UNIVERSITY OF CAMBRIDGE
INSTITUTE FOR SUSTAINABILITY LEADERSHIP

CLG Europe

Technical Report

Technology, employment, and climate change mitigation:
Modelling the iron and steel industry

funded by
WE MEAN BUSINESS COALITION

The University of Cambridge Institute for Sustainability Leadership

The University of Cambridge Institute for Sustainability Leadership (CISL) is a globally influential Institute developing leadership and solutions for a sustainable economy. We believe the economy can be 'rewired', through focused collaboration between business, government and finance institutions, to deliver positive outcomes for people and environment. For over three decades we have built the leadership capacity and capabilities of individuals and organisations, and created industry-leading collaborations, to catalyse change and accelerate the path to a sustainable economy. Our interdisciplinary research engagement builds the evidence base for practical action.

This piece of analysis was carried out as part of the larger CLG report *Working towards a climate neutral Europe: Jobs and skills in a changing world* funded by the We Mean Business Coalition and the European Climate Foundation and published in April 2020.

Authors

Pim Vercoulen, Cambridge Econometrics (Contact: pv@camecon.com)

Sanna Markkanen, University of Cambridge Institute for Sustainability Leadership.

Citing this report

Please cite this report as: Vercoulen, P. and Markkanen, S. (2020). Technology, employment, and climate change mitigation: Modelling the iron and steel industry. Technical Report. Cambridge, UK: CLG Europe.

Abstract

The steel industry is fundamental to the EU's economy but also a major source of CO_2 emissions. With EU leaders' endorsement of the 2050 climate neutrality objective, the steel industry is under intense pressure to improve energy efficiency, recycle more, and to switch to low carbon production processes. Although the process of decarbonising steel production in Europe will be highly disruptive, inability to do so will result either in the EU's failure to achieve its emissions reduction targets or the decline and eventual disappearance of the European steel industry. Relocation of the steel industry to beyond Europe's boundaries would lead to job losses, carbon leakage and reduced competitiveness of the EU industry. It would also increase the dependence of European producers on steel imports across all sectors of the economy, from domestic appliances to renewable energy technologies.

Successful decarbonisation of the steel sector, on the other hand, would enable the EU to meet its ambitious climate targets while retaining jobs in Europe and improving the competitiveness of the EU industry. Substantial funds are currently being directed at the efforts to develop and commercialise zero carbon steel production methods. However, in addition to technological development, policies to support the adoption of new technologies will be fundamental in determining the impact that any new technologies may have on the size of the steel industry, the number of jobs it supports and its contribution to the EU's emissions. In this short briefing, we apply Cambridge Econometrics' technology diffusion model Future Technology Transformations (FTT):Steel, together with the Energy–Economy–Environment Macro-econometric model (E3ME)[1] to illustrate how emissions and employment may be impacted in various scenarios where zero carbon steel production is enabled using hydrogen-based production technology.

Introduction

Steel – an alloy of iron and carbon – is used widely in almost all industries from construction to domestic appliances and many of the renewable energy technologies, with a growing trend around the globe. The steel industry is of high importance to the EU and global economies, with annual production in 2018 amounting to 1.8 billion tonnes. Some 9 per cent of global steel production takes place in the EU, where the iron and steel industry (measured by value of production) ranks as the fourth largest industrial sector[2] and a major employer.[3] In 2019, the EU steel industry generated 330,000 direct jobs across 23 member states, 1.62 million indirect jobs and 722,000 induced jobs, for a total of 2.67 million jobs.[3] While the steel industry is not in itself one of the biggest contributors to gross domestic product (GDP) and employment, it provides inputs to value chains for most other sectors, making it an important long-term objective to retain at least some degree of steel production within the EU.

However, steel production is emissions intensive: in 2016, the iron and steel industry was responsible for 5 per cent of the CO_2 emissions produced across the EU.[4] At present, steel is produced primarily through two methods: the blast furnace (BF-BOF), which uses iron ores and recycled steel as inputs and burns coal as the main energy input, and the electric arc furnace (EAF), which uses mainly recycled steel as inputs and uses electricity (produced using fossil fuels or renewable sources) as the main energy input.[5] The BF production method is currently the only widely used technology for so-called virgin steel production, while the EAF method can be used to produce steel solely from recycled steel scrap.

By using renewable or other low carbon electricity, the CO_2 emissions from steel production using EAF can be reduced to very low levels. However, without carbon capture and storage/use (CCS/CCU) technologies, even the EAF method cannot reduce production-related CO_2 emissions to zero. Moreover, the limited availability of scrap steel and the unsuitability of recycled steel for certain purposes means that the demand for virgin steel will continue into the future, although declining from the current share of 70 per cent of the total steel production globally[5] to approximately 50 per cent by 2050.[6] In addition, the decarbonisation of Europe's steel industry is essential to achieving Europe's climate goals without causing the delocalisation of EU steel production to non-European countries (a process which would also cause carbon leakage) and compromising European competitiveness.[7] The ability to retain virgin steel production in Europe also has substantial employment implications.

Recognising the importance of the steel sector for the European supply chain, employment and for environmental sustainability, the European Green Deal explicitly supports initiatives towards the development of zero carbon steelmaking technologies.[8] With financial support from both the EU and national governments, the new technologies that are currently being explored to decarbonise virgin steel production are subject to extensive research and investment. These technologies can be grouped into three categories: Carbon Direct Avoidance (CDA), Process Integration (PI) and Carbon Capture and Storage (CCS) and Usage (CCU).[9]

- CDA technologies seek to reduce CO_2 emissions directly by using alternative fuels or methods such as hydrogen, biomass and electrolysis to reduce iron ore and other elements involved in the steel production process. Examples of projects using the CDA approach include HYBRIT, ULCOS, IERO and SALCOS.
- PI technologies aim at reducing the use of carbon in steel production, for example by using organic sludge in steelmaking (OSMet S2) or by a better use of steel plant gases. Examples of projects exploring PI technologies include CO2RED and RenewableSteelGases).
- CCU technologies concern different methods of carbon capture based on chemical biological processes of CO_2 conversion and capturing. For example, projects are trying to convert industrial CO_2 into fuel, other chemical products and materials such as plastics (BIOCON-CO2, CarbonNext, Carbon4PUR).[10]

The broader, long-term impacts on the EU steel industry, including the size of the sector, its global competitiveness and the number of jobs it offers, will depend heavily on which of these technologies will be the first to achieve commercial viability. At the moment, all of the above-mentioned projects that focus on developing new technologies to decarbonise virgin steel production are exploratory in nature, and the employment opportunities associated with each are difficult to estimate. However, it is nevertheless useful to explore how the employment, emissions and level of output in the European steel industry *might* be affected if new technologies enable zero carbon steel production, and how the outcomes vary depending on the level of support that EU policies offer to incentivise the uptake of these new technologies.

In recent years, particular attention has been directed at the hydrogen-based approach, which involves replacing coke with hydrogen for iron ore reduction and produces water vapour as a by-product instead of CO_2. If the energy to produce hydrogen is derived from renewable sources, the production process of steel can become emission free.[11] Although it remains uncertain as to whether the hydrogen-based approach will prove to be successful (or commercially viable), we are using this technology here to explore some of the potential impacts that the availability of this new technology could have on a set of steel-producing countries in the EU, as well as the role that policy will play in influencing these outcomes.

Approach

Transition to new production processes may affect an industry and the economy in several important ways. Conversely, the economic environment also affects technological transitions. Modelling potential changes in modes of production for a given sector in a wider economic environment allows us to see how environmental targets can be met, as well as the associated employment impacts.

Using the steel industry as an example, the case studies in this briefing illustrate how such analysis can be carried out using macroeconomic modelling tools. Cambridge Econometrics uses the Future Technology Transformations (FTT) framework to simulate technology take-up in the steel industry. In this framework, the decision-making of investing agents is mimicked: investing agents are heterogeneous due to different perceptions of costs, imperfect foresight and knowledge, and different valuation of the future. Local characteristics add to the overall uncertainty. Prior to choosing to invest in a particular technology, investors assess the expected costs and benefits. Several cost categories may be affected by policies and the external economic environment (e.g. fuel prices, demand for steel, etc.). An estimate of investor preference is obtained by comparing the balances between all potential technology pairs.

However, uptake of new technologies does not depend solely on preferences, but also on the rate at which old technologies are eligible for replacement and certain sectoral constraints, which must be included in any simulation of technology take-up. In the iron and steel industry, one such constraint is the availability of steel scrap: once the supply of available scrap has been exhausted, take-up of the recycling mode is restricted. FTT:Steel uses an endogenous approach to estimating scrap availability, building on historical steel flows and estimates on product lifetime, based on the work of Pauliuk et al. (2013).[12] The scrap supply is traded across regions and then over technologies. Most modes of production can substitute at least a certain degree of their virgin material input by scrap, but scrap input is favoured to flow into the recycling dedicated production mode.

A change in the technology mix of the steel industry can have several economic impacts. First, as the technology mix changes, so does the demand for raw materials and energy carriers, which affects the supplying sectors. Second, steel prices might be influenced by policies and changing raw material prices, affecting the demand. Third, different technologies require different pre-processing of raw materials, with implications on employment. For example, steel recycling requires the least amount of employment as no pre-processing of raw materials is necessary. As a result, a change in the technology mix induces a change in employment, which may impact consumer expenditure through disposable income of the population. All of these changes are due to bidirectional feedback between FTT:Steel and E3ME. For a more detailed overview of E3ME, see Mercure et al. (2018)[13] or the E3ME model manual.[14]

In order to find out what the policy implications are it is necessary to compare a new policy scenario to the baseline. Here, the baseline is defined as business-as-usual (BAU), meaning that the EU Emissions Trading System (EU ETS) will continue to be in place, but no additional policies are implemented. Even without policy support, some technology substitution will take place.

A mitigation scenario was constructed to support low carbon steel technologies and at the same time penalise carbon-intensive technologies. The mitigation scenario comprises an economy-wide carbon tax, subsidies on capital investment for low carbon technologies in the steel and power sectors, subsidies on electricity and hydrogen consumption within the steel sector, and a phase-out regulation of carbon-intensive technologies in the steel and power sectors (see Table 1). These policies are implemented for a mitigation scenario in Sweden and a mitigation scenario in the top EU steel producers (Germany, France, Spain, Italy and Poland). Mitigation policies are likely to extend to other sectors, such as the power sector, through which they influence the price of electricity, which is an input for the recycling production mode.

Table 1: Policy portfolios for the Sweden and top EU producer case studies

	Case study: Sweden	Case study: Top EU producers
Baseline scenario	Emission permit price increases from 70.4 €/toe in 2020 to 324.1 €/toe in 2050 for all EU member states.	
	No additional policies are implemented.	
Mitigation scenario	Emission permit price increases from 70.4 €/toe in 2020 to 972.3 €/toe in 2050 for all EU member states.	
	Steel sector (in Sweden): - 30% of the capital investment of hydrogen-based technologies is subsidised. - Subsidised hydrogen use (60%) and subsidised electricity use (50%) of the sales price. - Phase-out regulation of the BF-BOF production mode.	Steel sector (in top EU producers): - 30% of the capital investment of hydrogen-based technologies is subsidised. - Subsidised hydrogen use (60%) and subsidised electricity use (50%) of the sales price. - Phase-out regulation of the BF-BOF production mode.
	Power sector (in Sweden): - 30% of the capital investment of onshore wind and solar PV is subsidised. 50% for offshore wind. - Phase out regulation of fossil fuel power plants (not applying to CCS options).	Power sector (in top EU producers): - 30% of the capital investment of onshore wind and solar PV is subsidised. 50% for offshore wind. - Phase out regulation of fossil fuel power plants (not applying to CCS options).

Note: toe = tonne of oil equivalent. For each case study, the subsidies are only applied in the case study regions.

FTT:Steel is capable of testing such scenarios in a well-tested empirical model that simulates the economic environment. Yet, the outputs from FTT:Steel rely heavily on high-quality inputs. Improved availability of detailed data as technologies mature will enable more accurate results.

Case study 1: Sweden

At the EU level, Sweden is a minor producer country, accounting for only 3 per cent of European steel production.[3] However, steel is a reasonably important industry for Sweden, accounting for 2 per cent of its GDP[4] and for 4 per cent of its total exports of goods.[15] In addition to providing 15,700 direct and 26,500 indirect jobs,[15] the steel industry also plays a key role in the country's industrial competitiveness.[16]

In Sweden, the commitment to develop fossil-free steel production is supported by both the Swedish government and the industry as a necessary prerequisite to achieving two major climate targets: 100 per cent renewable electricity generation by 2040 and a net zero carbon economy by

2045. With its abundant and fossil-free electricity production mix expected to create electricity surpluses in the future, Sweden is well placed for the production of fossil-free steel. Moreover, there is no resistance from the industry or from society to the adoption of the new technology, and cooperation in the industry is very strong: decarbonisation is embedded in the long-term plans of both of the country's large incumbent iron and steel producers: LKAB (a state-owned mining company) and SSAB, which operates the country's two remaining plants that use blast furnaces.[16] For these companies, investing in innovation in zero carbon steel production makes economic sense. At present, SSAB relies on imported coal to operate its blast furnaces, instead of using readily available, domestically generated, fossil-free electricity. Second, by taking the lead in the development and implementation of new technology, SSAB aims to enhance its competitiveness in the long term.[16]

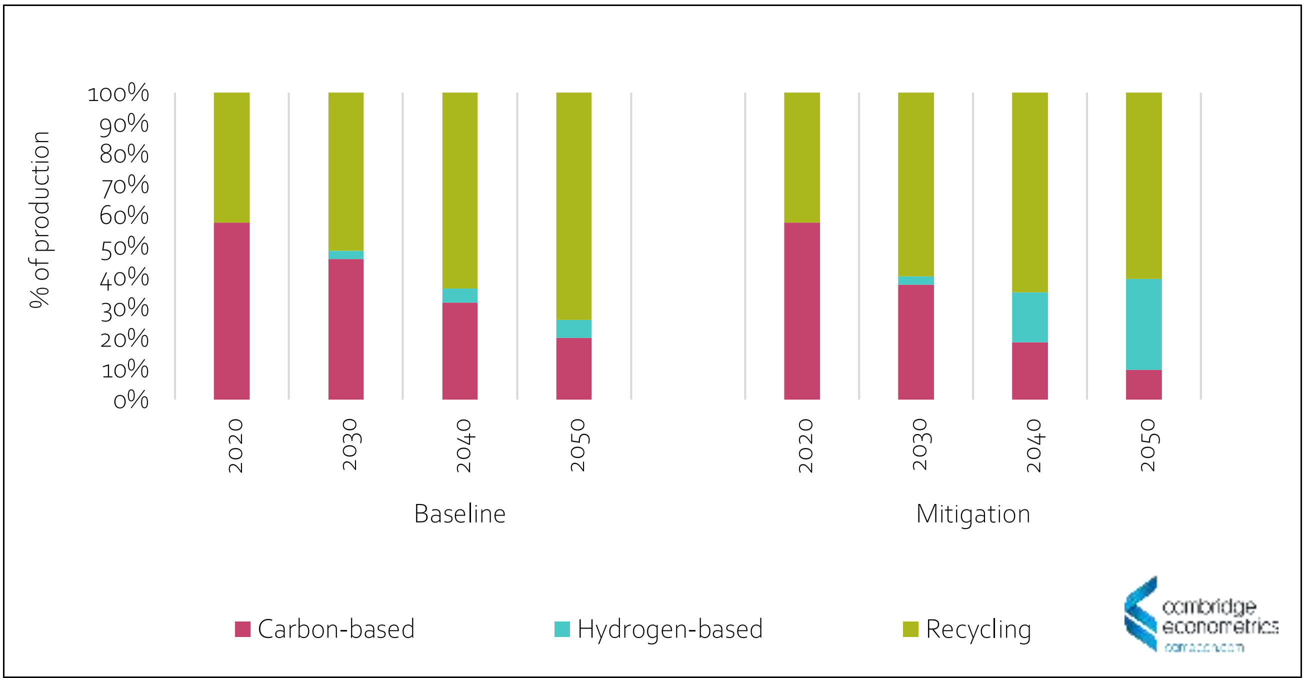
Under the HYBRIT joint venture, the Swedish firms SSAB, Vattenfall and LKAB are collaborating to develop a carbon-neutral hydrogen-based steelmaking process as an alternative to coal-based steelmaking by 2035. If this project proves successful, the broader adoption of the new technology will still depend largely on the policies enacted by the Swedish government and the EU. Using FTT:Steel in conjunction with E3ME, we can model the likely impacts using two different scenarios as presented in Table 1. The prevalence of three different types of steel production technologies (carbon-based, hydrogen-based and recycling) are presented in Figure 1.

As Figure 1 shows, in the baseline scenario the adoption of hydrogen-based production technology remains low, while the share of production using recycling grows steadily. This is because baseline conditions already encourage a shift towards recycling-based production. However, if all countries globally shift to recycling-based production to the same extent, the availability of scrap steel may start to constrain production capacity.

In the 'mitigation' scenario, where supporting policies for hydrogen-based production are introduced, this production mode becomes more competitive than the carbon-based and recycling production modes, substituting for a proportion of production through these modes. The phase-out regulation of BF-BOF (the main carbon-based production mode) creates a market gap for other technologies to fill. Support to encourage the uptake of the hydrogen-based production mode increases the likelihood of filling that gap with this production mode.

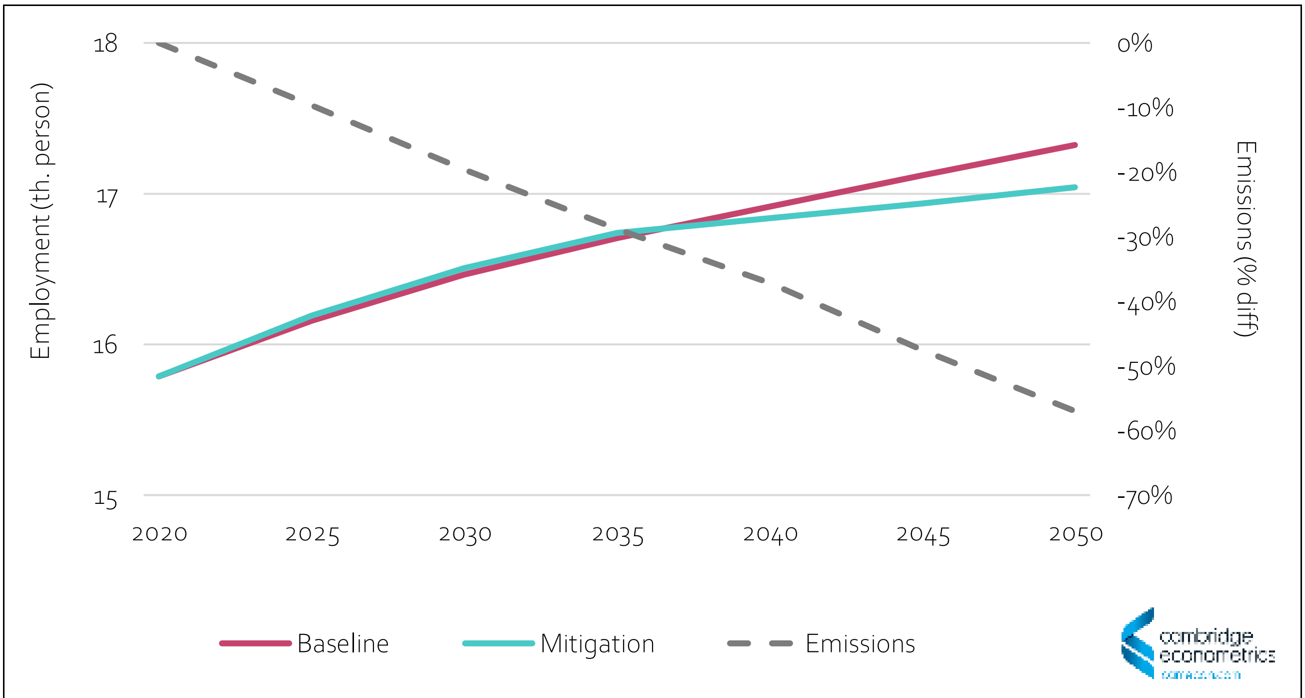
In Figure 2, we can see the emissions and employment impacts of the two scenarios. Emissions are presented as a percentage difference from the 'baseline' scenario, and show a substantial decrease in the emissions from steel production in the 'mitigation' scenario. This is primarily because of reduced virgin production using carbon-based technologies. The direct emission intensity of recycling and hydrogen-based production are negligible. Some emissions arise during the limited pre-processing steps. Indirectly, emissions may arise due to electricity generation or hydrogen production. However, hydrogen-based production is slightly less labour intensive than carbon-based production, so employment grows less in the mitigation scenario than the baseline scenario (a small increase in output is assumed here, which explains the slight increase in employment in both scenarios compared to 2020). The difference between 'mitigation' and 'baseline' employment is moderated by the fact that recycling-based production is less labour intensive than hydrogen-based production. For steel production to continue in a decarbonised economy, developing and deploying innovative zero carbon primary production methods like hydrogen will ensure minimal negative impacts on employment.

Figure 1: Production by technology



Source: Cambridge Econometrics' own calculations

Figure 2: Employment and emissions



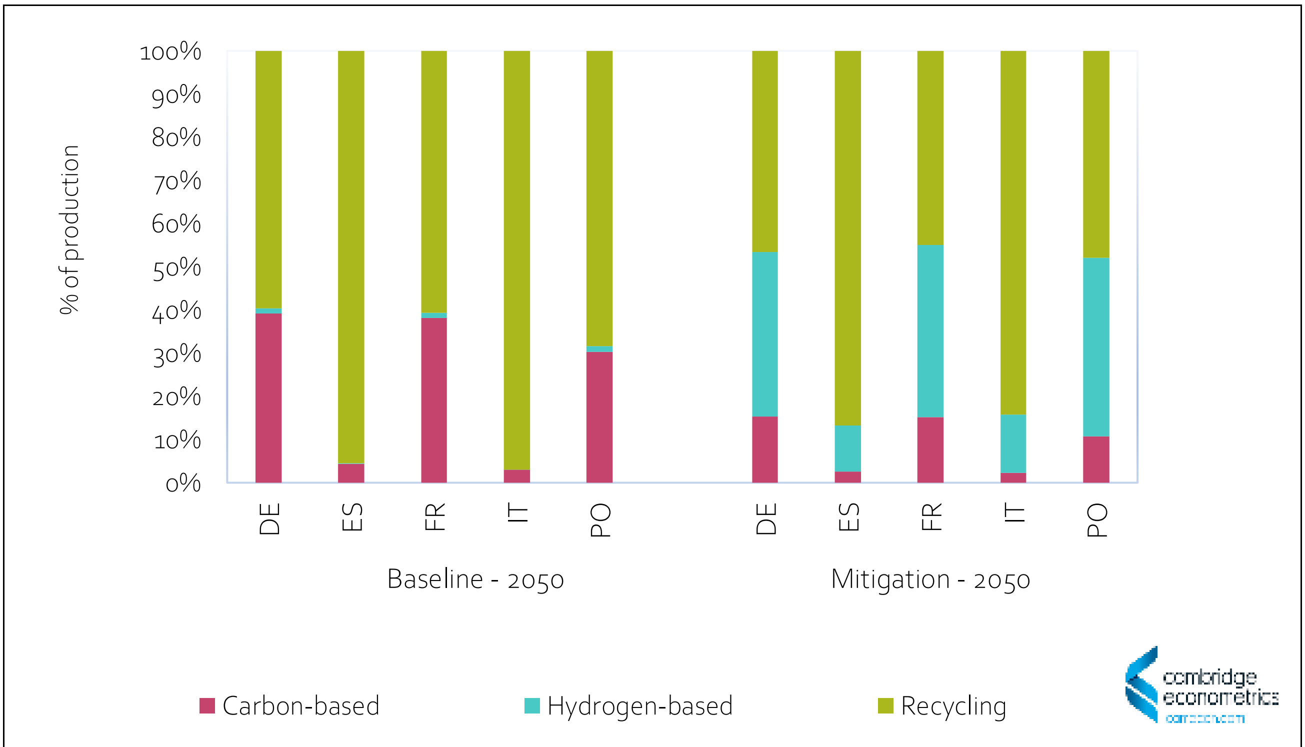
Source: Cambridge Econometrics' own calculations

Case study 2: top EU steel producers

Using E3ME–FTT:Steel to simulate the economic environment and change in mode of steel production, potential trade-offs between environment and economy can also be analysed for the EU top steel-producing countries. When a baseline scenario (no additional policies) is compared to a mitigation scenario for the whole EU (carbon tax, subsidies for clean technologies in steel and power sectors, and support for clean hydrogen production), potential effects can be better estimated (see Table 1 for more detail on the assumptions).

Comparing the development of the steel sector between the two scenarios in the top five steel-producing countries in the EU – Germany, France, Spain, Italy and Poland – the introduction of mitigation policies results in hydrogen-based steelmaking becoming much more prominent than carbon-based steelmaking in all countries, albeit to varying degrees. The support policies also lead to a situation where the hydrogen-based production mode can compete with the recycling production mode: in countries such as Poland, France and Germany, the hydrogen-based mode of production increases at the expense of steel recycling. In Spain and Italy, on the other hand, the phase-out regulation on BF-BOF (see Table 1) will not create a large enough market gap for the hydrogen-based production mode to fill. This is largely because recycling-based production already accounts for 75 per cent (Spain) and 85 per cent (Italy) market share of the production capacity, and this is reflected in the baseline production mode mix. Subsequently, in these two countries, most of the uptake of the new hydrogen-based production replaces recycling-based production.

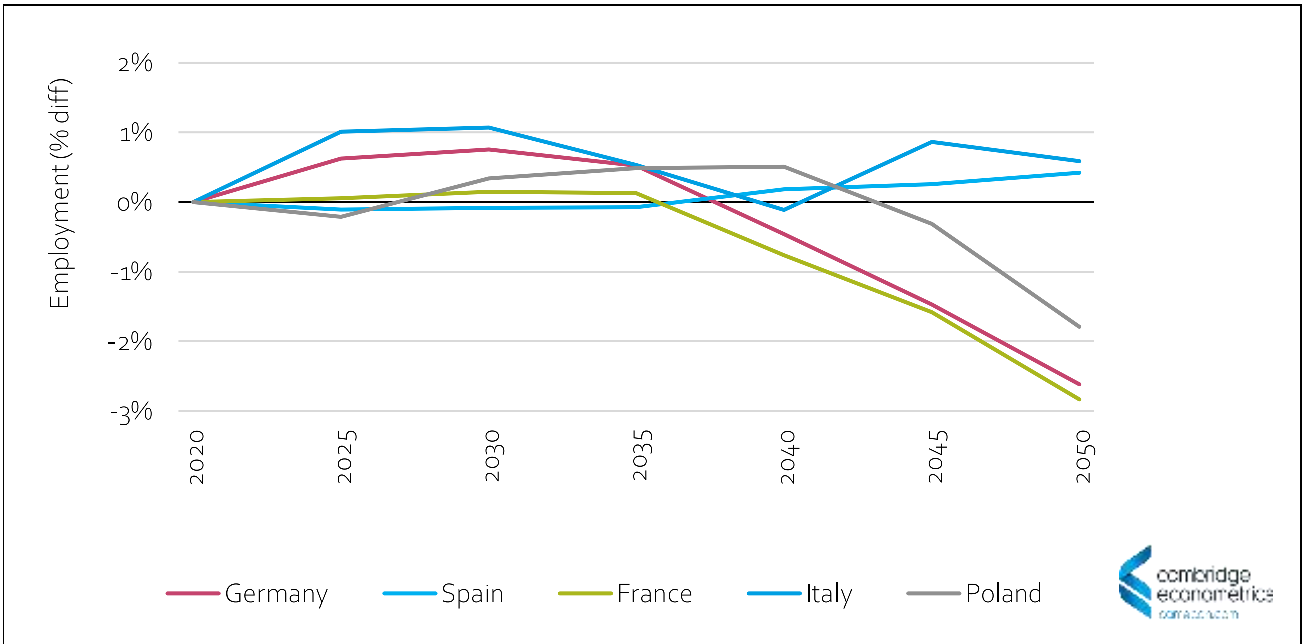
Figure 3: Breakdown of steel production (2050) for the baseline and mitigation scenarios



Source: Cambridge Econometrics' own calculations

In the ‘mitigation’ scenario, two main effects come into play that alter employment levels for the top EU producers. Employment levels are affected by changes in the technology mix within the iron and steel industry (as discussed previously), and changes in total domestic steel output. The latter can be affected by a change in regional competitiveness, which drives imports and exports. As shown in Figure 4, the analysis for Germany and Italy shows an initial increase in employment compared to the baseline scenario. The driver behind this is a slight increase in production levels, which compensates for a decrease in employment due to a change in the production mode. Towards the end of the simulation, employment in Germany drops compared to the baseline as slightly less labour-intensive hydrogen-based production reduces the share of carbon-based production more than it does recycling-based production, thereby outweighing the slight increase in production levels. A similar explanation applies to France and Poland, albeit France will slightly lose output levels while Poland remains roughly on par. The observed increase of employment in Poland in mid-simulation is due to the hydrogen-based production mode substituting the less labour-intensive recycling production mode.

Figure 4: Percentage difference of the mitigation scenario compared to the baseline scenario for employment



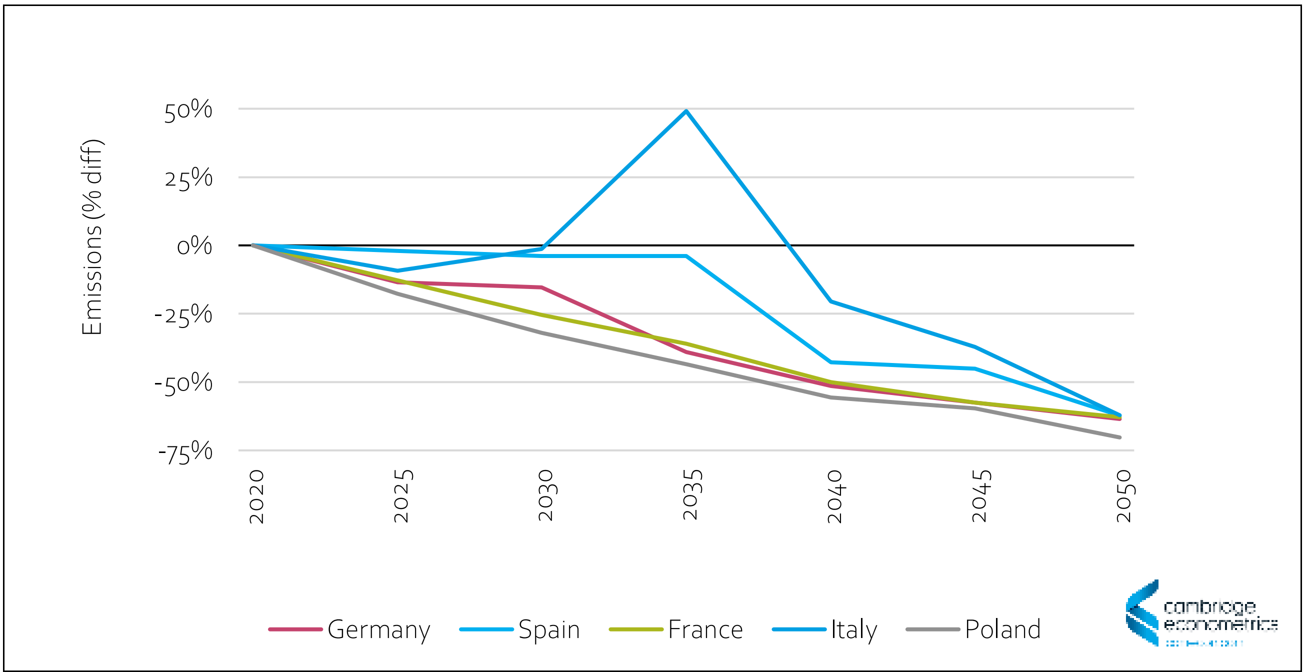
Source: Cambridge Econometrics’ own calculations

The Italian iron and steel industry is already largely recycling focused and therefore benefits employment-wise from a slight substitution to hydrogen-based production (hydrogen-based production being slightly more labour-intensive than recycling-based production). A similar explanation applies to the Spanish case. In the ‘baseline’ scenario, Germany, France and Poland retain a sizeable (30–40 per cent) carbon-based steel production in the mix (left side of Figure 3). A phase-out thereof in the ‘mitigation’ scenario ultimately leads to employment losses at similar output levels.

The amount of scrap steel that is needed in recycling-based production is subject to global demand, meaning that if a major producer such as China was to implement policies that incentivise greater transitioning to a recycling-based approach, growing competition over available scrap steel could further constrain the recycling-based approach in Europe. Once this constraint is reached, take-up of the recycling mode is restricted, creating a market gap for other production modes that are not limited by scrap availability. The impacts of greater competition for scrap steel at the global level has not been implemented in these scenarios, but could be if the model was run at a global level.

While the effect of the simulated policies has varying effects on employment levels, the policies are likely to be successful in promoting low carbon steelmaking and, as a result, reducing the carbon footprint of the steel industry. Emissions for each of the top-producing EU nations decrease by 60 to 70 per cent (Figure 5). It is noteworthy that absolute emissions are already comparatively lower in Spain and Italy due to a dominant position of steel recycling in the 'baseline'.

Figure 5: Percentage difference of the mitigation scenario compared to the baseline scenario for CO_2 emissions



Note: Spikes in the emissions graph are caused by shortages of steel scrap, which requires more carbon-intensive inputs.

Source: Cambridge Econometrics' own calculations

Closing comment

Promoting the hydrogen-based production mode helps to decarbonise the steel industry without becoming too reliant on recycling. It is likely that, at least until 2050, the global scrap supply will not be able to meet the global steel demand and therefore some steel production from virgin materials will be required. As Figure 2 and Figure 5 show, emissions decrease by 60–75 per cent (compared to baseline) for each of the case studies when both the recycling and hydrogen-based production modes are supported through policy interventions. In addition, each region becomes less reliant on the availability of steel scrap as the market share of the recycling-based mode is slightly lower in the 'mitigation' scenario compared to the 'baseline' scenario. However, countries such as France, Poland, Germany and Sweden that currently rely heavily on fossil-based production methods will experience some job losses in the steel industry as a result of the shift away from this production mode.

The wider economic impacts have not been discussed in either case study. It is likely that an increase in hydrogen-based steelmaking will lead to job creation in the hydrogen supply sector. The same goes for the power generation sector: an increase in electricity demand due to the recycling production mode gaining traction is likely to lead to an increase in employment. Furthermore, there are likely to be additional spill-over effects in other regions, which have not been discussed in this short briefing. For example, one effect that could be investigated in more detail is the potential for carbon leakage, i.e. where policies to achieve decarbonisation in a given context increase the price of domestic production, causing the industry to lose competitive advantage and resulting in domestically produced steel being replaced by imported steel. Conversely, when novel technologies are growing in market share, their costs will decrease through learning-by-doing, and other regions may benefit from this positive externality. Such issues and many more can be investigated using E3ME–FTT:Steel and similar sector-based models for other industries.

References

[1] Cambridge Econometrics. (2020). *E3ME*. Retrieved from: https://www.e3me.com/

[2] Oxford Economics. (2019). *The impact of the European steel industry on the EU economy*. Retrieved from: https://www.oxfordeconomics.com/recent-releases/The-impact-of-the-European-steel-industry-on-the-EU-economy

[3] Eurofer. (2020). *European Steel in Figures*. Retrieved from: https://www.eurofer.eu/assets/Uploads/European-Steel-in-Figures-2020.pdf

[4] Eurostat. (2016). Eurostat Greenhouse gas emissions by source sector. Retrieved from: https://ec.europa.eu/eurostat/web/climate-change/data/database#

[5] World Steel Association. (2018). *Steel Facts*. Retrieved from: https://www.worldsteel.org/en/dam/jcr:ab8be93e-1d2f-4215-9143-4eba6808bf03/20190207_steelFacts.pdf

[6] SSAB. (2020). *Steel production*. Retrieved from: https://www.ssab.com/company/sustainability/sustainable-operations/steel-production

[7] Draxler, M., Schenk, J., Bürgler, T., & Sormann, A. (2020). The Steel Industry in the European Union on the Crossroad to Carbon Lean Production—Status, Initiatives and Challenges, *BHM Berg- und Hüttenmännische Monatshefte*, *165*, 221–226. doi: https://doi.org/10.1007/s00501-020-00975-2

[8] European Commission. (2019). The European Green Deal. COM(2019) 640 final. Brussels. Retrieved from: https://ec.europa.eu/info/sites/info/files/european-green-deal-communication_en.pdf

[9] University of Cambridge Institute for Sustainability Leadership (CISL). (2020). *Working towards a climate neutral Europe: Jobs and skills in a changing world. Technical Report*. Cambridge, UK: CLG Europe. Retrieved from: https://www.corporateleadersgroup.com/reports-evidence-and-insights/technical-report-working-towards-a-climate-neutral-europe-jobs-and-skills-in-a-changing-world

[10] European Steel Skills Agenda. (2019). *Digital Transformation in European Steel Industry: State of Art and Future Scenario*. Retrieved from: https://www.estep.eu/assets/Uploads/Technological-and-Economic-Development-in-the-Steel-Industry-ESSA-D8.1.pdf

[11] Homann, Q. (2019). *Hydrogen as a Clean Alternative in the Iron and Steel Industry*. Fuel, Cell & Hydrogen Energy Association. Retrieved from: http://www.fchea.org/in-transition/2019/11/25/hydrogen-in-the-iron-and-steel-industry

[12] Pauliuk, S., Milford, R. L., Müller, D. B., & Allwood, J. M. (2013). The Steel Scrap Age. *Environmental Science & Technology, 47*(7). 3448–3454. doi: https://doi.org/10.1021/es303149z

[13] Mercure, J-F., Pollitt, H., Edwards, N. P., Holden, P. B., Chewpreecha, U., Salas, P., et al. (2018). Environmental impact assessment for climate change policy with the simulation-based integrated assessment model E3ME-FTT-GENIE. *Energy Strategy Reviews,* 20. 195–208. doi: https://doi.org/10.1016/j.esr.2018.03.003

[14] Cambridge Econometrics. (2020). *What is E3ME? Our Global Macro-econometric Model*. Retrieved from: https://www.e3me.com/what/e3me/

[15] Jernkontoret. (2020). *Steel Shapes a Better Future*. Retrieved from: https://www.jernkontoret.se/en/

[16] Nuur, C., Karakaya, E., & Gustavsson, L. (2018). Potential transitions in the iron and steel industry in Sweden: Towards a hydrogen-based future? *Journal of Cleaner Production*, *195*. doi: https://doi.org/10.1016/j.jclepro.2018.05.142