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Strategising steel sector capacities and employment in the Global South: the case of South Africa



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Steel producers in the Global South face increasing pressure from trade and required emissions cuts. Renewable-rich regions could become key suppliers of low-carbon steel, but this vision remains conceptual and risks perpetuating extractivist patterns. Using the Global Energy System Model (GENESYS-MOD), we assess technological, spatial and employment implications of South Africa's steel transition. We find that an early push for hydrogen-based capacities is beneficial – but needs to be embedded in a broader just transition framework.

Amidst geopolitical tensions and an increasing urgency to fight climate change, it has become more and more complex for steel-producing regions in the Global South to navigate the global supply chain landscape and strategise about the future of domestic steelmaking capacities^{1,2}. Historically, production sites have been located close to coal as a cost-effective energy carrier and reducing agent for primary steel production. Those fossil path dependencies have placed steel facilities at the industrial heart of emerging economies, including the build-up of supply chain infrastructures such as mines, rail, and ports, as well as the provision of stable and relatively well-paid jobs³.

However, in the Global South in particular, domestic fossil-based steel strategies have come under threat for two main reasons. First, protectionist policies in key steel-producing nations - tariffs in the US, innovation support in the EU, overcapacities in China - impede other countries' participation in global commodity markets, essentially pushing already small players entirely out of steel supply chains. Second, the EU's introduction of a Carbon Border Adjustment Mechanism (CBAM) has institutionalised a global trade order in which predominantly wealthier regions with more ambitious climate policies form a "coalition of the willing", de facto hindering countries with strong fossil path dependencies from trade with any coalition member⁴. This development could have more severe consequences for developing and emerging economies than initially thought^{5–8}.

On the other hand, due to abundant solar and wind energy potentials in some regions of the Global South, the international dash for green steel provides a big opportunity to profit from a re-structuring of global supply chains. There is increasing urgency to strategise for this opportunity, though, as the majority of global blast furnace capacities have been added in the early 2000s and consequently require re-investment in the coming decade³. While hydrogen (H₂) exports have shown to be a less promising option than initially thought⁹, a renewables pull towards exporting

hydrogen-based direct reduced iron (DRI) could become a major business case for producers in the Global South^{10–12}. This opportunity is amplified by geopolitical interests from the Global North, the EU in particular, aiming to form economic relations in times of uncertainty on international supply chains. The Global North's involvement in hydrogen projects has consequently raised doubts with regard to its underlying intentions, which have been characterised as being between green extractivism and green developmentalism, including the risk of perpetuating neocolonial and racist patterns^{13–15}.

South Africa serves as prime example for those global dynamics as its steel industry finds itself at a critical juncture. On the one hand, long steel operations are increasingly reliant on government support, revealing competitive weaknesses in the face of global overcapacities^{16–18}. At the same time, the country's production factors present a unique opportunity to profit from growing international green steel markets. This is not only due to its renewable energy potentials, but also because facilities to produce DRI already exist in the country, and could partly be operated with hydrogen at relatively little additional CAPEX investment. Recent research has consequently outlined a compelling vision in which South Africa becomes a global supplier of renewable hydrogen-based DRI^{19,20}. Furthermore, the Global North's interests in South Africa have manifested in coordinated support initiatives such as the Just Energy Transition Partnership (JETP), which has been criticised for its insufficient attention to social justice concerns^{21,22}. Within the JETP, considerable emphasis has been placed on attracting foreign private investment for the power sector transition, which holds promising implications for water and land resources²³ and would be conducive to low-carbon steelmaking in the future. This focus, however, also underscores the Global North's primary interest in securing access to resources from South Africa's emerging hydrogen economy¹³.

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Although the vision of low-carbon steel economies in the Global South is already the subject of fierce debate, it remains largely conceptual, with several critical questions still unanswered. Given the uncertainties around global protectionist policies and CBAM, how should governments strategise for their steel industries' futures? Which regions are best suited for low-carbon steel production, and how does existing infrastructure influence this potential? Speaking to debates on energy justice and aiming to improve initiatives like the JETP, what are the implications for job creation, and what are the risks if such a vision fails to materialise?

Using South Africa as a case study, this paper addresses these gaps by explicitly incorporating the steel sector in the Global Energy System Model (GENESYS-MOD). Through our integrated modelling approach, we assess the economic, spatial, and energy implications of transitioning to a hydrogen-based steel industry in South Africa as an exemplary economy in the Global South that needs to navigate new steel realities. Our analysis provides actionable insights into the feasibility, trade-offs, and potential of green steel as a driver of sustainable industrial development – contributing to both national policy debates and the broader discourse on green growth in emerging economies.

Our analysis contributes to a growing literature on energy systems modelling for an emerging economy context^{24–27}, but sets itself apart in two ways. First, we include a detailed representation of the steel sector and its distribution across South Africa's nine provinces. The sector is calibrated to current capacities, with largest production facilities in Vanderbijlpark (Gauteng region), Newcastle (KwaZulu Natal), and Saldanha (Western Cape)²⁸. Company announcements for capacity additions or closures are taken into account until 2035. We implement the following technologies: conventional blast-furnace blast-oxygen-furnace (BF-BOF), DRI with coal, natural gas (NG), and hydrogen, as well as electric arc furnaces (EAF) for steel recycling and DRI processing. Additionally, DRI capacities in Gauteng can be equipped with CCS technology assuming potential storage in the Durban Basin²⁹.

Our second main methodological contribution is the consideration of direct and indirect employment effects from steel sector development over time. To do so, we use an ex-post employment factor approach, capturing employment numbers for multiple job types (manufacturing, construction and installation, operation and maintenance, and supply jobs) both in the steel sector directly, as well as for indirect jobs in mining and the power sector.

Results

We approach the research questions outlined above from three angles. First, we investigate both production volumes and capacities to analyse how steel production technologies develop over time. In doing so, we ask which technology routes firms and governments can focus on to build a future-proof steel sector. Second, we analyse how future steelmaking capacities could be distributed regionally. This should give decision makers an indication of where strategic capacity build-up is preferable – e.g. whether, in the future, low-carbon steel plants should be placed close to iron ore or coal mines, renewable electricity and hydrogen infrastructure, or trade infrastructure like ports. Third, we delve into implications for employment in steel and indirectly affected sectors of mining and power generation. Acknowledging the “dual challenge” of eradicating poverty and unemployment while transitioning to low-carbon economies^{1,4}, with this final angle we aim to make the synergies and trade-offs in employment between sectors explicit. We structure the results across four scenarios, which are constructed along two dimensions: national climate targets and demand for low-carbon DRI and steel (see Methods). Two High Demand Scenarios (HDSs) represent increases in both domestic crude steel production and exports of hydrogen-based DRI. Out of the two, one is aligned with a 2 degree emission reduction target, aiming for a net-zero energy system by 2050, the other follows a business as usual (BAU) climate trajectory. Similarly, we employ two respective Low Demand Scenarios (LDSs), representing a decline in crude steel demand and no exports of hydrogen-based DRI until 2050.

Technologies over time: structural shift to hydrogen-based steelmaking

Across all scenarios, the long-term trajectory for South Africa's steel production volumes points towards a decline of coal-based steelmaking and the rise of EAFs and H₂-DRI over time (Fig. 1). The steel sector's development goes hand in hand with a transition of the power sector, for which solar and wind become the dominating generation technologies from 2040 onwards in all scenarios (see Supplementary Fig. 2).

In both high-demand scenarios, the steel transition is rapidly driven by export opportunities for low-carbon DRI. We observe H₂-DRI cost below 300 EUR/t from 2040 onwards, reaching 250 EUR/t in 2050, which is competitive with current DRI commodity prices (see Supplementary Fig. 4). Even in the low-demand-scenarios, the comparative advantages of H₂-DRI therefore drive a virtually complete phase-out of coal-based steelmaking by mid-century – regardless of whether they align with a 2 °C climate target or follow a BAU pathway.

CCS does not play a role in any of the considered scenarios, underlining its inability to compete with renewables-based routes in the South African context. The results imply that, while policy interventions could influence the transition's pace, its direction is robust: by 2050, coal-based steelmaking is no longer part of South Africa's industrial landscape. Instead, the sector is structurally reshaped around hydrogen-based processes, with implications for energy system planning, export infrastructure, and labour markets.

Moving on to steelmaking capacities, the equipment deployed mostly reflects the production patterns above, although utilisation varies between technologies in some instances (Fig. 2). Most striking is the required ramp-up of H₂-DRI capacities between 2030 and 2050 in both high-demand scenarios. This expansion is driven by the need to meet demand for low-carbon DRI exports, regardless of emissions constraints. In practice, such a rapid build-out is likely to face bottlenecks in equipment supply, and it implies considerable demand for sources of finance – which could drive up capital costs in the future³⁰.

Capacity results also confirm the risk of coal-based steel facilities becoming stranded assets in the long run. In the BAU low-demand pathway, the model does not decommission BF-BOF capacity entirely by 2050, but barely operates those units after 2040. Similarly, existing coal-based DRI facilities, currently located in Gauteng, are retained until 2040 in all scenarios but contribute little to total production (cf. Fig. 1).

Regional capacity distribution: industrial base remains, but increasing role for provinces with renewable potentials

The regional distribution of steelmaking capacities in our scenarios mirrors the broader structural transformation of the sector: a gradual but pronounced shift towards provinces with abundant renewable energy resources (Fig. 3). In this sense, we observe a domestic renewables pull between provinces^{10,11}. Some capacities remain at production locations historically anchored to coal supply chains even in the long-run, but their relative importance decreases over time. While access to low-cost solar and wind potential is the primary driver of this redistribution, proximity to iron ore deposits and the availability of efficient transport links to export ports also shape the geography of future steel production.

The Northern Cape emerges as the clear beneficiary of this shift. Its unique combination of vast renewable generation potential, proximity to major iron ore mines, and direct connection to Saldanha port via the Sishen Ore Corridor railway positions it as the natural hub for hydrogen-based DRI and EAF deployment. Moreover, Saldanha in the Western Cape serves as a nucleus for a low-carbon steel economy, because its already existing facilities – the Saldanha Steel works, and infrastructure lead to an early adoption of H₂-DRI production in all scenarios.

The industrial base in Gauteng and KwaZulu-Natal is upheld in a sense that we observe a transformation rather than a shutdown of steel operations in these provinces. However, particularly in the high-demand scenarios,

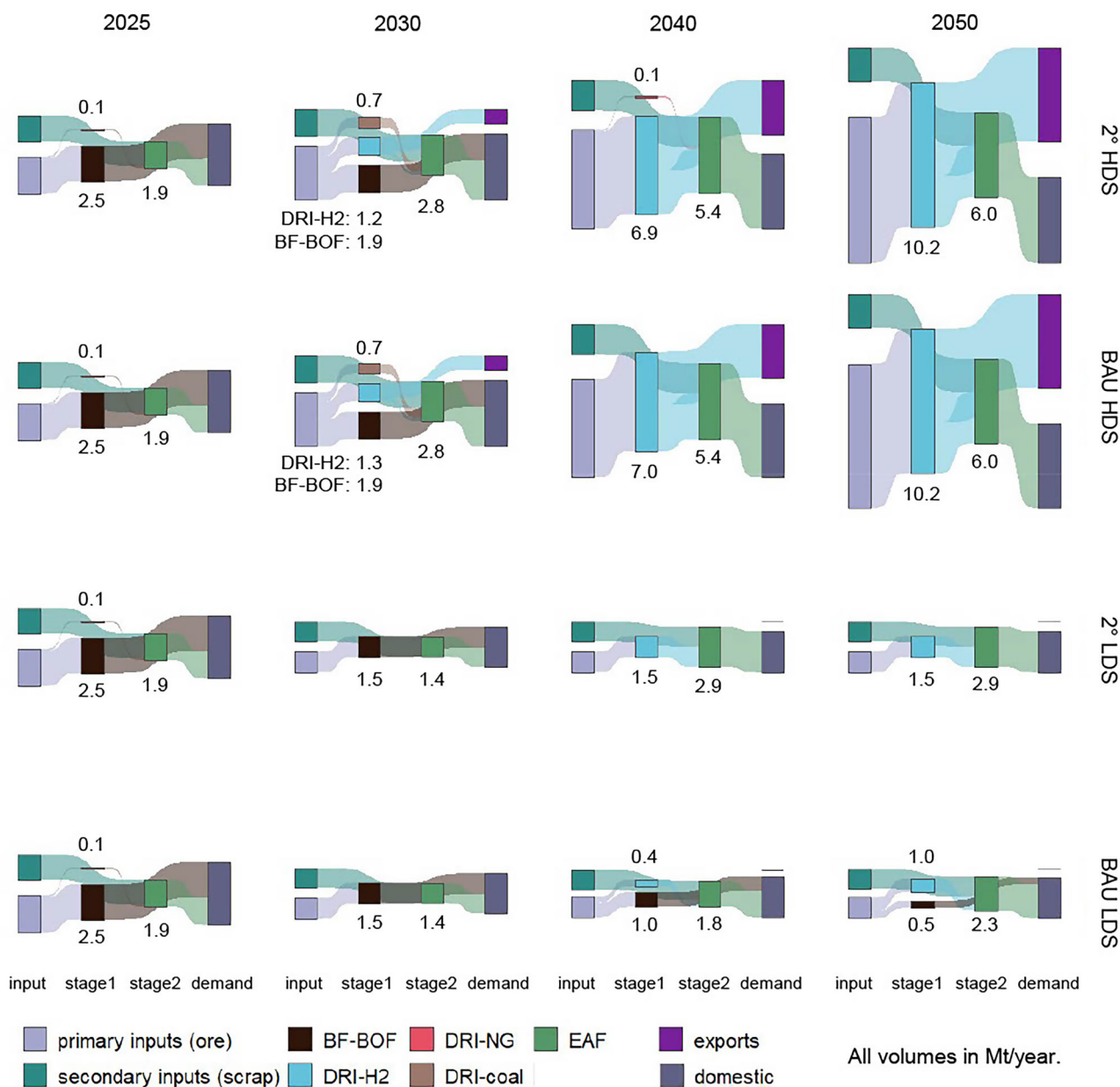


Fig. 1 | Sankey diagramme of steel production volumes per technology in South Africa up until 2050 for the four considered scenarios – high and low demand, 2 °C compliant or BAU, respectively. Stage 1 either represents the initial reduction step in a DRI plant, or steelmaking in an integrated BF-BOF plant directly. Stage 2 comprises EAF steelmaking, both for secondary (scrap) and primary (DRI) steel. The demand stage consists of domestic steel use and low-carbon DRI exports as reflected by our demand assumptions (see SI for further information). In both HDS, H₂-DRI steel capacities enter the mix by 2030. When the whole economy is

decarbonising and there is competition for H₂ with other sectors (2° HDS), the final bits of demand are met with existing DRI-coal kilns (2030) or DRI-NG (2040). The following decade sees an accelerated phase-out of the integrated BF-BOF route, with coal-based steelmaking disappearing from the national steel mix by 2040. In contrast, both LDS retain a key role for BF-BOF until around 2030, but still start to phase-out coal-based steel production thereafter. Only in the BAU LDS, a small fraction of BF-BOF production remains in 2050.

their relative long-term role for South African steel is smaller compared to capacities in the Northern Cape. In Gauteng, the early phase-out of blast furnaces – combined with the long-term idling of existing coal-based DRI plants – diminishes the province's role as the central steelmaking hub it holds today. In high-demand scenarios, EAF capacities are added in line with ArcelorMittal's announced decarbonisation roadmap. KwaZulu-Natal's Newcastle plant holds the last blast furnace in the BAU low-demand scenario, but even here, high demand prompts an early replacement with H₂-DRI and EAF facilities. In addition, despite Gauteng's relative proximity to the Durban Basin – a location technically suitable for CCS deployment²⁹ – the model finds no cost-optimal role for CCS-based steelmaking in any scenario.

Implications for employment: more jobs from renewable than from fossil iron- and steelmaking

Results on employment robustly indicate that, in the mid- and long-term, the emerging renewable-based steelmaking sector will be a more significant source of employment than conventional fossil steelmaking, regardless of demand or national climate policy (Fig. 4). While higher demand for South African steel obviously results in substantially higher employment numbers, national climate targets only play a minor role in the overall picture.

Both for the steel sector directly and for indirect jobs, employment is mainly driven by the development of a South African hydrogen economy. In the high-demand scenarios in particular (cf. High Demand Scenario (HDS) in Fig. 4), most direct jobs come from the build-up of H₂-DRI capacities, and

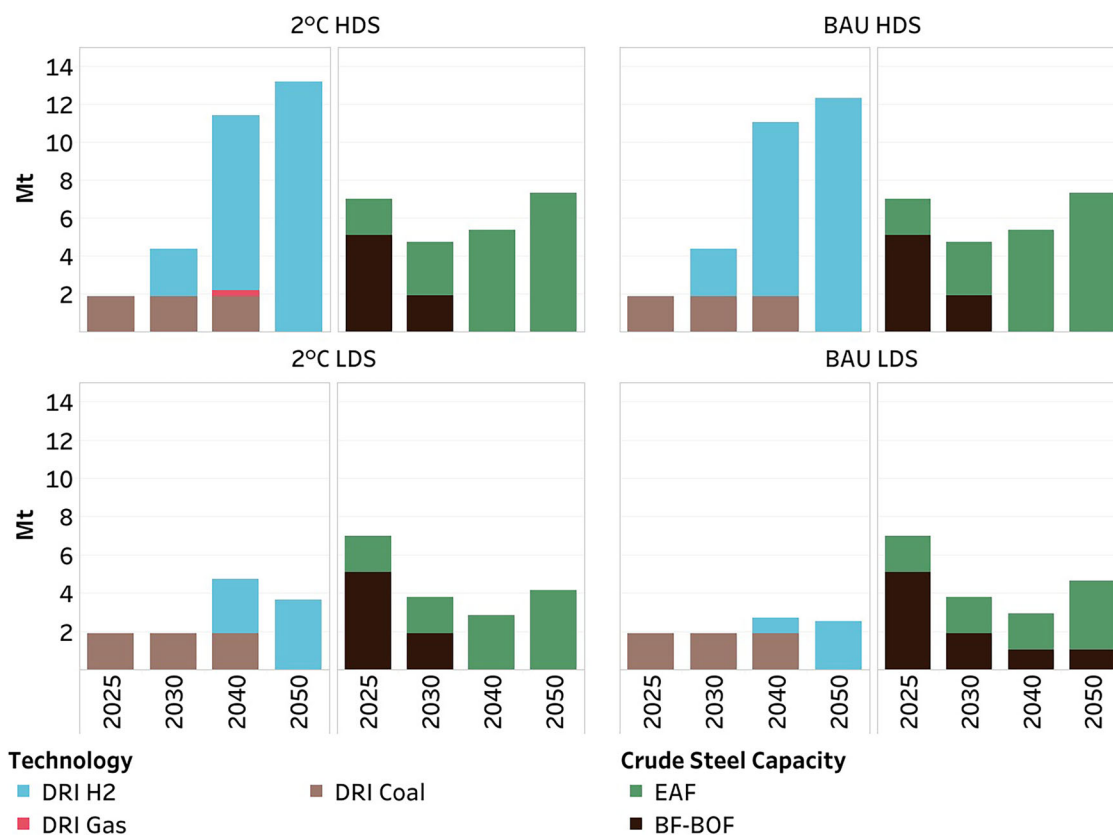


Fig. 2 | Development of steel production capacities per technology in South Africa over time, up until 2050, for all four scenarios. DRI capacities are separated from BF-BOF and EAF steelmaking to reflect the opportunity of splitting the value chain in order to export low-carbon DRI directly. The results indicate a robust decline of fossil steel capacities in favour of EAF and H₂-DRI capacities, regardless of demand and emissions target assumptions. For the domestic market in particular, EAFs fully replace BF-BOFs as the dominant steelmaking technology by mid-century. Under high demand, this is primarily driven by the synergetic ramp-up of

H₂-DRI capacities, which are required to meet export demand in any case, but can also be used to feed into downstream EAF steelmaking. During the transition (2030–2040), DRI-coal and DRI-NG are used as bridging technologies until sufficient cost-effective H₂ is available, particularly when the rest of the economy also decarbonises swiftly and competition for low-carbon energy is high (2 °C HDS). In low-demand scenarios, the shift is more gradual and stems from a combination of modest DRI expansion and steady steel recycling rates over time.

most indirect jobs are created from the ramp-up of electrolyser capacity for local H₂ generation. As a consequence, we observe an initial employment spike in the mid-2030s, which is then followed by a drop as soon as initial capacities have been installed. Only in the late 2040s, when demand for H₂-DRI exports rises steadily, the need for additional capacities leads to a second, even higher employment spike. When demand for South African steel is low, however, production is still mainly carried out with fossil jobs until 2030, and jobs in low-carbon steelmaking only start to play a more dominant role throughout the 2040s.

The drop in employment after the initial wave of capacity installations in both high-demand scenarios highlights the risks of an extractivist hydrogen economy in which demand for low-skilled labour is high in the short run, but high-skilled long-term jobs mostly remain in countries that process the exported H₂-DRI and hence keep the subsequent, more value-adding parts of the supply chain^{11,15}. This highlights the need for additional measures to ensure a just and sustainable ramp-up of hydrogen capacities in the Global South, which guarantees employment not only for short-term capacity build-up, but also in the long run.

Lastly, the regional distribution of direct steel jobs follows the capacity build-up patterns described above (cf. Fig. 2). That is, in high demand scenarios most direct employment opportunities will be located in the Northern Cape. For a more detailed perspective, we provide direct employment figures at the province-level in Supplementary Fig. 1. Indirect mining jobs obviously continue to occur at the existing locations, however with a declining relevance in coal mining

and, at least in the high-demand scenarios, an increase in iron ore mining activities to meet H₂-DRI exports. For indirect power sector jobs, regional employment depends on the level of system integration – specifically whether power demand from electrolyzers is met directly at the plant or more distributed through the grid – which goes beyond the scope of our study.

Discussion

For steel economies in the Global South, we have shown that the dual challenge – de-coupling from fossil path-dependencies without compromising on reducing unemployment and eradicating poverty^{1,4} – is best addressed with a push for renewable-based DRI and EAF capacities in regions with abundant renewable potentials. Three key findings have direct implications for policymakers.

First, in countries with favourable conditions for low-carbon steel from renewable energy, the steel sector's transition will be driven from global demand for green steel rather than national climate policy. As soon as H₂-DRI commodity markets have formed, capturing even a small share provides sufficient incentives to phase-out fossil steel and deploy low-carbon steelmaking technologies in these countries – with or without additional national climate policies in place. While one might argue that fossil capacities should be kept in place to meet domestic steel demands, our results clearly indicate that, in countries with vast renewable potentials like South Africa, renewable-based steel is going to be more cost-effective in the long run. In addition, being an early mover at this transition – also for domestic markets – secures countries a strategic advantage, opening opportunities to

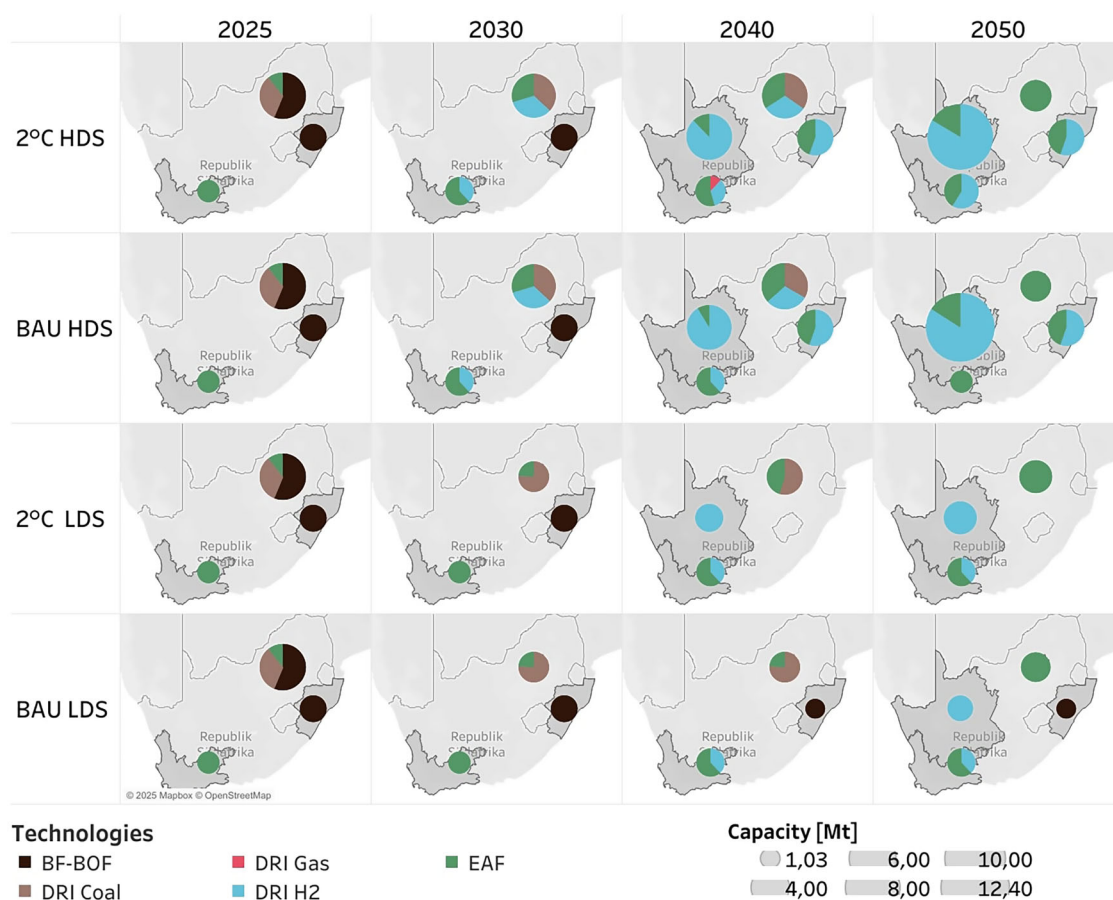


Fig. 3 | Regional steel capacity distribution in South Africa's provinces over time, up until 2050, for considered demand and emissions scenarios. Volume pie charts are representative for each province and do not stand for actual production locations on the map. Results consistently show that, for a cost-effective transition, capacities

“follow the energy”. That is, conventional fossil capacity close to coal mines is retained to a certain degree, but loses in relative importance compared to regions with abundant renewable potentials – here the Northern Cape specifically.

capture larger market shares over time. At the same time, early-stage hydrogen projects come with considerable risks, which need to be accounted for. This is particularly the case at a time where the implementation gap for hydrogen has widened³¹. Megaprojects in the South African context specifically do not only need to factor in business and technology risks, but arguably even more so risks in relation to market and supply chains, project execution, as well as political risk³². Support instruments from the Global North could add real value in safeguarding and insuring against these uncertainties, in turn improving project bankability and lowering cost of finance.

Second, against the widespread perception that climate policy costs jobs and causes unemployment, our results show that embracing the low-carbon transition can stimulate direct employment in the steel sector, but also in indirect jobs – mainly from the build-up of electrolyser capacity and power capacity to generate H₂. When global demand for low-carbon steel is high, we observe substantial employment opportunities from DRI-H₂ exports. In this case, the model finds almost 10,000 direct steel jobs in the 2030s already, and an even larger potentials for indirect jobs in the power sector. Those potentials would remain untapped if strategic decisions are made to stick to coal-based steelmaking and CCS. When demand is low, however, climate targets do not lead to additional unemployment as coal-based steelmaking is already in decline. At the same time, a just transfer of the workers at risk is essential and re-training takes time. This gives additional reasons to start with the ramp-up of renewable-based iron and steel rather sooner than later.

Third, while our results might make policies for a low-carbon steel transition seem like a no-regret, they also highlight the challenges of a

structural capacity shift between regions, as well as the need to secure long-term and high-skilled jobs. Since distributional implications of a transition come on top of compounding injustices, decision makers need to take a people-centred approach and engage with local communities to consider procedural and recognition justice, as well^{33,34}. Concerning the Global North's role in this transition, initiatives like the JETP need to get better at ensuring that support schemes serve vulnerable groups on the ground²¹. For the CBAM specifically, collaboration and support from the EU should be granted to implement the instrument in the Global South, and to ensure the levy's impact on local businesses and jobs is minimised⁴.

While our results are generalisable beyond the South African context to some extent, in practice strategies will depend on regional and local constraints. This raises two important limitations of our work. First, we analyse the steel sector from an integrated and long-term systems perspective, thereby abstracting from short-term political challenges such as previous abuse of market power in the South African steel market³⁵, or ongoing negotiations in an attempt by the South African government and the Industrial Development Corporation to secure domestic long steel operations¹⁸. Our modelling approach also requires us to omit details on transport infrastructure for energy inputs, raw materials, iron, and steel. For power demand from electrolysers specifically, in practice, renewable capacity is likely to be often built independent of the grid, which we are not able to capture in GENESYS-MOD. Second, for our employment calculations we did not take stock of required skills or labour market equilibrium effects, hence neglecting the training needed to meet the requirements of a rapid low-carbon transition, as well as resulting wage developments. As both of these aspects pose central bottlenecks to the sector's development, future

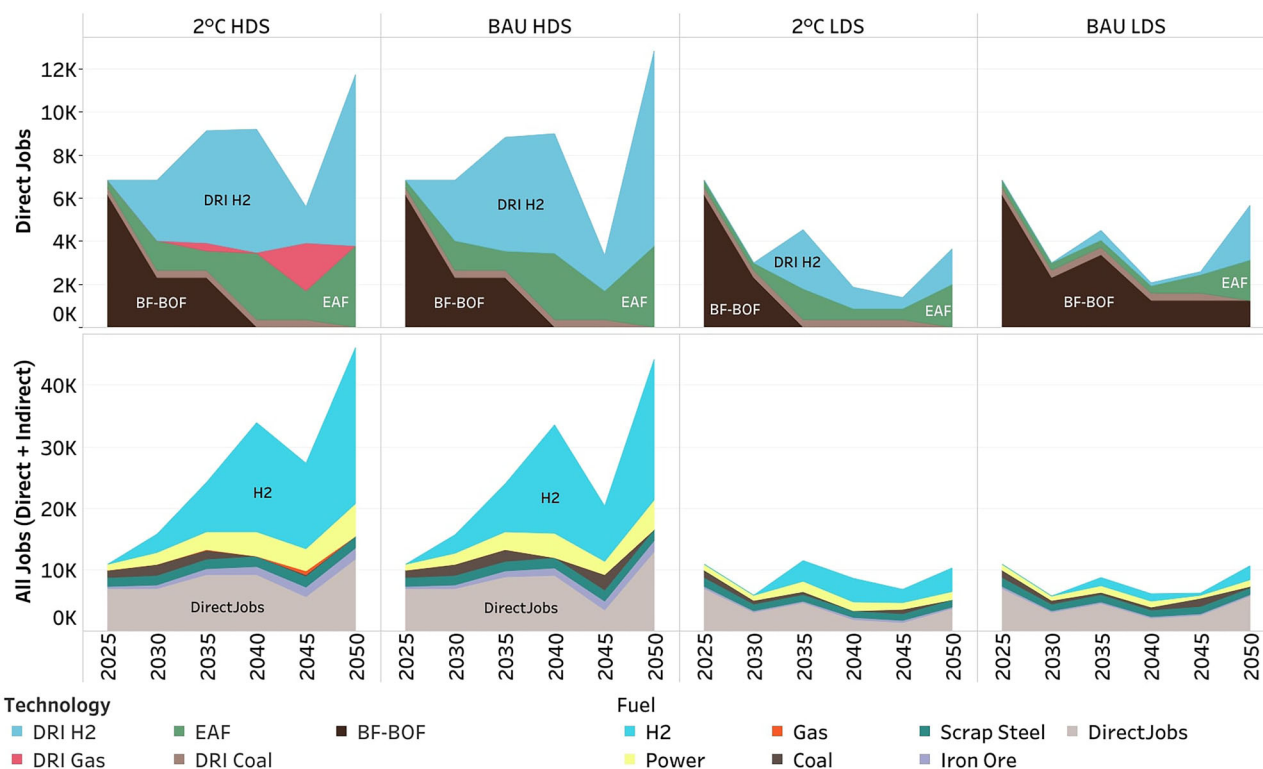


Fig. 4 | Direct and indirect steel sector jobs over time for each scenario. We provide a regional estimate per province in Supplementary Fig. 1 and direct jobs in the power sector in Supplementary Fig. 3. Indirect jobs include power sector jobs to meet energy demand from steel, as well as jobs associated with iron ore and coal mining. The model's job module captures employment in manufacturing, construction and installation, operation and maintenance, and supply (see SI for detailed information). In all four scenarios, indirect jobs gain in importance for overall employment over time. In the high-demand scenarios, low-carbon steel starts

to crowd out fossil steelmaking jobs from 2030 onwards. When competition for H₂ with other sectors is high, jobs for the DRI-NG buildup bridge the gap before this capacity is converted to H₂-DRI, as well. Even in a scenario with lower demand and without ambitious emissions targets (BAU LDS), both direct and indirect low-carbon steel jobs play a larger role than fossil steel jobs from 2040 onwards. In both high-demand scenarios, we observe two spikes associated with the ramp-up of hydrogen and H₂-DRI equipment.

work is needed to investigate both specific production locations with required transport infrastructures for energy and material, as well as the skillsets and labour market developments implied by our employment results.

Last but not least, by the modelling-focused nature of this study, we put techno-economic considerations at the centre of our analysis, thereby neglecting to a substantial degree how the transition is experienced by affected workers and their communities¹⁵. Further research should ensure in close cooperation with civil society that low-carbon steelmaking projects are embedded into the greater context of a just energy transition. Initiatives should hence move away from green extractivism and towards emancipatory hydrogen futures that include international support for additional macroeconomic policies, fair trade agreements, and knowledge and technology transfers^{14,30}.

Methods

Scenario design

We centre our study around the effects of national climate targets and demand for low-carbon DRI and steel. To measure the impact of both factors, we consequently employ four scenarios. Two HDSs depict increases in both domestic crude steel production and exports of hydrogen-based DRI until 2050. Out of the two, one is aligned with a 2 degree emission reduction target, aiming for a net-zero energy system by 2050, the other follows a business as usual (BAU) climate trajectory. Similarly, we employ two respective Low Demand Scenarios (LDSs), representing a decline in crude steel demand and no exports of hydrogen-based DRI until 2050.

More specifically, in the HDS, long steel operations in Newcastle (SA-KW) remain active beyond 2025 and demand for crude steel used

domestically is assumed to increase 1% each year. The additional demand of 1% each year is not tied to a specific region but can be satisfied by any region, allowing for flexibility when it comes to additional demand in the high scenario. Exports of hydrogen based DRI increase significantly by 2050, representing a best-case scenario for South Africa's export potential of H₂-DRI, capturing 1% of expected global demand³⁶. The LDS, on the other hand, represents a decline in both domestic and export production, with no share of the global renewable-based DRI market being captured. The resulting exogenous demand assumptions are summarised in Supplementary Table 1.

The two emission scenarios that are deployed in combination with the two demand scenarios are constructed as follows: The BAU scenario reflects South Africa's energy trajectory under current policies and trends as outlined in the Integrated Resource Plan 2023 (IRP 2023)³⁷. The scenario follows the older peak, plateau, and decline emissions reduction trajectory from South Africa's 2020 Low Emission Development Strategy, which does not target net-zero by 2050³⁸. This scenario serves as a baseline against which more ambitious pathways can be compared. The Steel sector is assumed to make up 3% of emissions and it assessed separately in the model set-up allowing for control over the sector-specific emissions. The 2 °C scenario aligns South Africa's energy transition with the international objective of limiting the global temperature rise to no more than 2 °C above pre-industrial levels. This pathway entails ambitious carbon emissions reductions³⁹, introducing yearly emission caps to gradually reach net-zero by 2050. The resulting emissions constraints are reported in Supplementary Table 2.

Modelling South Africa's steel transition with GENeSYS-MOD

The scenarios are implemented in the latest Julia-based version 4.0 of GENeSYS-MOD, which has been extended and adapted to the South

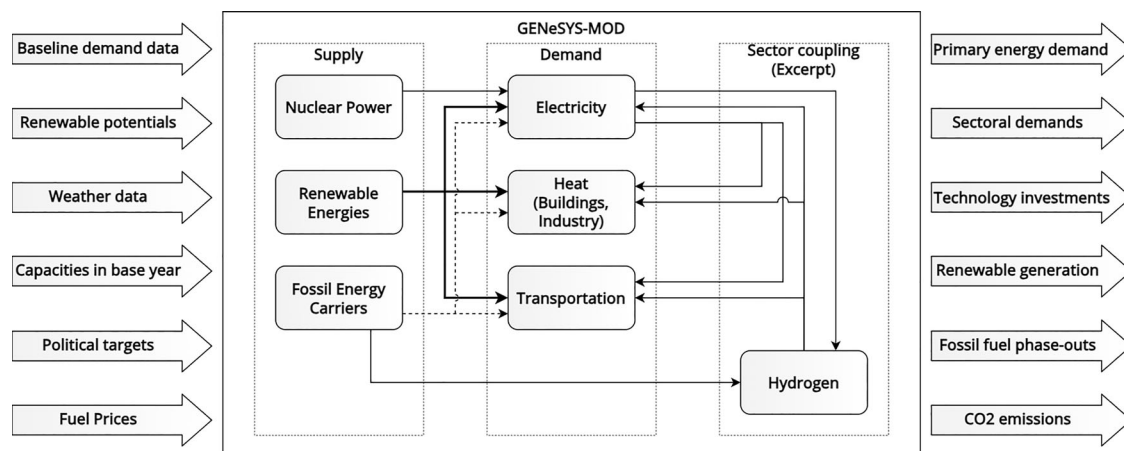


Fig. 5 | Stylized graph of GENeSYS-MOD. The model uses key inputs (baseline demand, renewable potentials, weather, existing capacities, political targets, and fuel prices) to optimize a least-cost, constrained energy system by minimizing the net present value of total system costs. It balances supply and demand across regions,

years, and time steps while considering sector-coupling options, and outputs key parameters including primary energy demand, sectoral demands, technology investments, renewable generation, fossil-fuel phase-outs, and emissions.

African context^{27,40,41}. Our research questions outlined above require a method that couples low-carbon iron and steel technology pathways with the energy system as a whole, as well as captures the spatial distribution of capacities and production. To date, other optimisation models for South Africa, such as PyPSA, OseMOSYS, or Plexos are focused on power systems modelling only. SATIM-GE, a TIMES energy model linked to a Computable General Equilibrium, is the only optimisation model for South Africa that includes power and demand sectors, like industry, but is single node and does not represent sub-regions of the country⁴². Accordingly, GENeSYS-MOD currently constitutes the only modelling framework with the necessary spatial and sectoral resolution to adequately address the research questions formulated in this study.

GENeSYS-MOD minimizes the net present value of total system costs, constructing an energy system that meets demand while adhering to constraints for a least-cost solution. The baseline year is 2018. The time frame extends to 2050, with investment steps starting in 2025 and progressing in five-year intervals. The framework incorporates sector coupling decisions that consider energy needs in multiple sectors, including electricity, transport, residential heating, and industrial processes (Fig. 5). Further information on the model can be found on the [GENeSYS-MOD GitHub](#) page.

Implementing the steel sector

The steel sector in our model is calibrated to current capacities in South Africa, with largest production facilities in Vanderbijlpark (Gauteng region), Newcastle (KwaZulu Natal), and Saldanha (Western Cape)²⁸. In the current model version, we have implemented multiple technologies: conventional blast-furnace blast-oxygen-furnace (BF-BOF), conventional blast-furnace blast-oxygen-furnace with CCS (BF-BOF-CCS), electric arc furnace (EAF), steel recycling, as well as DRI with coal, natural gas or hydrogen. Furthermore, DRI capacities in Gauteng can be equipped with CCS technology assuming potential storage in the Durban Basin²⁹. Input energy, material and cost parameters are derived from Agora Energy's study on breakthrough technologies for energy-intensive industries⁴³ and can be seen in Supplementary Tables 3, 4. For the DRI gas capacities, we assume high capital costs to account for the built-up of gas infrastructure. These technologies can switch to using hydrogen for H₂-DRI production in 2050. To account for the cost of inputs in the steel-producing processes, we specify variable cost for scrap steel and iron ore procurement. Additionally, variable costs representing pelletizers are added to hydrogen- and gas-based DRI.

The steel capacities data for South Africa are listed in Supplementary Table 5. Assuming that in a HDS, crude steel demand is expected to remain stable and potentially increase, BF-BOF capacities in Newcastle are only

decommissioned by 2040 in the HDS compared to a decommission by 2030 in the LDS). Company announcements for capacity additions are taken into account until 2035 (see Supplementary Table 6). Furthermore, new capacities for BF-BOF are restricted to the regions SA-GA (Gauteng), SA-MP (Mpumalanga), and SA-KW (KwaZulu-Natal) to realistically reflect existing industrial infrastructure that can support the development of blast furnaces, as well as proximity to coal resources.

Trade between provinces and transport cost are considered at three stages of the value chain, i.e. (i) upstream from iron ore mines in the Northern Cape (mostly Sishen and Khumani) to the initial reduction step, (ii) midstream for the direct reduction route, i.e. potential transport of DRI from location A to EAFs in location B, as well as (iii) downstream transport of crude steel. The two main existing rail lines – i.e. the Coal Line from Mpumalanga to Richards Bay and the Iron Ore Line from Sishen to Saldanha Bay – are taken into account for the calculation of transport cost. Road transport is assumed for any other internal trade options.

Multiple current capacities in South Africa could potentially be retrofitted to work either with a different fuel, such as a switch from coal-based to gas-based DRI, or the addition of CCS to reduce overall emissions. Coal-based DRI could be retrofitted to work with natural gas. This is only allowed by 2035 given the technological changes and uncertainty about natural gas use as most of it would need to be imported. In total, 1.5 Mt of capacity could be retrofitted in Vanderbijlpark (SA-GA). We assume retrofitting cost to be 30% of capital costs for gas-based DRI. The coal-based DRI in Vanderbijlpark could also be equipped with CCS technology. A capture rate of 90% is expected based on⁴⁴. Capital cost for retrofitting are 70% of a new built capacity. A mothballed DRI capacity 0.8 Mt in Saldanha (SA-WC) could be brought back on as a hydrogen-based DRI by 2030. We assume 10% of capital costs of DRI for the retrofit.

Job module

We employ a job module based on ref. 27, extended to include the Steel sector. Using an employment factor approach, job numbers for different job types are calculated. These include: manufacturing, construction & installation, operation & maintenance, and supply jobs. For manufacturing, a local manufacturing factor is provided, specifying the share of actual production of parts in the country. For South Africa, we assume a general share of 30% for the power sector and 20% for the steel sector. The regional adjustment factor of 2.15 is applied to all values.

An overview of assumptions for job factors in the power sector and steel sector can be seen in Supplementary Table 7. These job factors are used to calculate direct jobs. Indirect jobs (fuel use) from the steel sector for most

fuels can be quantified easily via supply (mining) jobs. But for power and hydrogen, jobs need to be calculated first. Thus, we calculate average employment in the power sector and for Electrolyzers, leaving us with a Jobs/PJ value we can use to approximate indirect jobs.

Data availability

The model used in this research can be found at the public GitHub page of GENeSYS-MOD (<https://github.com/GENeSYS-MOD>) and the data in the open Zenodo repository for the GENeSYS-MOD dataset under <https://doi.org/10.5281/zenodo.16811216>.

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References

- Hector, M. *Greening Industrial Policy in South Africa: Insights from China, the United States and the European Union*. Tech. Rep., Trade and Industrial Policy Strategies, Pretoria, South Africa <https://gems3.ai/wp-content/uploads/2025/02/GREENING-INDUSTRIAL-POLICY-IN-SOUTH-AFRICA.pdf> (2025).
- Algers, J. & Åhman, M. Phase-in and phase-out policies in the global steel transition. *Clim. Policy* **24**, 1163–1176 (2024).
- Vogl, V., Olsson, O. & Nykvist, B. Phasing out the blast furnace to meet global climate targets. *Joule* **5**, 2646–2662 (2021).
- Zhang, W. & Sovacool, B. K. The Geopolitics of Net-Zero Transitions: Exploring the Political Economy of Carbon Border Adjustment Mechanism Implementation in the Global South <https://www.ssrn.com/abstract=4853573> (2024).
- Eicke, L., Weko, S., Apergi, M. & Marian, A. Pulling up the carbon ladder? Decarbonization, dependence, and third-country risks from the European carbon border adjustment mechanism. *Energy Res. Soc. Sci.* **80**, 102240 (2021).
- Böhringer, C., Fischer, C., Rosendahl, K. E. & Rutherford, T. F. Potential impacts and challenges of border carbon adjustments. *Nat. Clim. Change* **12**, 22–29 (2022).
- Magacho, G., Espagne, E. & Godin, A. Impacts of the CBAM on EU trade partners: consequences for developing countries. *Clim. Policy* **24**, 243–259 (2024).
- Zhong, J. & Pei, J. Beggar thy neighbor? On the competitiveness and welfare impacts of the EU's proposed carbon border adjustment mechanism. *Energy Policy* **162**, 112802 (2022).
- Egli, F. et al. Mapping the cost competitiveness of African green hydrogen imports to Europe. *Nat. Energy* **10**, 750–761 (2025).
- Samadi, S., Fischer, A. & Lechtenböhmer, S. The renewables pull effect: How regional differences in renewable energy costs could influence where industrial production is located in the future. *Energy Res. Soc. Sci.* **104**, 103257 (2023).
- Verpoort, P. C., Gast, L., Hofmann, A. & Ueckerdt, F. Impact of global heterogeneity of renewable energy supply on heavy industrial production and green value chains. *Nat. Energy* **9**, 491–503 (2024).
- Nykvist, B., Gong, J., Algers, J. & Åhman, M. Renewables pull and strategic push - What drives hydrogen-based steel relocation?. *Appl. Energy* **395**, 126189 (2025).
- Kalt, T., Simon, J., Tunn, J. & Hennig, J. Between green extractivism and energy justice: competing strategies in South Africa's hydrogen transition in the context of climate crisis. *Rev. Afr. Political Econ.* **50**, 302–321 (2023).
- Kalt, T. & Tunn, J. Shipping the sunshine? A critical research agenda on the global hydrogen transition. *GAIA - Ecol. Perspect. Sci. Soc.* **31**, 72–76 (2022).
- Tunn, J., Müller, F., Kalt, T. & Simon, J. Why coloniality matters in the hydrogen hype - A reply to Walker and Kalvelage 2025. *Political Geogr.* **120**, 103352 (2025).
- Banya, N. ArcelorMittal South Africa is in talks to defer long steel plant closure. *Reuters* <https://www.reuters.com/markets/commodities/>
- arcelmittal-south-africa-is-talks-defer-long-steel-plant-closure-2025-03-19/ (2025).
- Panchia, Y. Temporary reprieve for ArcelorMittal SA's long steel division as closure deferred amid financial woes. *Daily Maverick* <https://www.dailymaverick.co.za/article/2025-04-03-temporary-reprieve-for-arcelmittal-sas-long-steel-division-as-closure-deferred-amid-financial-woes/> (2025).
- Adeyemi, S. Global steel giant to exit South Africa with \$460m takeover imminent. *Business Insider Africa* <https://africa.businessinsider.com/local/markets/global-steel-giant-to-exit-south-africa-with-dollar460m-takeover-imminent/nnv4scm> (2025).
- Trollip, H., McCall, B. & Bataille, C. How green primary iron production in South Africa could help global decarbonization. *Clim. Policy* **22**, 236–247 (2022).
- Bataille, C. et al. Towards net-zero emissions concrete and steel in India, Brazil and South Africa. *Clim. Policy* **0**, 1–16 (2023).
- Xaba, N. Whose just energy transition? A South African perspective. *WIREs Energy Environ.* **12**, e478 (2023).
- Tamasiga, P. Challenges and opportunities for just energy transition partnerships in Africa. *Policy Brief / Megatrends Afrika* 30 <https://www.megatrends-afrika.de/en/publication/policy-brief-30-challenges-and-opportunities-for-just-energy-transition-partnerships-in-africa> (2024).
- Van Huyssteen, T., Thiam, D. & Nonhebel, S. The water, land, and carbon intensity of electricity production: the case of South Africa. *J. Clean. Prod.* **411**, 136945 (2023).
- Altieri, K. E. et al. Achieving development and mitigation objectives through a decarbonization development pathway in South Africa. *Clim. Policy* **16**, S78–S91 (2016).
- Arndt, C. et al. A sequential approach to integrated energy modeling in South Africa. *Appl. Energy* **161**, 591–599 (2016).
- Hughes, A. et al. Developing and maintaining a policy-focussed, comprehensive, energy systems model in a developing country context: the case of SATIM in South Africa. *Energy Strategy Rev.* **56**, 101594 (2024).
- Hanto, J. et al. Effects of decarbonization on the energy system and related employment effects in South Africa. *Environ. Sci. Policy* **124**, 73–84 (2021).
- Global Energy Monitor. Global Iron and Steel Tracker <https://globalenergymonitor.org/projects/global-iron-and-steel-tracker/> (2025).
- Arndt, J. et al. *Carbon Capture in South Africa: An overview on Carbon Capture and Storage or Utilisation in South Africa*. Tech. Rep., International PtX Hub, Pretoria, South Africa https://ptx-hub.org/wp-content/uploads/2024/03/International-PtX-Hub_202403_Carbon-Capturing-South-Africa.pdf (2024).
- Omer, O. & Capaldo, J. The risks of the wrong climate policy for developing countries: scenarios for South Africa. *Ecol. Econ.* **211**, 107874 (2023).
- Odenweller, A. & Ueckerdt, F. The green hydrogen ambition and implementation gap. *Nat. Energy* **10**, 110–123 (2025).
- McGregor, C., Young, B. & Hildebrandt, D. Risk assessment framework for green hydrogen megaprojects: Balancing climate goals with project viability. *Appl. Therm. Eng.* **262**, 125197 (2025).
- Abe, O. & Azubike, V. (Re)examining the intersection between energy justice and energy transition in Africa. *J. Energy Nat. Resour. Law* **42**, 279–299 (2024).
- Hermwille, L. et al. Compounding injustices can impede a just energy transition. *Nat. Energy* <https://www.nature.com/articles/s41560-025-01785-x> (2025).
- Competition Commission South Africa. ArcelorMittal to pay R1.5 billion fine for its involvement in cartels <https://www.compcom.co.za/wp-content/uploads/2016/01/Press-release-ArcelorMittal-final-2.pdf> (2016).
- Watari, T. & McLellan, B. Global demand for green hydrogen-based steel: insights from 28 scenarios. *Int. J. Hydrog. Energy* **79**, 630–635 (2024).

37. Department of Mineral Resources and Energy. *Integrated Resource Plan, 2023*. Tech. Rep. Government Notice 4238; Government Gazette No. 49974, Republic of South Africa, Department of Mineral Resources and Energy, Pretoria, South Africa https://www.dmr.gov.za/Portals/0/Energy_Website/IRP/2023/IRP%20Government%20Gazette%202023.pdf (2024).
38. DFFE. *South Africa's Low Emission Development Strategy 2050*. Tech. Rep., Department: Forestry, Fisheries and the Environment https://www.dffe.gov.za/sites/default/files/docs/2020lowemission_developmentstrategy.pdf (2020).
39. Friedlingstein, P. et al. Global carbon budget 2021. *Earth Syst. Sci. Data* **14**, 1917–2005 (2022).
40. Löffler, K. et al. Designing a model for the global energy system-GENESYS-MOD: an application of the open-source energy modeling system (OSeMOSYS). *Energies* **10**, 1468 (2017).
41. Diesing, A., Hanto, J. & Löffler, K. Unlocking solar and hydrogen potentials: a comparative analysis of solar tracking systems for South Africa's energy transition. *Renew. Energy* **256**, 124066 (2026).
42. Tatham, J., Merven, B. & von Blottnitz, H. *A Review of Energy Systems and Economic Modelling Tools Capable of Estimating the Finance Needs and Responses Relevant to Energy, Water, and Food Security in South Africa in the Face of Climate Change*. Tech. Rep. SA-TIED Working Paper 233, South Africa (SA-TIED, 2024).
43. Agora Energiewende & Wuppertal Institute. *Breakthrough Strategies for Climate-Neutral Industry in Europe (Summary): Policy and Technology Pathways for Raising EU Climate Ambition*. Tech. Rep. (Agora Energiewende & Wuppertal Institute, 2020).
44. Benavides, K. et al. Mitigating emissions in the global steel industry: representing CCS and hydrogen technologies in integrated assessment modeling. *Int. J. Greenh. Gas. Control* **131**, 103963 (2024).

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Conceptualization: J.H., D.S.; Data handling: J.H., D.S.; Model development: J.H.; Validation: J.H., D.S., B.M.; Analysis: J.H., D.S., B.M.; Visualization: J.H., D.S.; Supervision: P.-Y.O.; Writing - original draft: J.H., D.S.; Review & editing: J.H., D.S., B.M., P.-Y.O.

Competing interests

The authors declare no competing interests.

Additional information

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