Monte-Carlo simulation in which the optimisation was repeated for 8192 random configurations of the

input parameters for non-emitting electricity, total emissions budget, biomass and CCS capacity, with a uniform distribution of values within the ranges defined above.

A variance-based sensitivity analysis using Sobol indices (Sobol, 2001) was conducted to assess the impact of changes in the input parameters on the model output and the robustness of the model (Saltelli et al., 2010). The Sobol index S_i is the ratio between the variance explained by variable X_i and the total output variance ($V(Y)$):

$$S_i = \frac{V_{X_i}(E_X(Y|X_i))}{V(Y)} \quad (2-15)$$

The closer S_i is to 1, the more important the variable X_i is at explaining the variance in the production level. The total-order index (ST) quantifies the contribution to the output variance caused by a model input, while the first-order indices (S1) measure the contribution of one input parameter to the output variance (e.g., non-emitting electricity to production output). The indices determine how much of the relative uncertainty and variance of the production output can be attributed to each input variable and so can be used to rank the different input parameters based on their relative importance.

3. Results

The production model was used to anticipate material production levels compatible with a trajectory to net zero emissions in 2050.

3.1. Material production trajectory

The analysis finds that, even using very optimistic estimates, forecast production levels are considerably lower than those currently expected in 2050. The most-likely 2050 production values estimated by the model are 1810 Mt steel, 120 Mt aluminium and 420 Mt paper. Fig. 4 visualises the estimated production levels in the model compared against those which would not be aligned with net zero emissions as estimated by material production forecasts in scenarios by producers' associations and in the IEA's Sustainable Development Scenario.

Fig. 5 presents the material production trajectories for different technologies for the three materials. Primary production decreases significantly in the years closer to 2050 due to the tightening emissions budget. The model finds that production of blast furnace steel decreases while it is replaced with increasing quantities of DRI-based steel production. Secondary production for steel depends on scrap availability and increases significantly. Paper production could increase up to the expected demand levels given sufficient supply of biomass. However, since the optimisation requires constant relative shares of the production of the materials, the overall paper production is below the expected demand levels. Primary production for aluminium decreases from 2030

due to residual emissions from the production process, which can only be negated by CCS technologies so are limited by its capacity.

Overall, the results highlight a substantial gap between forecast supply and demand for zero emissions materials by 2050. However, they suggest that 2020 production levels could be achieved in 2050 with net zero emissions.

The emissions and energy needs of the production processes differ markedly. For example, Fig. 6 shows how the primary energy demand and emissions of different steel production technologies with and without CCS.

3.2. Variance-based sensitivity analysis

The analysis of the Sobol indices highlights the relative importance of the input parameters to forecast outputs. Fig. 7 presents Sobol indices for production in the years 2030, 2040 and 2050. The first order Sobol indices (S1) are represented with blue bars and total-order Sobol indices (ST) are represented with orange. The confidence intervals are added using error bars.

The most important parameter explaining overall variance is the availability of non-emitting electricity, followed by CCS and scrap in 2030. The importance of scrap reduces over time, while the importance of non-emitting electricity and CCS increases. The total-order indices (ST) are not significantly larger than the first order (S1) indices.

The results of the model highlight a gap between expected production levels and demand for zero emissions materials. Production in 2050 is forecast to be dominated by secondary production with almost no primary production for paper, and significantly lower primary production for aluminium and steel (based on DRI). The limiting factor of production in 2050 is the availability non-emitting electricity.

4. Discussion

The results reveal a likely shortfall in net zero material production. The forecast trajectory depends strongly on the availability of zero emissions resources. Strategies for material efficiency could be pursued to address the estimated gap in the provision of materials to meet the same service levels. Alongside this, increasing deployment of ZERs could help to quantify needs, identify potential shortages, and address shortfalls in their supply.

4.1. Material production with net zero emissions

The model of this paper differs from other forecasts, e.g., the IEA's net zero scenario and the roadmaps to production in 2050, in three ways. Firstly, it is assumed that net zero emissions by 2050 are achieved. Secondly, material demand is not defined externally but potential supply

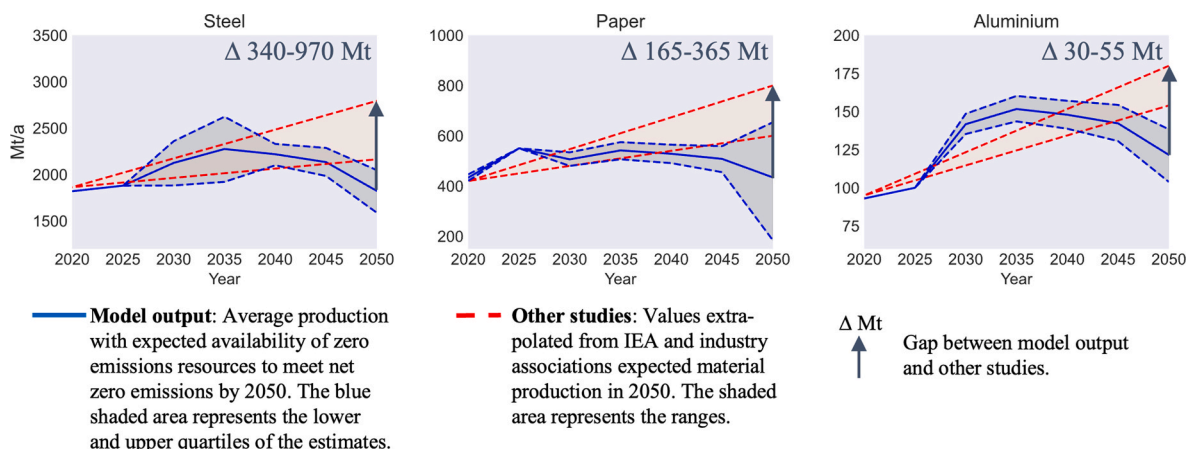


Fig. 4. Production trajectories for the materials steel, paper, and aluminium.

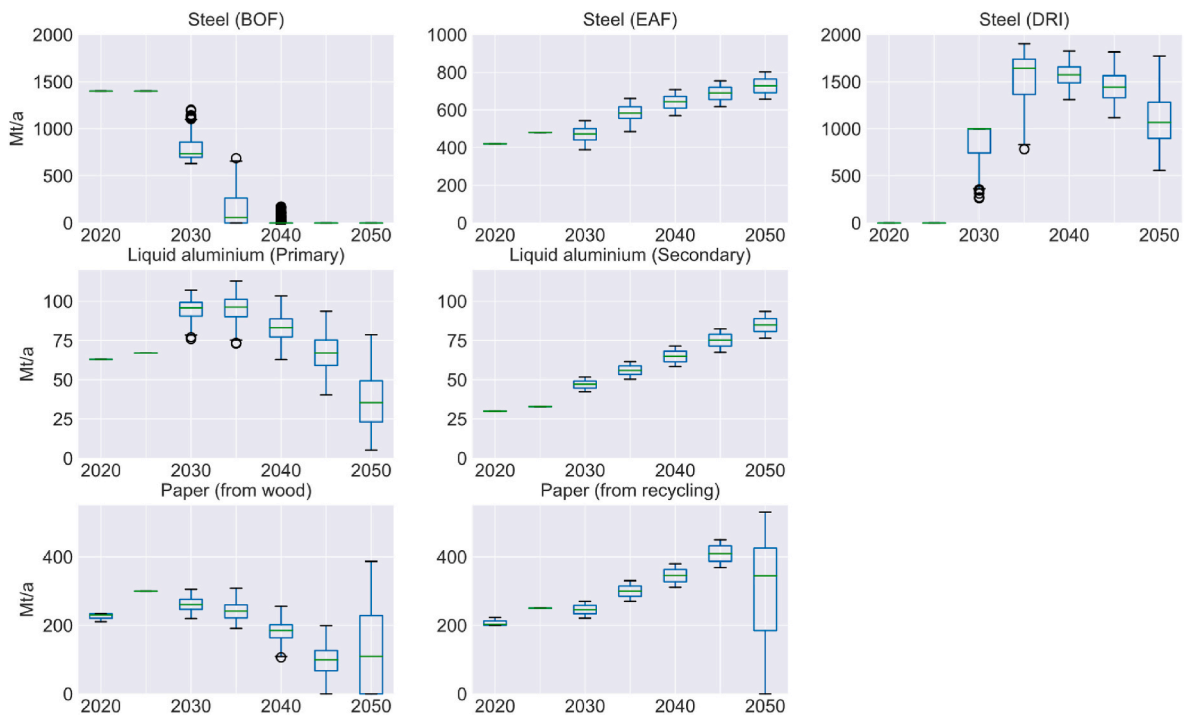


Fig. 5. Material production on a trajectory to net zero emissions in 2050 in Mt.

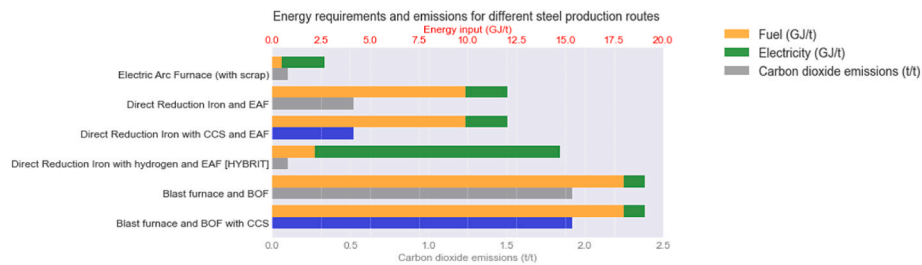


Fig. 6. Visualisation of the primary energy demand and carbon dioxide emission per ton of steel production output.

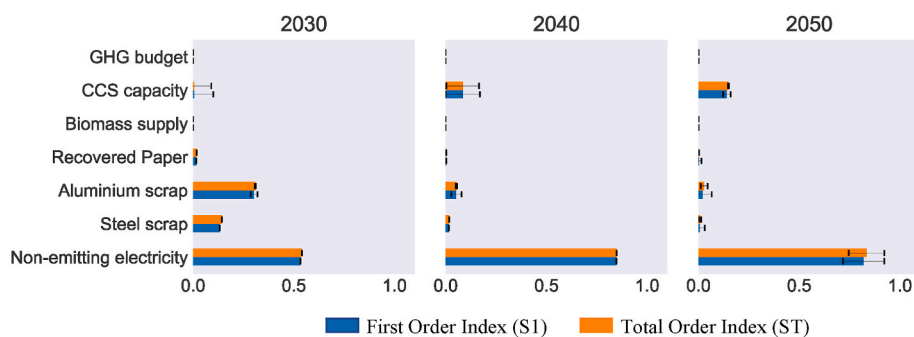


Fig. 7. Results of the Sobol index analysis.

of the zero emissions resources is taken as an input parameter and production levels calculated within the model. Thirdly, the model uses process-level recipes for a global production system without considering regional differences.

The results of the model highlight a significant gap between the expected material demand in 2050 and the possible net zero production in 2050, given resource constraints: the gap is up to 340–970 Mt for steel, 165–365 Mt for paper, and up to 30–55 Mt for aluminium. There are few other quantitative analyses against which to compare these

results. The Low-Energy-Demand analysis by Grubler et al. (2018) includes a scenario for a reduced material production. They estimate that material demand for global commodities falls by around 15%. Those reductions are mainly driven by dematerialisation (one third) and improvements in material efficiency (two thirds). This scenario highlights that a reduction in material production is possible while maintaining similar levels of energy services.

The costs of delivering on the scenarios of this paper are highly uncertain both due to the cost of technologies and commodities and due to

the scale of governmental infrastructure investments over the next decades. The need for public investment in infrastructure and other measures to de-risk private investment is described by IEA (2022). At a national level, for Germany, the scale of investment required up to 2030 is already estimated at 860 billion € (Burchardt et al., 2021).

4.2. Reducing material demand to meet service levels

In the face of likely population and wealth growth and with forecast material supply in 2050 being only 60–100% of today's production, the model demonstrates a strong need to reduce material demand if we are to maintain today's service levels. This is in strong contrast to the expected doubling of material production over the next decades (OECD, 2019). To address this, strategies for material efficiency can be implemented including business model and technological innovations.

The conclusion of this analysis is consistent with calls for material demand reduction as described by Allwood et al. (2011) and highlighted in the recent IPCC report (Bashmakov et al., 2022). Strategies to provide the same service with less material have been explored for different production sectors including construction (Moynihan and Allwood, 2014). Policy recommendations for increasing material efficiency are presented in a recent report by UNEP and International Resource Panel (2020). These include increasing product lifetimes, increasing recovery rates and using less material for providing the same service. Several types of business model innovations leading to a direct reduction of environmental impact are summarised in a review by Geissdoerfer et al. (2018). These include sharing services (e.g., bike sharing) or returning items at the end-of-service life to facilitate in-house recycling (e.g., furniture). At a process-level, radical innovations to produce materials with significantly less energy demand and carbon dioxide emissions could influence the supply of materials. Technology innovations could include direct electrolysis for steel production (BostonMetal, 2022), inert anodes for aluminium production (He et al., 2021), and paper production by de-inking recovered paper (Zhao et al., 2022). There may be time to develop these technologies but, given their low technology readiness level, their rapid deployment is unlikely.

4.3. Deployment of net zero resources and reporting

The gap between potential supply and expected demand in other analyses can only be overcome if the zero emissions resource supply increases rapidly. A better reporting of zero emissions resources supply and demand could help to identify shortages and address it with resource policies.

The uncertainty analysis and Monte-Carlo simulation in this paper accounts for ranges of potential resource availability. The approach includes both conservative and optimistic scenarios for the deployment of ZER. The historical evidence of technology deployment and transitions, however, indicates that the realisable potential of capacities for carbon capture, transport and storage might be at the lower end of the estimates; evidence shows a linear growth rate once a new technology reaches market penetration of around 5% (Nelson and Allwood, 2021). Uncertainty regarding the availability of zero emissions resources could be addressed through more detailed modelling of the availability, potentials, and constraints of those resources. For example, deployment rates of infrastructure for pipelines for transporting and storing carbon dioxide from CCS and the subsequent potential bottleneck of its deployment are not included in this analysis.

In the European Union, the Corporate Sustainability Reporting Directive (European Commission, 2022) and the European Sustainability Reporting Standard (EFRAG, 2022) include requirements for companies to disclose information regarding their strategies to achieve net zero emissions. Although they contain detailed reporting requirements on decarbonisation levers and mitigation actions to achieve net zero emissions, they do not currently contain reporting requirements on the resource requirements and a risk assessment on the resource availability.

To avoid a potential shortage, industrial stakeholders could report the requirements to facilitate policymaking for the provision and could ensure the future provision through market-based mechanisms. Markets for zero emissions resources and finance tools such as zero emissions purchasing agreements as proposed by Nelson et al. (2021) could help to incentivise increased resource efficiency and attract investments in provision of zero emissions resources. Demand for the three zero emissions resources could also usefully be included in corporate reports, integrated assessment models (IAM) and other policy analyses. This would help with risk analysis for different technology pathways. One option to report and communicate the potential need for these zero-emissions resources could be a disclosure as part of environmental reporting schemes (e.g., EU's Eco-Management and Audit Scheme (European Commission, 2017)).

The results of the model can inform policymaking in three ways. Firstly, they highlight the large gap between potential production, and estimates from previous production trajectories. Secondly, they highlight the implications of limited availability of non-emitting electricity and scrap. Thirdly, they provide an estimate of resource flows in a system with net zero emissions. The paper estimates that maximum possible production with net zero emissions in 2050 is up to 40% lower than current production levels. Hence, some fraction of the material required to build infrastructure and support inclusive and sustainable industrial development will be unavailable.

4.4. Effect of model assumptions

The model developed in this paper relies on four key assumptions, stated in the methodology section, and briefly discussed here:

- The analysis is global with five-year time-steps so blind to shorter-term fluctuations such as the intermittency of renewable electricity generation. The goal of the paper has been to draw attention to likely shortfalls in future materials supply, which would probably be exacerbated by consideration of intermittency or other faster cycles of variability.
- The relative production rates of the three materials are fixed. In reality, as the model forecasts a supply shortfall for all three materials, their prices would rise – but, by definition, there is empirical evidence for the cross-elasticities of demand between these materials in response to the radical price rises that would occur with significant shortage, so the assumption allows us to create indicative results.
- Production capacity for the three materials is unlimited while trajectories for the maximum availability of the three zero emissions resources over the timespan of the analysis are specified exogenously. In reality, capacity can grow only at constrained rates, and much previous policy analysis has been misleading in assuming that these rates can be accelerated, frictionlessly. The most cautious trajectories of zero-emission resource supply used in the analysis (Fig. 2) are all linear extrapolations based on the past decade, so very likely to be achievable. The more ambitious trajectories may well be unrealisable given the inevitable complexities of the many one-off projects required to deploy large energy infrastructure.
- An unbreakable budget for annual emissions over the timespan of the analysis is specified exogenously and determines the maximum output of previous emitting production processes. In reality it is unclear how society will respond to failure to meet current target emissions budgets. Politically, the pressure to delay action now dominates, while in future, at the point that climate impacts become sufficiently severe, there will be an abrupt change to demanding faster and more radical action. We do not know how these forces will work against each other, so use the fixed trajectories as a means to explore current policy.

The analysis in this paper draws on published data for mass balances and energy requirements in producing these three materials. In future,

there could be some academic merit in extending this approach to use exergy instead of energy flows. Exergy-based metrics, as summarised by Hernandez and Cullen (2019) and illustrated for a steel plant by Sun et al. (2021) have the advantage that both material and energy efficiency can be reported in a single metric. However, despite its theoretical attraction, exergy analysis does not always give good predictions of what can be achieved in practice and at present there is insufficient published data to support the approach across the span of processes included here.

CRedit authorship contribution statement

Lukas Gast: Conceptualization, Methodology, Software. **Julian M. Allwood:** Conceptualization, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgements

This work was supported by Engineering and Physical Sciences Research Council (EPSRC) in the United Kingdom through UK FIRES (grant reference EP/S019111/1). The authors thank Marcel Weiss, Jennifer Hawkin, Hannes Gauch, and Jack Lynch for helpful comments on earlier versions of this article.

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.jclepro.2023.138346>.

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