Steelanol

A full energy system perspective

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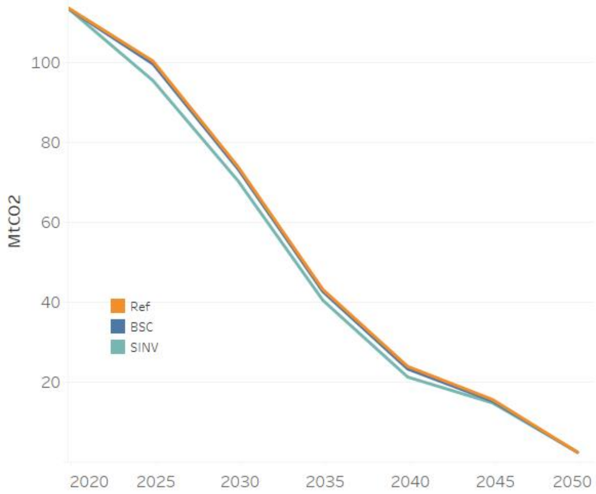
Executive summary

The European Union's Green Deal initiative has set a goal for 55% reduction in greenhouse gas (GHG) emissions by 2030 compared to 1990 levels, with a target of 61% reduction for Emissions Trading System (ETS) sectors. In this context, Belgium must take steps to lower GHG emissions of energy-intensive industries, including the steel sector, and embrace the circular economy. The Belgian Steel Federation has urged the authorities to avoid fast-tracking new regulations, citing concerns about technical and economic feasibility. Furthermore, the federation has called for an allocation of circular economy opportunities. ArcelorMittal, the world's leading steel and mining company, has set a 25% reduction target in GHG emissions compared to 2018 levels for its global operations, and a more ambitious target of 35% reduction for its European operations, due to supportive policies. To achieve this target, ArcelorMittal is focusing on two viable pathways: 'Smart Carbon' and 'Innovative DRI.' ArcelorMittal Ghent has set up demonstration projects, including Torero and Steelanol, to progress these pathways.

Following the ‘Smart Carbon’ pathway, the ‘Torero’ plant converts waste wood into bio-coal through a process called torrefaction. This bio-coal can replace part of the coal in the BF-BOF route. The second pathway is Steelanol, which is a prime example of Lanzatech’s gas-fermentation technology that converts waste gases into ethanol. When making use of CO and CO_2 from biogenic origin (the Torero produced bio-coal) the Steelanol plant produces bioethanol. This bioethanol can be used in the transport sector, to produce sustainable aviation fuels, in the production of plastics, as feedstock for pharmaceutics, cosmetics and cleaning products, as well as in the food and beverage industry. Furthermore, the ‘Innovative DRI’ aims to have a natural gas-based DRI-EAF route operational by 2026, taking over 40% of the BOF-BF route capacity and allowing for hydrogen replacement in the future.

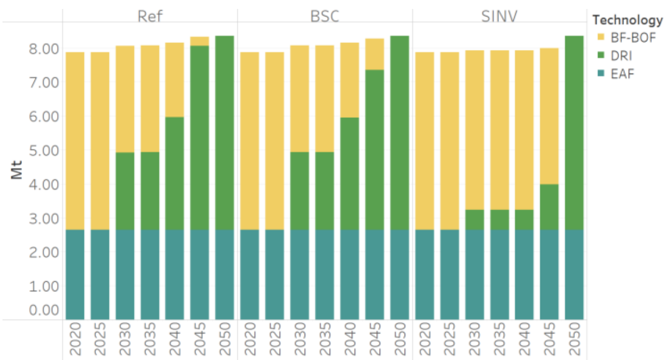
Whilst the immediate GHG emissions reduction derived from the commissioning of the Steelanol and Torero plants has been investigated by ArcelorMittal, the repercussions in the entire energy system haven’t been analysed. This study aims to evaluate the impact of Steelanol production on the entire Belgian energy system using a holistic approach with the TIMES-BE model. The study explores different scenarios based on the end-uses of Steelanol bioethanol. In all scenarios, the TIMES-BE model includes enough technological options to reach carbon-neutral steel production by 2050. The scenarios include a reference case (REF) without Torero or Steelanol, a base case (BSC) that considers the Steelanol and Torero plants, a scenario with complete export restriction (SNEA), a scenario that introduces an ethanol-to-ethylene production route (SE2E), and a scenario that invests in additional Steelanol and Torero capacity (SINV). The analysis focuses on REF, BSC, and SINV scenarios, as SNEA and SE2E results are similar to BSC.

For all scenarios, the model suggests that Steelanol is an economically attractive technology during the transition to a net-zero 2050 future, but Steelanol production is terminated in 2050. Biodiesel blending is the most preferred end-use for Steelanol, while gasoline blending is less attractive due to cheaper alternatives and the trend towards electrification of passenger vehicles. Steelanol is exclusively exported in 2040, and it is not used for biokerosene or ethylene production due to higher production costs compared to fossil alternatives. Further research will be needed, however, as further incentives and legislation could make it an economically viable option in the future. The presence of Steelanol and Torero postpones the replacement of BF-BOF capacity with the DRI-EAF route. The cumulative emission reduction of the SINV scenario by 2050 is 60% higher than the BSC scenario due to an increase in bio-coal consumption of the BF-BOF. In the SINV scenario, emissions are higher than in the REF scenario after 2035, while in the BSC scenario, the emissions reductions in the steel sector are lower than in the ArcelorMittal site.



Total system annual emissions per scenario.

Figure 6 presents a comparison of the steel production technology mix for each of the scenarios. These results show that the presence of Steelanol and Torero postpones the replacement of the remaining BF-BOF capacity with the DRI-EAF route. The CO_2 abatement in the ArcelorMittal site equals the avoided emissions from the coal displaced by bio-coal from Torero. The annual CO_2 abatement in the BSC scenario is 0.22 $MtCO_2$ in 2025. In the SINV scenario, the annual emission reduction increases to 1.6 $MtCO_2$, as a result of an increase in the bio-coal consumption of the BF-BOF. The cumulative emission reduction of the SINV (8.9 $MtCO_2$) scenario by 2050 is 60% higher than in the BSC scenario (5.5 $MtCO_2$).



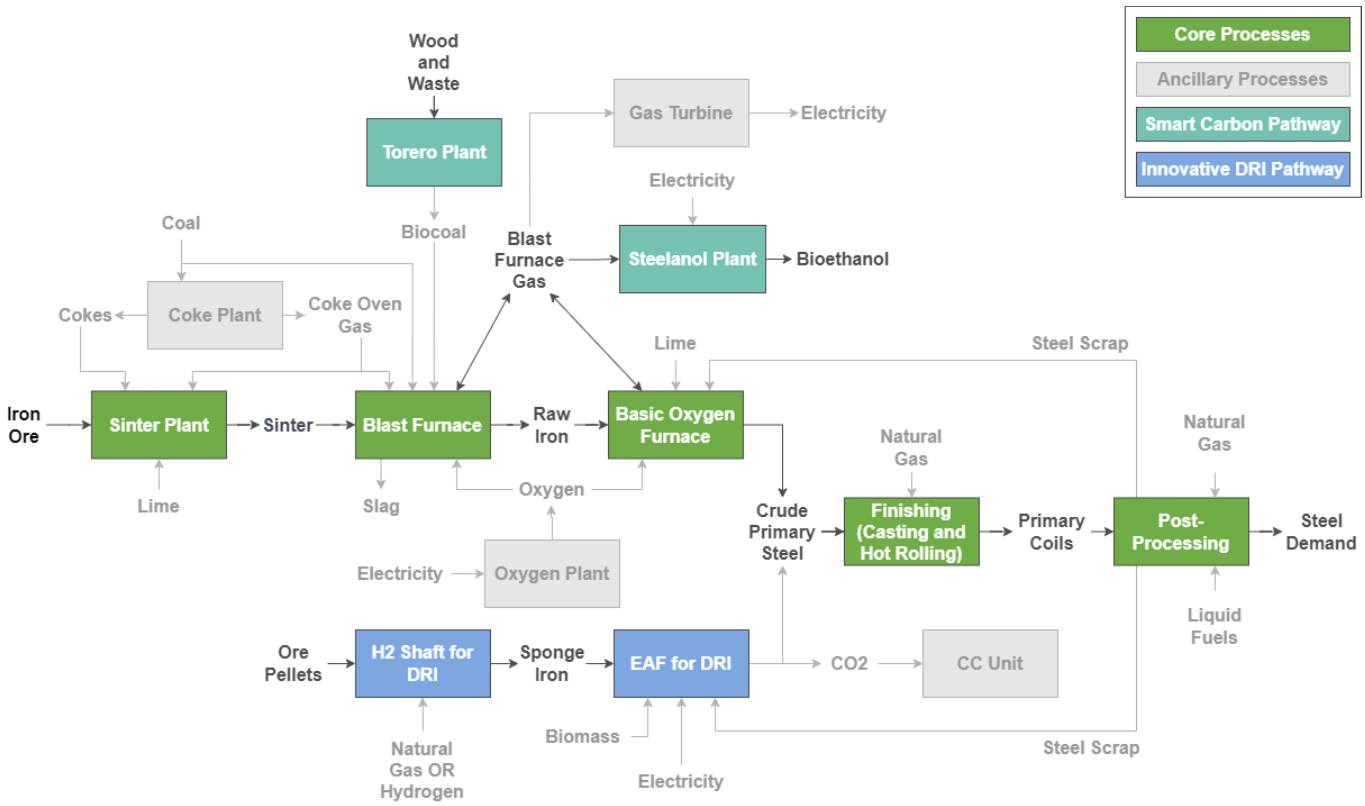
Steel production by technology

Steelanol can significantly reduce emissions, with reductions of 0.39-0.73 $MtCO_2$/yr. between 2025 and 2045. The abatement potential increases to 0.84-4.90 $MtCO_2$/yr. with investments in additional capacity (SINV). There are also cost savings in several sectors, particularly in the steel and power sectors, mostly derived from the extension of a modified BF that can replace up to 20% of the use of coal with bio-coal, deferring the investment in DRI to replace the BF to 2050. In the electricity sector, in the BSC scenario, Steelanol reduces blast furnace gas use and increases natural gas, solar PV, and battery use. However, the prolonged use of the blast furnace in the production of steel in the SINV scenario leads to lower electricity demand and capacity requirements. Finally, there is a slight decrease in the agriculture sector's use of biomass between 2025 and 2030 as it is allocated to the Torero plant. This is due to the fact that the total Belgian biomass use in the model is limited to the base year biomass use, no further increase is allowed. However, we learn from this result that it is more cost-efficient to use biomass for Steelanol rather than through combustion for heating purposes.

Steelanol has proven to be economically attractive as a transition technology towards a net-zero 2050 future. Aside from being economically attractive, the technology has proven to be beneficial from an emissions perspective. Steelanol is used in navigation and freight road transport for diesel blending and in passenger road transport for gasoline blending –only in 2025 and 2030 in the transition towards electric vehicles. Afterwards, Steelanol can be exported or used as feedstock for chemical processes. For the latter, more incentives will be needed to overcome the higher costs compared to fossil alternatives.

The use of Torero and Steelanol plants, particularly with additional capacity, could have a positive impact by mainly extending the use of the existing BF-BOF as well as making a clean biofuel available for the transport sector at competitive prices. In all scenarios, the model opts to not utilize the technology in 2050 as the net-zero constraint leads to replacing the remaining BF-BOF with the DRI alternative, making blast furnace gas not available. However, if the Steelanol plant could be fed with an alternative biogenic carbon gas source in 2050 from other sectors, it has the potential to remain operational. Further research on the viability of these alternatives for Steelanol seems appealing.

Finally, the presence of the Steelanol plant, as part of the Smart Carbon solution, evaluated within an Electrification context (as the one explored in PATHS2050), produces near-identical results regarding the deployment of Torero and Steelanol capacity.



ArcelorMittal Primary Steel Production Routes 2026 in TIMES-BE (graph can be seen in Figure 2 in the report)

1 Introduction

Background

On the road to a climate-neutral Europe in 2050, the main objective of the European Union's Green Deal initiative, the 'Fit for 55' package (FF55) was launched in July of 2021. This package describes the intermediate goal to reach 55% of EU-wide greenhouse gas reduction by 2030 compared to 1990 with a specific target of 61% reduction for ETS sectors, which is evaluated to be increased to 62%[1]. To be in line with FF55, ETS sectors must reduce their emissions by 43% compared with 2005 levels[2], which will be driven by strengthening the EU ETS, better-targeted carbon leakage and funding low-carbon innovation and energy sector modernisation. With this deadline on the horizon, Europe is set up for a challenge. Belgium especially, being an energy-intensive country, will have to make a conscious effort to achieve this goal. Not only the power sector but also all other sectors will have to start playing a bigger role in the decarbonization journey.

More recently, and after Russia's invasion of Ukraine, the European Commission presented REPowerEU as a plan to respond to the energy market's critical situation. The main goal of the plan is to rapidly reduce the dependency on Russian gas, which will, at the same time, help the European Union to move towards its climate objectives. REPowerEU includes some direct and indirect implications for the industry. For instance, it seeks to increase the European renewable target for 2030 from 40% to 45% and accelerate the deployment of hydrogen production within the EU to build 17.5GW of electrolyzers by 2025 and provide the industry with 10 million tons of hydrogen by 2030[3]. The European Commission also identifies a great potential for energy efficiency and electrification of industrial processes. In particular, for the steel sector, the proposed plan expects that nearly 30% of EU primary steel production will be decarbonized on the basis of hydrogen use by 2030[4].

Steel sector decarbonization challenge

In particular, energy-intensive industries like the steel sector will be put under pressure. The European steel sector has achieved high levels of efficiency in the last 30 years, leading to considerable CO_2 emissions reductions. However, the sector is reaching its limits in the carbon-intensive blast furnace – basic oxygen furnace route (BF-BOF). The Joint Research Centre (JRC) considers that the sector has a strong inclination to pursue the use of the hydrogen-based direct reduction of iron (H-DRI)[5]. Nonetheless, the same report acknowledges that carbon capture technologies are explored as a possible alternative for the reduction of CO_2 emissions. The sector is currently following both approaches as several projects have been announced within what the European Steel Federation –EUROFER– calls Carbon Direct Avoidance (DRI and electrification), and to a lesser extent Smart Carbon Usage and Carbon Capture and Storage (CCS)[6]. Already in 2019, EUROFER estimated that by 2050 the sector will need around 162 TWh/year of electricity and around 5.5 MtH_2 to reach high decarbonization levels[7]. On top of the energy demand, the sector will require access to CCS ranging from 21 $MtCO_2$ to 63 $MtCO_2$.

The Belgian Steel Federation has put forward three main concerns or challenges in its annual report for 2021[8]. Firstly, they urge the authorities not to fast-track new regulations at a pace at which the steel industry cannot follow technically and economically. Secondly, Belgian steel exports make up 10% of all steel outside the EU. Given the extra challenge of decarbonization and its resulting cost increase, the steel sector wants to safeguard its competitiveness of exports throughout the transition. Lastly, the federation notes that the opportunities offered by the circular economy should be allocated correctly. Currently, more steel scrap is being exported to countries with an uncertain environmental status.

According to the International Energy Agency's (IEA) Iron and Steel technology roadmap[9], the sector is responsible for 7% of global greenhouse gas emissions, while being responsible for about 8% of the global energy demand. This large contribution to global emissions is due to the high reliance on the usage of coal in the sector. This results in a high share of process emissions embedded in the product. Currently, two main routes are used in practice to produce two quality levels of steel. Primary steel is produced using the BF-BOF route which uses the blast furnace to reduce iron ore to pig iron using cokes and pulverized coal

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[1] Fit for 55, European Council website, accessed on 23 February 2023. https://www.consilium.europa.eu/en/policies/green-deal/fit-for-55-the-eu-plan-for-a-green-transition/#:~:text=The%20European%20climate%20law%20makes,EU%20climate%2Dneutral%20by%202050.

[2] Revision for phase 4 (2021-2030), accessed on 23 February 2023. https://climate.ec.europa.eu/eu-action/eu-emissions-trading-system-eu-ets/revision-phase-4-2021-2030_en

[3] REPowerEU Actions, European Commission, 2022. https://ec.europa.eu/commission/presscorner/detail/en/FS_22_3133

[4] REPowerEU: affordable, secure and sustainable energy for Europe, accessed on 23 of February 2023. https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal/repowereu-affordable-secure-and-sustainable-energy-europe_en

[5] Somers, J., Technologies to decarbonise the EU steel industry, EUR 30982 EN, Publications Office of the European Union, Luxembourg, 2022, ISBN 978-92-76-47147-9, doi:10.2760/069150 , JRC127468.

[6] Low-CO2 emissions projects in the EU steel industry, accessed on 23 February 2023. https://www.eurofer.eu/issues/climate-and-energy/maps-of-key-low-carbon-steel-projects/

[7] Low carbon roadmap pathways to a co2-neutral European steel industry, EUROFER, 2019. https://www.eurofer.eu/assets/Uploads/EUROFER-Low-Carbon-Roadmap-Pathways-to-a-CO2-neutral-European-Steel-Industry.pdf

[8] Philippe Coigné, "Belgian Steel in 2021" (GSV Belgian Steel Federation, n.d.). https://steelbel.be/images/2021UK.pdf

[9] "Iron and Steel Technology Roadmap – Analysis - IEA," accessed January 9, 2023, https://www.iea.org/reports/iron-and-steel-technology-roadmap.

injection (PCI). The coal and coke input provide the required energy and play the role of a reducing agent. This carbon-rich pig iron, complemented by 15 to 25% of steel scrap, is transformed into primary steel in the basic oxygen furnace (BOF). Consequently, coal plays an essential role in the production route of primary steel. Alternatively, secondary steel is mainly made from steel scrap, using an electric arc furnace (EAF) to melt scrap, with a low carbon content of approximately 0.05%[10] and a lower iron purity level. These disadvantages are accompanied by a much smaller carbon footprint. This indicates that the first decarbonization method for the steel sector could be to replace some of the primary steel production with more secondary steel production. However, due to the impurities in steel scrap and the quality required in some cases, such as the automotive industry, primary steel production will remain necessary for a global economy[11]. This means that an improvement in the circularity of steel[12] as well as the decarbonization of primary steel production technologies are required. Thus, there are three main strategies to decarbonize the sector: carbon capture usage and storage (CCUS), electrification (e.g. molten oxide electrolysis, electrowinning) and direct reduction of iron (e.g.; natural gas DRI or H-DRI).

The Case of ArcelorMittal

Within the current climate and energy landscape, ArcelorMittal has set a 25% reduction target, compared to 2018 emission levels, on their global steel and mining operations. In Europe, this target is sharpened to 35% due to its supporting policy environment, allowing for an accelerated decarbonisation[13]. The company announced its decarbonisation strategy in the Climate Action Reports 2021[14]. The report presents its net-zero roadmap, describing the project planning and related financial aspects in different countries. Three technology pathways have been identified: 'Innovative DRI', 'Smart Carbon' and 'Direct Electrolysis'. This last pathway is promising but not yet mature. For this reason, ArcelorMittal is focusing on these first two viable pathways[15].

Firstly, the 'Innovative DRI' pathway applies on the direct reduced iron –electric arc furnace (DRI-EAF) route where sponge iron from the DRI is used as input, aside from scrap, in the EAF. This allows for an alternative production route to primary steel without the use of coal as an input. Instead of reducing the iron ore in the blast furnace using cokes as a reducing agent, the iron ore is reduced directly using natural gas or hydrogen in the DRI shaft. The promise of this DRI technology is the potential to fully replace natural gas with hydrogen as the reductant. If green hydrogen supply is guaranteed, and most of the process' carbon needs are met with biomass, as in the HYBRIT project[16], the DRI route could become carbon neutral. Using renewable energy to power the EAF, leads to a zero carbon-emission steel plant. ArcelorMittal's full-scale facility in Spain will become the world's first of this kind[17].

Secondly, the 'Smart Carbon' pathway aims to partially replace the coal use in the primary steel BOF-BF route with alternative circular sources of carbon. Aside from providing recycling on the input side, the 'Smart Carbon' pathway also investigates recycling methodologies on the output side by allowing the integration of carbon capture and usage (CCU) or CCS technologies.

ArcelorMittal Ghent has set up multiple demonstration projects over the last years to further aid in the progression of these two pathways. Following the 'Smart Carbon' pathway, two main projects have been set up. A first demonstration plant is 'Torero' which converts waste wood into bio-coal through a process called torrefaction. The waste wood and plastic are developed in the SMART LIFE project [18] where AlterCoal pellets are produced from end-of-life non-recyclable residues. This bio-coal can replace part of the coal which is consumed in the BF-BOF route. Furthermore, 'Carbalyst' includes a family of technologies for carbon capture and usage.

Steelanol is a prime example which uses gas-fermentation technology by Lanzatech[19] to convert waste gases into bioethanol. This bioethanol can be used in the transport sector for blending with gasoline –or diesel– to produce sustainable aviation fuels[20], in the production of plastics (employing an ethanol-to-ethylene process[21]) or as feedstock for pharmaceutics, cosmetics and cleaning products[22], as well as in food and beverage industry[23]. Lastly, the 'Innovative DRI' pathway is also included in the climate

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[10] "Steel - Electric-Arc Steelmaking | Britannica," accessed January 9, 2023, https://www.britannica.com/technology/steel/Electric-arc-steelmaking.
[11] "Establishing a Global Standard for Low-Carbon Emissions Steelmaking" (ArcelorMittal, n.d.).
[12] "Circularity in Steel," Bellona.org, March 1, 2022, https://bellona.org/news/climate-change/2022-03-circularity-in-steel.
[13] "Climate Action Report 2" (ArcelorMittal, July 2021). https://corporate-media.arcelormittal.com/media/ob3lpdom/car_2.pdf
[14] "Climate Action Report 2."
[15] "Technology Pathways to Net-Zero Steel | ArcelorMittal," accessed January 9, 2023, https://corporate.arcelormittal.com/climate-action/technology-pathways-to-net-zero-steel/.
[16] Summary of findings from HYBRIT Pre-Feasibility Study 2016–2017, Swedish Energy Agency, SSAB, LKAB, and Vattenfall. https://dh5k8ug1gwbyz.cloudfront.net/uploads/2021/02/Hybrit-broschure-engelska.pdf
[17] "ArcelorMittal's decarbonisation plan for Spain moves forward with government commitment to funding" ArcelorMittal, accessed March 4, 2023. https://corporate.arcelormittal.com/media/news-articles/arcelormittal-s-decarbonisation-plan-for-spain-moves-forward-with-government-commitment-to-funding
[18] "Recovering the Non-Recyclable," Life Smart, accessed January 9, 2023, https://www.life-smart.eu.
[19] " Lanzatech Corporate Presentation-2023" accessed March 21, 2023, https://ir.lanzatech.com/static-files/12226c62-40af-4c2c-8dec-715c136b2a25
[20] The Alcohol-to-Jet Conversion Pathway for Drop-In Biofuels: Techno-Economic Evaluation; Geleynse, S. et al., 2018,
[21] Dehydration of Ethanol to Ethylene; Minhua Zhang and Yingzhe Yu; Industrial & Engineering Chemistry Research 2013 52 (28), 9505-9514; https://doi.org/10.1021/ie401157c
[22] "Ethanol-ChemicalSafetyFacts.org" accessed March 21, 2023, https://www.chemicalsafetyfacts.org/chemicals/ethanol/
[23] Renewable Ethanol for Beverage and Industrial Uses, ePURE, 2020. https://www.epure.org/wp-content/uploads/2020/11/renewable-ethanol.pdf

strategy for the Ghent facility. ArcelorMittal Ghent aims to have a natural gas-based DRI-EAF route operational by 2026, taking over 40% of the BOF-BF route capacity and allowing for hydrogen input in the future.

Research Objective

Whilst the immediate GHG emissions reduction derived from the commissioning of the Steelanol and Torero plants has been investigated by ArcelorMittal, the repercussions in the entire energy system haven't been analyzed. Thus, the goal of this study is to assess the impact of the production of Steelanol in the steelmaking process and the full Belgian energy system. To this end, the impact is determined by the carbon abatement, changes in the energy mix, as well as the system cost reduction in scenarios that comply with carbon-neutrality targets by 2050. The assessment will be performed using a system approach, utilizing the TIMES-BE model, to test the situation without Steelanol and compare it against cases where Steelanol is present. Furthermore, the study involves a more detailed analysis of the steel sector, looking at the specific technology decisions made by the model to decarbonize the production of primary steel.

2 Energy system model

2.1. TIMES-BE

TIMES, as defined on its website[24], is a modelling framework used to model energy systems varying the spatial and temporal resolution (e.g.: regions, countries, hours, seasons, years) which allows the development of both top-down and bottom-up models. The TIMES model is developed as part of the IEA-ETSAP's methodology for energy scenarios to conduct in-depth energy and environmental analyses[25].

TIMES is able to represent the full value chain from the import or mining of energy and material resources up to meeting final demands, either energy or products (e.g.: ammonia, glass, space heating, lighting). The modelling framework uses what is called commodities to represent the flow of energy carriers and materials between processes. These processes can represent transformation processes such as electricity production, and coke ovens; or final energy-consuming processes such as vehicles, and industrial processes. Processes, commodities and special constraints are used to build the mathematical representation of the energy system –the Linear Program (LP)– which is then optimized. Finally, the results of the model provide detailed information including installed capacity, energy and material flows, marginal production cost, CO_2 emissions, investments and O&M cost needed to meet the different demands in a cost-optimal manner. The TIMES-BE model has been developed by VITO - EnergyVille for several years, incorporating insights and good practices from projects in which the model has been used. More detailed documentation of TIMES-BE can be found on the PATHS2050[26] website or other scientific repositories[27].

2.2. Steel sector representation: Current and future technologies

The existing steel production technologies in Belgium are the BF-BOF, which is assumed to be used for high-quality steel, and the EAF, used mostly for low-quality steel. The steel sector is generally divided into iron ore pre-treatment, iron reduction, steel production, rolling & casting, auxiliary processes and finishing and forming –this last process represents small and distributed companies at the end of the supply chain. The energy and mass balance for each process was defined from literature reviews, sector reports and the Belgian energy balance available in EUROSTAT. The age of the assets is another important parameter to consider, thus, the technical lifespan of the steel assets is constantly extended by annual investments. On the other hand, after a couple of decades, furnaces might need to go through an overhauling process as happened in the ArcelorMittal plant in Ghent[28].

In the steel sector, process emissions are estimated to be around 80% of the total emissions. Moreover, the use of blast furnace gas (BFG) for the production of electricity is accounted for in the power sector, which reduces the emissions allocated to the steel sector. There are two main paths for the steel sector to be decarbonized: hydrogen for the direct reduction of iron and CCUS. These strategies are in line with sector associations' roadmaps and ArcelorMittal's vision[15]. For instance, EUROFER estimates that by 2050 the steel sector will consume 400 TWh (seven times the current EU steel industry current demand) for electric processes and hydrogen production[7]. Additionally, the report highlights that steelmaking in Europe will need to reduce around 21 $MtCO_2$/yr. through CCUS –this value could be higher depending on the availability of electricity and hydrogen.

[24] https://iea-etsap.org/index.php/etsap-tools/model-generators/times
[25] Documentation for the MARKAL Family of models, Loulou, et al. 2004. https://unfccc.int/resource/cd_roms/na1/mitigation/Module_5/Module_5_1/b_tools/MARKAL/MARKAL_Manual.pdf
[26] PATHS2050, accessed March 21, 2023. https://perspective2050.energyville.be/method
[27] PATHS2050 - Scenarios towards a carbon neutral Belgium by 2050. https://doi.org/10.5281/zenodo.7614844
[28] https://www.spglobal.com/commodityinsights/en/market-insights/latest-news/metals/020121-arcelormittal-confirms-ghent-blast-furnace-b-to-restart-production-by-mid-feb

Table 1. Steel production in Belgium by steel quality.

Sector	Sub-sector	Product	Unit	Demand/ production	Sources
Iron and Steel	Virgin steel	High-quality steel	Mt	5.14	Worldsteel[29]
	Scrap based steel	Low-quality steel	Mt	2.46	

Table 2. Emission reduction options for the steel sector in the TIMES model, grouped by strategy.

Demand/ Product	Current process	Fuel replacement	Hydrogen/ Molecules	Electrification	Carbon Capture & Storage/Reuse CCUS
High-quality steel	- Blast Furnace-Blast Oxygen Furnace (BF-BOF)	- Bio-coal (Torero) - Blast Furnace-H_2_injections - Blast Furnace-Plastic use	- Hydrogen - Direct Reduction (DRI) - H_2-based heat (finishing)	- Molten Oxide Electrolysis - Electrowinning	- BF-BOF/ with carbon capture & storage - Natural Gas - DRI/CCUS
Low-quality steel	- Electric Arc Furnace (EAF)	- Electric Arc Furnace (Electricity + Biomass)	-	- Electric Arc Furnace (100% Electricity)	- CCUS

[29] https://www.worldsteel.org/en/dam/jcr:7f5a36e2-e71e-4c58-b93f-f78d0c5933e4/WSIF_2015_vfinal.pdf

2.3. Steelanol integration in the energy system

The steel sector, and more specifically the impacts resulting from ArcelorMittal's 'smart carbon' and 'innovative DRI' strategies, have been integrated into TIMES-BE. To reflect these decisions, the model was updated accordingly. Firstly, the Torero and Steelanol plants were included in the existing primary steelmaking sector representation. Secondly, the natural gas DRI production route, as announced by Arcelor Mittal, is scheduled to commence operation in 2026, thereby replacing the production capacity of one of the two blast furnaces in Ghent. The changes made to the model are presented in Figure 2, which highlights the key modifications.

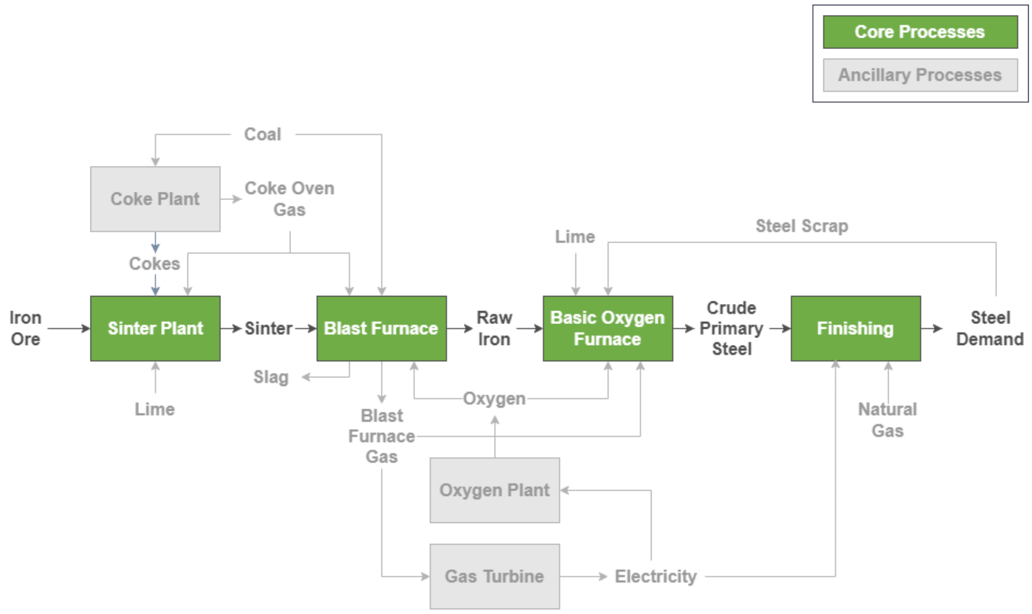

Figure 1. ArcelorMittal Primary Steel Production Route 2022

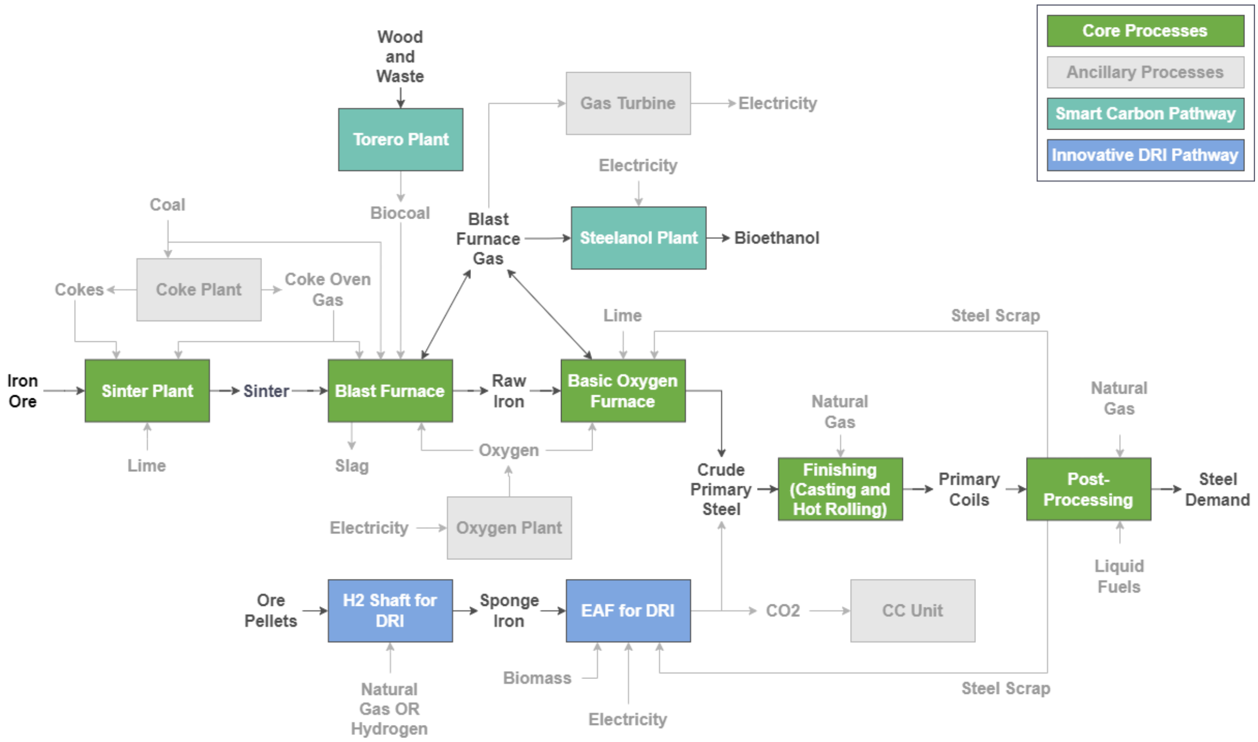

Figure 2. ArcelorMittal Primary Steel Production Routes 2026

Smart Carbon Pathway

At the ArcelorMittal site in Gent, the 'Smart Carbon Pathway' provides decarbonisation alternatives to the primary steel production route, described previously as the 'BF-BOF' route and indicated in green in Figure 2. Two main demonstration projects are set up to be implemented: the Steelanol plant and the Torero plant. As opposed to the 'Innovative DRI' pathway, these two projects do not aim to replace the existing primary steel production route, but rather to implement carbon capture and utilisation strategies on the existing facilities, as well as replace coal use in the BF by bio-coal.

Bioethanol is produced using a fermentation process developed by Lanzatech[30], a US-based company founded in 2005. This process uses carbon-hungry microbes to digest carbon emissions and convert them into ethanol. Lanzatech has always focussed on the use of waste gas from the steel industry, therefore partnering up with ArcelorMittal to build a first full-scale demonstration plant using a 500,000-liter reactor[31] –the Steelanol plant. This plant size allows the production of 60 million litres of ethanol every year. Adding the Steelanol plant to the current model implies adding a new process which takes the blast furnace gas as an input and simply produces bioethanol as an output. The Steelanol process is set to be operational from 2023 onward.

For the produced ethanol to be labelled as 'bioethanol', the embedded carbon in the blast furnace gas should (partially) be of renewable origin. This requirement is fulfilled through the Torero project which produces bio-coal or 'AlterCoal' from wood and waste, feeding the blast furnace to provide a carbon source for the sinter to be reduced into raw iron. The first Torero reactor will start operations in 2023, alongside Steelanol. The second reactor is estimated to be commissioned and increase the consumption of biocharcoal from 2026 onwards.

Innovative DRI Pathway

The 'Innovative DRI' pathway is reflected in ArcelorMittal's site in Ghent through its plan to replace 40% of the integrated steel plant route with the new innovative DRI-EAF production route by 2026. This requires a new process path in the TIMES-BE model, indicated in blue in Figure 2. The path is split up into three main processes. The first process is the DRI shaft, where imported pelletised iron ore is then reduced, producing the so-called 'sponge iron'. The DRI uses natural gas as an energy source and for the reduction as opposed to coke and pulverized coal (PCI) in the BF-BOF route. Sponge iron is then fed to the EAF to be converted into liquid steel. Note that by using direct reduced iron instead of scrap iron, this DRI-EAF production route can achieve the same quality of steel as with the BF-BOF route. The steel finishing process now takes 60% of crude primary steel from the original BF-BOF route and 40% from the new DRI-EAF route[32].

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[30] "LanzaTech," accessed January 9, 2023, https://lanzatech.com/.
[31] "Forum VBO-FEB" (Innovation Across Borders, n.d.).
[32] "Making Iron & Steel - DRI Furnace | ArcelorMittal," accessed January 9, 2023, https://corporate.arcelormittal.com/about/making-steel/making-iron-steel-dri-furnace/.

3 Input data, assumptions and scenarios definition

3.1. Energy commodity prices

Belgium's heavy reliance on energy imports is a well-established fact. Of particular interest is the recent surge in natural gas prices, which can be attributed to the rapid economic recovery following the COVID-19 pandemic and the severe reduction in Russian pipeline deliveries triggered by the war in Ukraine. This study considers a price peak of €$_{2020}$125/MWh in 2022-2023, followed by a projected decline to €$_{2020}$50/MWh in the mid-term –around 2025–, ultimately leading to a long-term price of €$_{2020}$35/MWh. Table 3 presents an overview of the main fuel and material price assumptions incorporated into the model. Furthermore, in all scenarios, it is assumed that by 2050, the price of CO_2 emission will reach €$_{2020}$350/tCO_2, in alignment with the results from the IEA and the European Commission. The CO_2 cost is applied uniformly across ETS and non-ETS sectors, including residential and commercial sectors, where no CO_2 tax is currently in place.

Table 3. Energy commodity price projections in TIMES-BE.

Commodity	Unit	2020	2025	2030	2035	2040	2045	2050	Source
Natural Gas[33]	€$_{2020}$/MWh	33.86	72.15	38.52	35.00	35.00	35.00	35.00	EnergyVille/VITO
Coal	€$_{2020}$/MWh	15.50	23.05	11.20	11.11	11.20	11.47	11.52	IEA[34]
Crude Oil	€$_{2020}$/MWh	30.60	31.32	31.68	30.96	30.24	29.52	28.80	
LPG	€$_{2020}$/MWh	68.40	43.81	44.32	43.31	42.30	41.29	40.28	Adapted from IEA[34]
Gasoline	€$_{2020}$/MWh	29.20	38.38	38.81	37.91	37.04	36.14	35.28	
Kerosene	€$_{2020}$/MWh	28.01	51.98	52.56	51.37	50.18	49.00	47.81	
Naphtha	€$_{2020}$/MWh	24.12	33.84	34.24	33.44	32.65	31.90	31.10	
Diesel	€$_{2020}$/MWh	26.28	40.61	41.08	40.14	39.24	38.30	37.37	
Fuel oil	€$_{2020}$/MWh	13.86	22.86	23.15	22.61	22.07	21.56	21.02	
Oven coke	€$_{2020}$/MWh	30.00	30.00	30.00	30.00	30.00	30.00	30.00	steelonthenet[35]
Nuclear fuel	€$_{2020}$/MWh	1.69	1.69	1.69	1.69	1.69	1.69	1.69	ENTSO-E[36]
Biomass	€$_{2020}$/MWh	16.20	16.92	16.92	16.92	18.00	18.00	18.00	HRM-EU[37]
Hydrogen	€$_{2020}$/MWh	149.87	123.39	96.91	92.38	87.84	83.30	78.77	H2IC[38]
Ammonia	€$_{2020}$/MWh	83.12	76.19	69.26	66.91	64.56	62.21	59.85	
Bioethanol	€$_{2020}$/MWh	104.04	104.04	104.04	104.04	104.04	104.04	104.04	E3-Modelling[39]
Biodiesel	€$_{2020}$/MWh	123.82	123.82	123.82	123.82	123.82	123.82	123.82	
CO_2 emissions cost	€$_{2020}$/t	50	100	150	200	250	300	350	IEA[40], EU[41]

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[33] takes into account the current energy prices after the Russia-Ukraine conflict, inflation and post COVID-19 economic impact.
[34] IEA-WEO 2021 - https://prod.iea.org/reports/world-energy-outlook-2021
[35] https://www.steelonthenet.com/files/blast-furnace-coke.html
[36] https://2020.entsos-tyndp-scenarios.eu/fuel-commodities-and-carbon-prices/
[37] https://heatroadmap.eu/wp-content/uploads/2020/01/HRE4_D6.1-Future-fuel-price-review.pdf
[38] Shipping sun and wind to Belgium is key in climate neutral economy. 2021.
[39] 2030 Transport Decarbonization in the EU, E3 Modelling, 2021. https://www.farm-europe.eu/wp-content/uploads/2021/12/E3M_Transport_decarbonization_EU_in_2030.pdf
[40] Net Zero by 2050 (Table 2.2), IEA, 2021. https://iea.blob.core.windows.net/assets/deebef5d-0c34-4539-9d0c-10b13d840027/NetZeroby2050-ARoadmapfortheGlobalEnergySector_CORR.pdf
[41] SWD(2021) 612 final (pg. 149), European Commission, 2021. https://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=SWD:2021:0611:FIN:EN:PDF

3.2. Scenarios

On the 12th of October 2022, the 'PATHS2050' platform was launched[42] , presenting alternative scenarios towards a carbon-neutral Belgium by 2050. To this end, three scenarios and various sensitivities cases were investigated. The central scenario represents a pathway following current future expectations in terms of technology development and availability. The Electrification scenario explores the effect of having direct access to more offshore wind and the possibility to invest in new nuclear technology. The third scenario, the Clean Molecules scenario, evaluates the impact of having lower-cost synthetic molecules import and limited access to cross-border CO_2 storage. This present study explores different scenarios built upon the central scenario from PATSH2050 and aligned with the end-uses of bioethanol from Steelanol as shown in Figure 3.

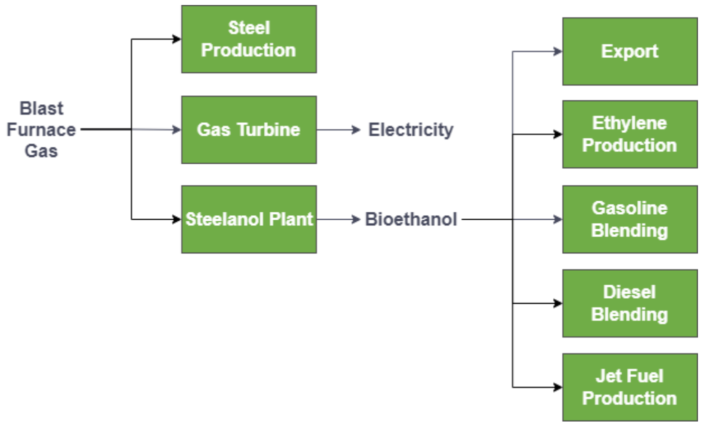

Figure 3: TIMES-BE blast furnace gas and bioethanol end-uses

Firstly, a 'business-as-usual' scenario serves as a reference case (REF) in which the planned investments regarding the new DRI route are modelled to be built and operational according to plan, but not the Steelanol and Torero plants. This allows for an isolated comparison of the influence of the Steelanol plant in different end-use cases on the energy system. Next, the base case (BSC) is set up, which includes the Steelanol and Torero plants and two possible end-uses for the bioethanol being biofuel blending in the transport sector and exports. The third scenario explores the ability to invest in additional capacity of the Steelanol plant and includes all possible end-uses of Steelanol (SINV). Table 4 shows the description of the five explored scenarios as well as the different assumptions used in each.

Table 4. Scenarios' description summary

Scenario alias	Scenario name	Scenario description	Modifications with respect to the reference case				
			Torero/ Steelanol	Use in transport	Bioethanol exports	Ethylene production	Additional investments
REF	Reference	DRI from 2026 but no Steelanol plant	-	-	-	-	-
BSC	Base Steelanol case	DRI from 2026 and Steelanol plant from 2023	YES	YES	YES	-	-
SINV	Additional Torero/Steelanol capacity	DRI from 2026 and Steelanol plant from 2023, and the option to invest in an Ethanol-to-Ethylene plant, and additional Torero & Steelanol capacity.	YES	YES	YES	YES	YES

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4 Results and discussion

In this section, we delve into the impact of Steelanol in the production of virgin steel, the complete steel sector and the full energy system. The purpose of this chapter is to understand how the production of Steelanol and its end-uses compete with other decarbonization alternatives. To this end, the model outcome is evaluated from four different perspectives. The chapter begins with discussing the results for the isolated primary steel production routes. This section evaluates the impact of Torero and Steelanol on primary steel production, without considering CCS installations as they would distort the isolated perspective. The next section zooms out to primary and secondary steel production, now including all steel sector possible future CCS units. This perspective illustrates the impact of the Torero and Steelanol plant in a broader steel sector context. Next, the results are evaluated in a full Belgian energy system perspective, which includes all sector interactions. This perspective provides insights in the net impact of Torero and Steelanol on the full Belgian energy system. Lastly, this chapter ends with a section describing indirect effects on other sectors which aims to investigate these other sector interactions in more detail. Table 5 gives an overview of the elements which are considered in the different sections of this chapter.

Table 5. Results contents of chapter 4

Section	Results	Contents
4.1 Primary steel production results	Primary steel production processes	All primary steel production elements from the BF-BOF and DRI-EAF routes, excluding CC units
4.2 Steel sector results	Primary + secondary steel + CCS	All primary and secondary steel production elements, steel post-processing activities and all steel sector related CC units
4.3 Full energy system perspective results	Full system	Total Belgian energy system overview: all elements of all sectors and their interactions included
4.4 Indirect effects on other sectors results	Other sectors	Full system results, isolating effects on a sectoral level: agriculture, industry, power/heat and residential sectors

4.1. Primary steel production results

This section considers all processes related to primary steel production while excluding possible future CCS units to be able to fully isolate the influence of Torero and Steelanol on ArcelorMittal's activities. To assess the impact, multiple aspects are discussed: the production and consumption of Steelanol, the carbon emissions and the Steelanol production cost.

Figure 4 illustrates the production of Steelanol and its final consumption in the different end-uses for the BSC and SINV scenarios. A first observation is the increase in production for the investment scenario (SINV) compared to the base case (BSC) by a factor five. If allowed, the model decides to invest in additional Steelanol capacity as it reduces the total system cost. The origin of the total system cost reduction will be explored in more detail in section 4.3. However, this increase in capacity is likely to not happen as quickly as presented by this scenario. Practical obstructions will delay the construction of these plants resulting in a more gradual increase in capacity. A second observation is the termination of the Steelanol production by 2050 for all scenarios. From this behaviour, we can conclude that Steelanol is an economically attractive technology to be used during the transition to a net-zero 2050 future. Additionally, finding alternative biobased feedstock streams might be an appealing alternative to keep the Steelanol plant operational in the case the BF is closed.

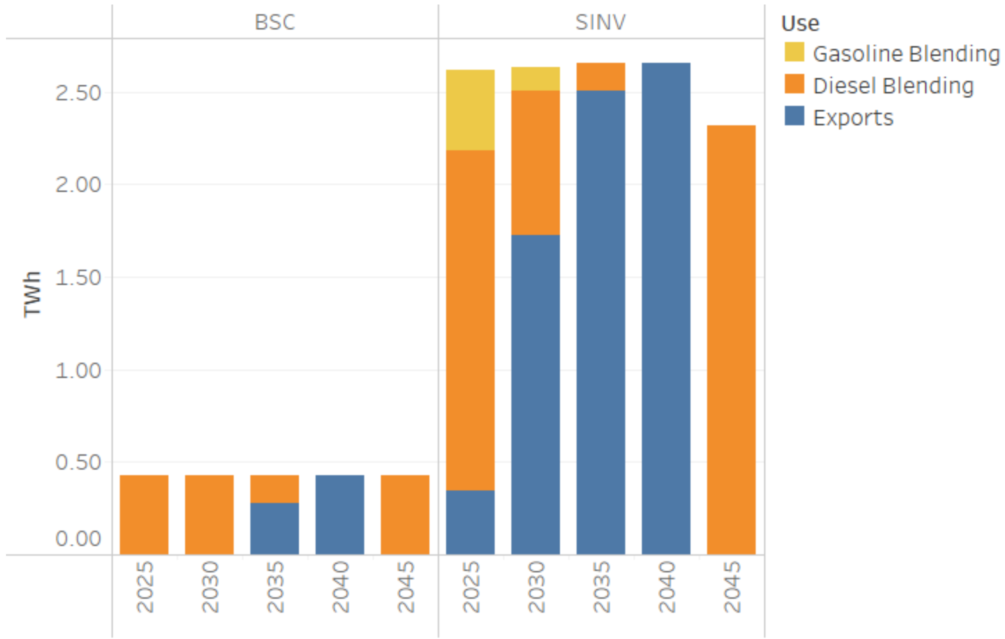


Figure 4. Steelanol production and consumption by end-use

Table 6 shows the marginal production cost of Steelanol as determined by the model. Note that the price of Steelanol is set by the most valuable end-use as they are competing against each other for Steelanol. For this reason, the prices can be related to Figure 4 where the final end-uses are presented.

In the BSC scenario, Steelanol is solely used for diesel blending in 2025, 2030 and 2045 because this end-use renders the highest benefits. In 2025 and 2030, ethanol for diesel blending in trucks is covered by Steelanol as much as possible while the rest is covered by biodiesel. In 2035, Steelanol is used for both export and diesel blending, as all diesel blending is now covered by Steelanol alone and no additional biodiesel is imported for diesel blending. This decrease in diesel blending is due to the increasing electrification of trucks. The remaining Steelanol is then exported, therefore setting the Steelanol value with the ethanol export price which equals $€_{2020}$7.87/MWh. In 2035 and 2040, Steelanol is partially and then completely exported as blending for inland navigation is only viable from 2045 onwards, while blending in trucks fades out due to the increasing electrification. By 2045, blended diesel becomes an attractive end-use again due to an increasing CO_2 emissions cost but this time, it is used for inland navigation. Since all Steelanol is going to this end-use, the marginal cost of Steelanol equals the cost of importing one unit of biodiesel in return, which has decreased to $€_{2020}$8.82/MWh in 2045.

Similar observations can be made in the SINV scenario. From 2025 to 2040, aside from export, Steelanol is used for diesel and gasoline blending throughout this period in the transition towards electric vehicles. Due to the fact that the import price of bioethanol for gasoline blending is lower than the import price of biodiesel, the model will give priority for Steelanol to cover diesel blending in 2025 and 2030. Afterwards, when there is still Steelanol left over to cover gasoline blending, the model will do so, covering all gasoline blending as well in 2025 and 2030. The excess Steelanol is then exported. Identical to the BSC scenario in 2045, Steelanol is used again in the freight transport sector as the biofuel-diesel mix becomes more economically attractive, influenced by CO_2 emissions costs and the cost advantages of using the existing trucks fleet. Steelanol is never used for biokerosene or ethylene production as the resulting production cost of such alternative routes cannot outcompete hydrogen or other synthetic aviation fuels and the production of ethylene from Naphtha. However, the current implementation for ethylene production from Naphtha in the model does not provide a driver to decarbonize this process. This means the model does not take into account the potential carbon tax savings of using Steelanol when comparing it to the alternative production route from Naphta. This aspect of the model is to be improved in the future which could change these results.

Table 6. Steelanol and end-use commodity value [€2020/MWh]

Scenario	Commodity	2025	2030	2035	2040	2045
BSC	Steelanol	123.82	123.82	101.96	101.96	114.35
	Gasoline Blending	104.04	104.04	83.88	101.96	104.04
	Diesel Blending	123.82	123.82	101.96	101.85	114.35
	Export	101.96	101.96	101.96	101.96	101.96
SINV	Steelanol	101.96	101.96	101.96	101.96	114.35
	Gasoline Blending	101.96	101.96	83.88	101.96	104.04
	Diesel Blending	101.96	101.96	101.96	101.96	114.35
	Export	101.96	101.96	101.96	101.96	101.96

As a second evaluation of the production of Steelanol, Figure 5 depicts the use of the blast furnace gas (BFG), as Steelanol competes for its use with the power sector for electricity production and the steel production route itself. In the BSC scenario, Steelanol replaces part of the generator activity throughout the blast furnace lifetime. In the SINV scenario, the generator activity diminishes even further as most of the blast furnace gas is used to produce Steelanol. Additionally, a large part of the blast furnace gas is reused in the BF-BOF route to meet its energy needs.

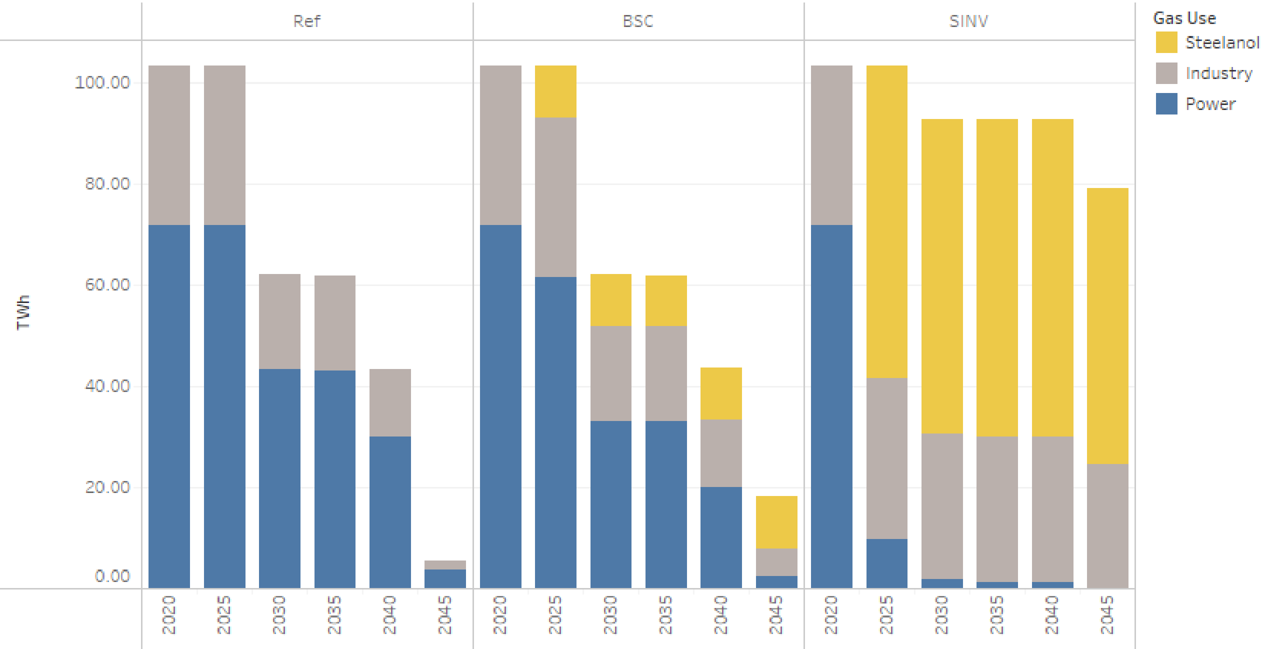


Figure 5. Blast furnace gas use.

Figure 6 presents a comparison of the steel production technology mix for each of the scenarios. These results show that the presence of Steelanol and Torero postpones the replacement of the remaining BF-BOF capacity with the DRI-EAF route. Instead, the model chooses to keep the blast furnace running until the sector moves completely to the DRI-EAF alternative in 2050. As a consequence, the steel sector emissions increase compared to the reference scenario because of the prolonged use of the carbon-intensive blast furnace (see Figure 7).

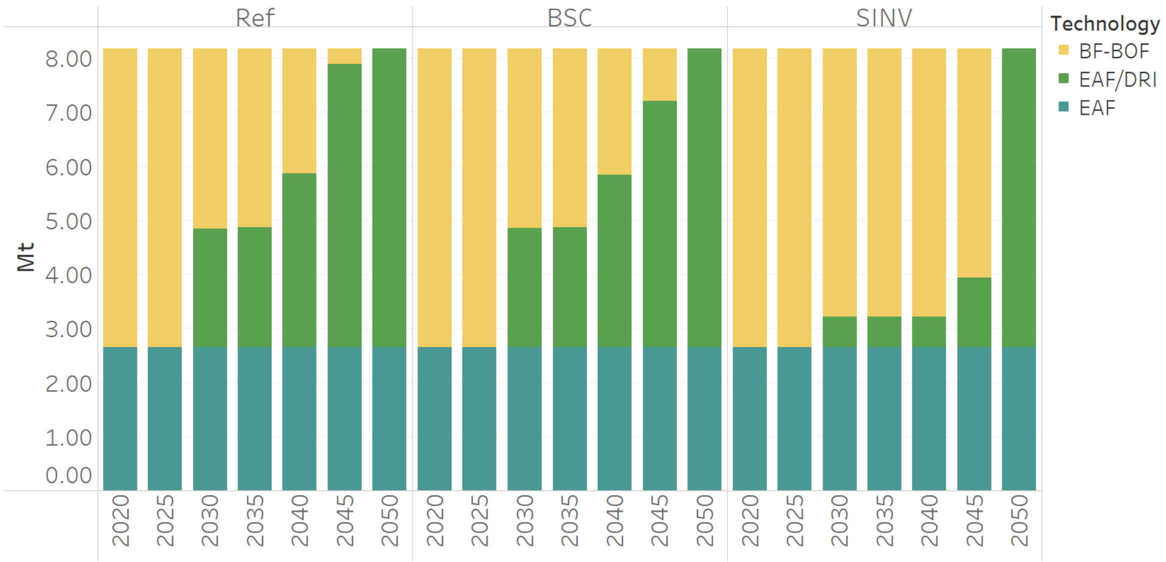
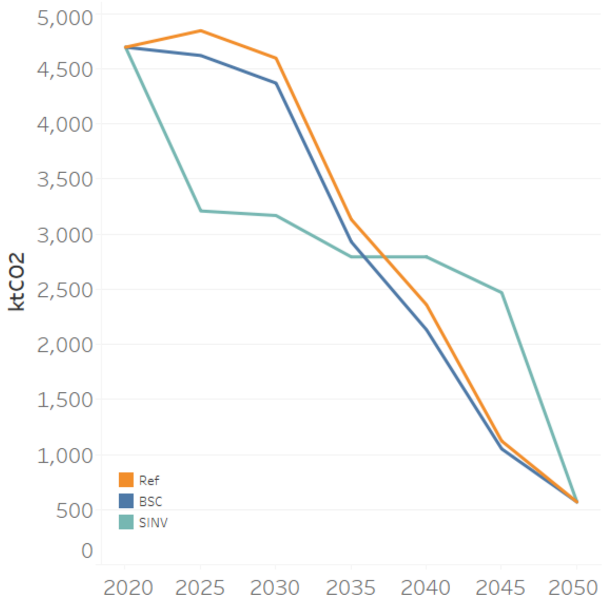


Figure 6. Steel production by technology

The carbon abatement in primary steel production is shown in Figure 7 and Table 7. The carbon abatement is realised due to the Torero plant which decreases the use of coal in the blast furnace and replaces it with bio-coal, which has no emissions attributed to it. Therefore, the abatement equals the carbon content of the amount of coal that was avoided. The annual CO_2 abatement in the BSC scenario corresponds with the estimated CO_2 abatement of 225 kton in 2025. This abatement remains approximately unchanged until 2045 after which the abatement reduces due to the postponed use of the DRI. This is related to the linear nature of TIMES and the increased DRI capacity while in reality, the remaining furnace would be fully replaced. In the SINV scenario, where additional Steelanol and Torero capacities are installed, the annual emission reduction increases in 2025 and 2030 due to the additional Torero capacity. This additional capacity increases the bio-coal consumption of the blast furnace while decreasing the consumption of normal coal for unchanged steel production activity. After 2035, the annual emissions increase in the SINV scenario compared to the REF scenario due to the postponement of the replacement of the blast furnace with the DRI. However, the cumulative emission reduction of the SINV scenario by 2050 remains greater than the cumulative reduction realised in the base case.

This relative increase in emissions for the SINV scenario in some periods is partially compensated by an increase in the use of CCUS technologies as illustrated in Figure 8, which shows the CO_2 emissions of primary steel production by technology.



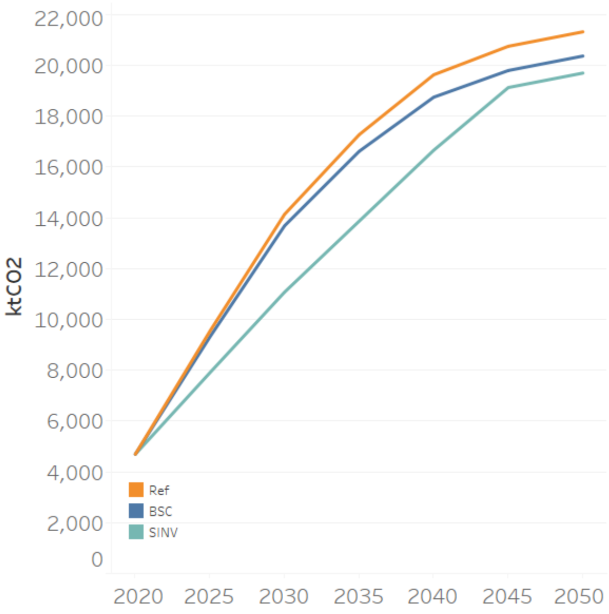


Figure 7. Primary steel production CO_2 emissions: annual emissions (left) and cumulative emissions 2018-2050 (right) per scenario.

Table 7. Primary steel production CO_2 emission reduction by scenario (annual and cumulative) [$MtCO_2$]

Emissions	Scenario	2025	2030	2035	2040	2045	2050
Annual	BSC	0.23	0.23	0.20	0.23	0.07	0.00
	SINV	1.64	1.43	0.34	-0.43	-1.35	0.00
Cumulative	BSC	1.88	3.01	4.03	5.16	5.52	5.51
	SINV	8.93	16.07	17.77	15.61	8.87	8.87

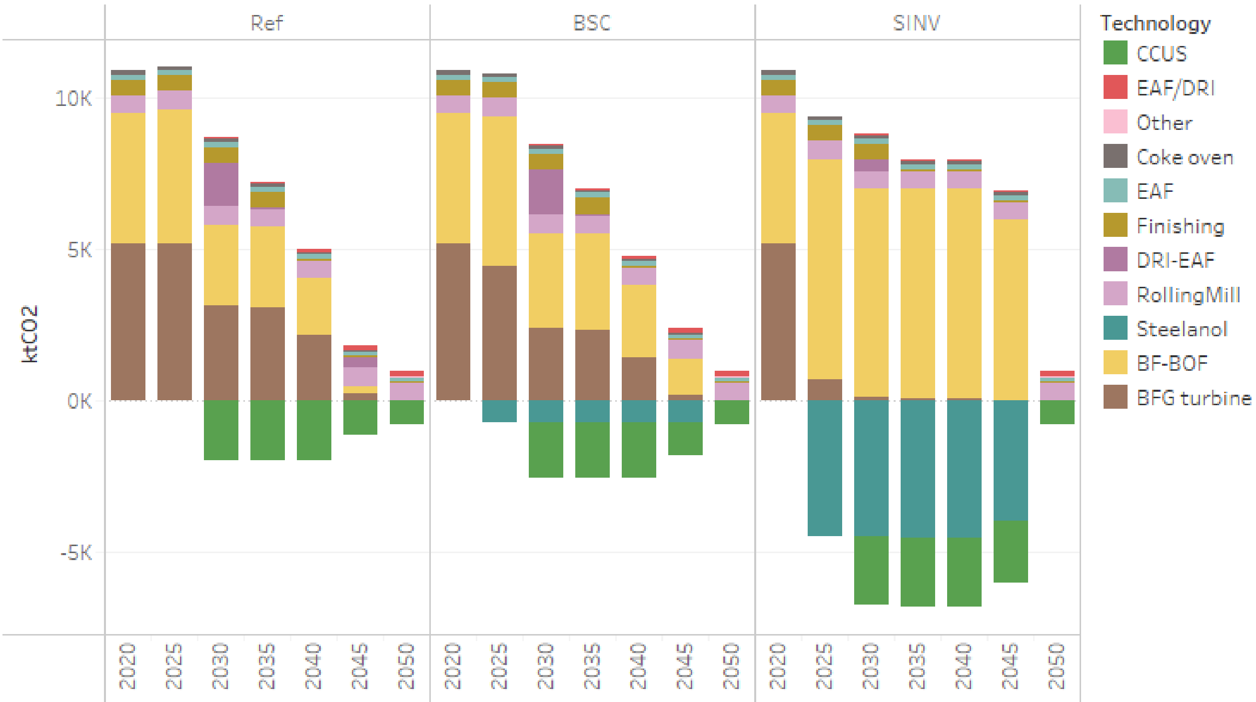


Figure 8. Primary steel production CO_2 emissions by technology. CO_2 emissions of the BFG Turbine (Knippegroen powerplant), officially reported under the 'Power sector', are included in the graph.

4.2. Steel sector results

This section will expand the view on primary steel production to a broader view on the whole Belgian steel sector. All elements related to primary and secondary steel production are included as well as post-processing activities and all steel sector CCS units. This context allows us to evaluate the impact of Torero and Steelanol on the Belgian steel sector. To this end, the steel sector emissions, final energy consumption and production cost of primary and secondary steel are evaluated.

The CO_2 emission reduction compared to the reference scenario are shown in Table 8 and Figure 9. For the BSC scenario, the emission savings after 2030 have decreased compared to the isolated primary steel production evaluation. This is due to the postponement of the EAF-DRI route which contains a CCS unit by default which is now included in the evaluation. Figure 10 illustrates the installed CCS capacity in the steel sector. Therefore, the CCS capacity in the BSC scenario reduces compared to the REF scenario, reducing the positive emission savings effect of introducing Torero and Steelanol. As a consequence, the cumulative emission reduction in 2050 equals 2.8 $MtCO_2$ compared to 5.5 $MtCO_2$ for the isolated primary steel production perspective.

The opposite effect occurs in the SINV scenario where the emissions savings increase even more after 2035 compared to the isolated primary steel emissions (see Table 7) due to additional CCS capacity compared to the REF scenario (see Figure 10). The cumulative emission reduction by 2050 reaches 20.6 $MtCO_2$ savings for the whole steel sector compared to 8.8 $MtCO_2$ for the primary steel production. The additional emissions of the BF-BOF route (compared to EAF-DRI) reach a certain threshold which incentivises the model to now invest in CCS capacity, whereas the additional emissions in the BSC scenario were not sufficient to justify the investment in CCS and the model was better off paying carbon taxes instead.

Figure 9. Steel sector emissions: annual emissions (left) and cumulative emissions 2018-2050 (right) per scenario.

Table 8. Steel sector CO_2 emission reduction (annual and cumulative) [$MtCO_2$]

Emissions	Scenario	2025	2030	2035	2040	2045	2050
Annual	BSC	0.23	0.07	0.04	0.07	0.02	0.00
	SINV	1.64	1.74	1.13	-0.13	-0.40	0.00
Cumulative	BSC	1.88	2.20	2.41	2.74	2.84	2.84
	SINV	8.93	17.61	23.24	22.62	20.63	20.64

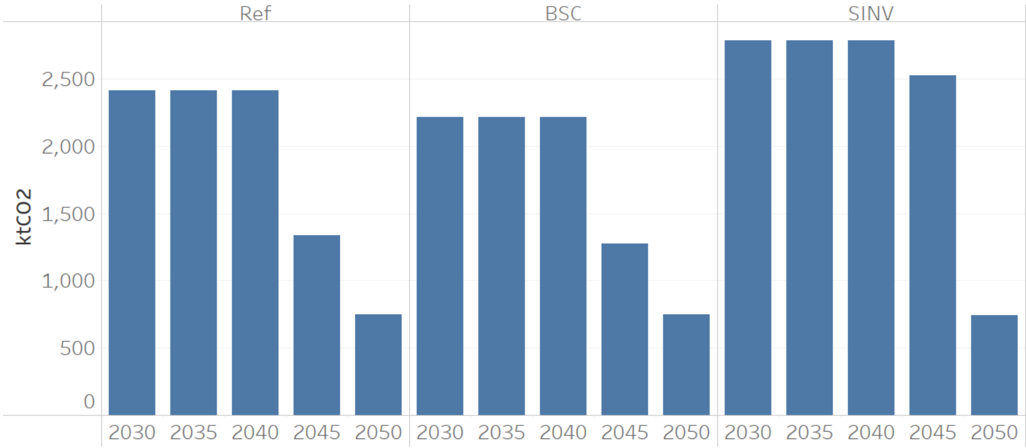


Figure 10. Steel sector CCS capacity per scenario: installed capacity

Table 9 shows the production cost of primary and secondary steel as well as the cost difference compared to the reference scenario. In the BSC scenario, only a small cost difference is noticeable for primary and secondary steel compared to the REF scenario while the SINV scenario does show a significant cost reduction for primary steel due to the influence of the Torero and Steelanol plant, particularly for the periods 2040 and 2045 where a cost reduction of respectively 32.5% and 39.1%. One of the main causes for this reduction in production cost is the decrease in the electricity price (discussed in more detail in section 4.4). The price is driven down far enough to overcome the additional costs due to carbon taxes because of the extended use of the blast furnace as opposed to the DRI in the REF scenario. In this way, the model decides to use the existing assets rather than to incur in additional investments in the DRI-EAF route and other sectors of the energy system indirectly impacted as explained later in section 4.4.

Table 9. Primary and secondary steel marginal cost [€$_{2020}$/ton steel]

Steel	Scenario	2014	2016	2020	2025	2030	2035	2040	2045	2050
Primary	Ref	495.17	534.51	597.46	709.63	586.39	640.47	651.36	649.36	770.02
	BSC	495.17	533.93	594.70	709.30	586.62	641.26	651.79	647.86	769.95
	SINV	495.17	533.93	594.70	695.17	591.80	606.70	491.55	466.81	769.12
secondary	Ref	261.43	261.69	255.81	358.57	325.46	330.20	320.86	355.20	513.42
	BSC	261.43	261.69	255.81	358.43	325.45	330.12	320.81	355.88	513.38
	SINV	261.43	261.69	255.81	358.94	327.61	331.65	318.67	352.34	512.93

The extension of BF-BOF in the SINV has an impact on the steel sector energy mix. Figure 11 illustrates the steel sector energy mix by source. The energy mix explains the steel production costs from Table 9. Note that carbon taxes are not embedded in the production costs presented in this section. For 2025, a price increase is present for all scenario's due to a large increase in gas (see Table 3) and electricity prices (see Table 12) representing the current energy crisis. By 2030, the natural gas price recovers and approximates 2020 prices again. However, due to nuclear closure, the electricity price does not recover at the same rate and remains relatively high. Due to the dependency of hydrogen on electricity, hydrogen prices follow a similar trend as the electricity price evolution.

Fossil energy consumption for primary steel production in 2030 is high for all scenarios since they are either using the BF-BOF route, or the DRI-EAF route using natural gas as a reducing agent. Therefore, the primary steel cost tends to follow the fast-recovering natal gas price and consequently drops in 2030. Afterwards, the model switches to a hydrogen driven DRI by 2035 for all scenarios, decreasing the cost dependency on the natural gas price and increasing the cost dependency on the hydrogen price in return. Therefore, an increase in cost is visible again for 2035 for all scenarios. Due to the lower share of hydrogen DRI-EAF in the SINV scenario, primary steel production cost remains lower compared to the REF and BSC scenarios. After 2035, hydrogen consumption gradually increases for all scenarios but to a lesser extend in the SINV scenario. This allows the SINV scenario to benefit from the relatively low gas prices for longer, reducing the primary steel prices compared to the other scenarios. In all scenarios, the primary steel price converges to a high price of 700 $€_{2020}$/ton due to the net-zero constraint, forcing all scenarios to the hydrogen based EAF-DRI route.

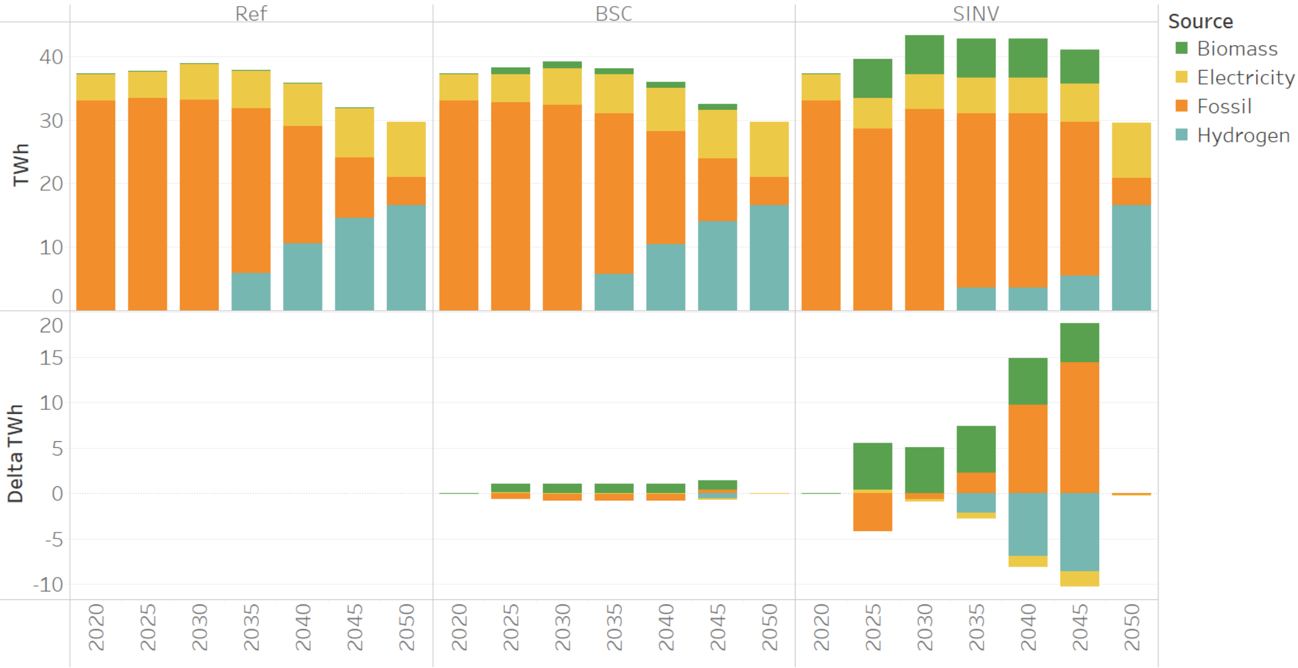


Figure 11. Steel sector energy mix

4.3. Full energy system perspective results

This section describes the results evaluated from a full Belgian energy system perspective which includes all sectors (industry, residential/commercial, transport, agriculture and power sector) and their interactions. This broader system perspective allows to compare the total system emissions with the steel sector emissions, emphasizing the scope of the impact of Torero and Steelanol in a full energy system perspective. Additionally, the total system cost can be investigated.

Evaluating the emissions reduction on a system level and per sector makes it possible to determine the level of influence of Steelanol in terms of emissions, energy consumption and costs. Figure 12 shows total scope 1 system CO_2 emissions per scenario, as well as the cumulative emissions up to 2050 for Belgium. Although the emissions trajectory of the REF and BSC scenarios are similar, it is already possible to note that Steelanol is helping to reduce 0.39-0.73 MtCO2/yr. between 2025 and 2045 (see Table 10). When investments in additional capacity are allowed (SINV), the abatement potential increases to 0.84-4.90 $MtCO_2$/yr. While compared with the emissions abatement in the integrated steelmaking route (section 4), and the whole steel sector (section 4.2), it is evident that Torero and Steelanol have an influence beyond the steel sector. Thus, in the BSC scenario, average annual CO_2 emissions reductions at the system level reach 0.57 $MtCO_2$/yr compared to the primary steel production reductions which has an average annual reduction of 0.23 $MtCO_2$/yr. In the SINV scenario, the average annual total system abatement increases up to 2.9 $MtCO_2$/yr starting from average annual steel sector abatement of 0.8 $MtCO_2$/yr.

Besides the CO_2 reductions in the SINV scenario, in which investment in additional Steelanol and Torero capacity is allowed, the savings in total system cost could be mostly linked to the extension of a modified BF that can replace up to 20% of the use of coal with biocharcoal from Torero. This leads to savings in several sectors and in particular in the steel and power sector, as well as avoiding CO_2 emissions costs. On the one hand, in the steel sector, the investment in DRI to replace the BF is deferred to 2050, as well as natural gas or hydrogen costs, which might be higher than the traditional use of coal. On the other hand, in the power sector, the need for less electricity leads to lower capacity, in particular solar PV and batteries.

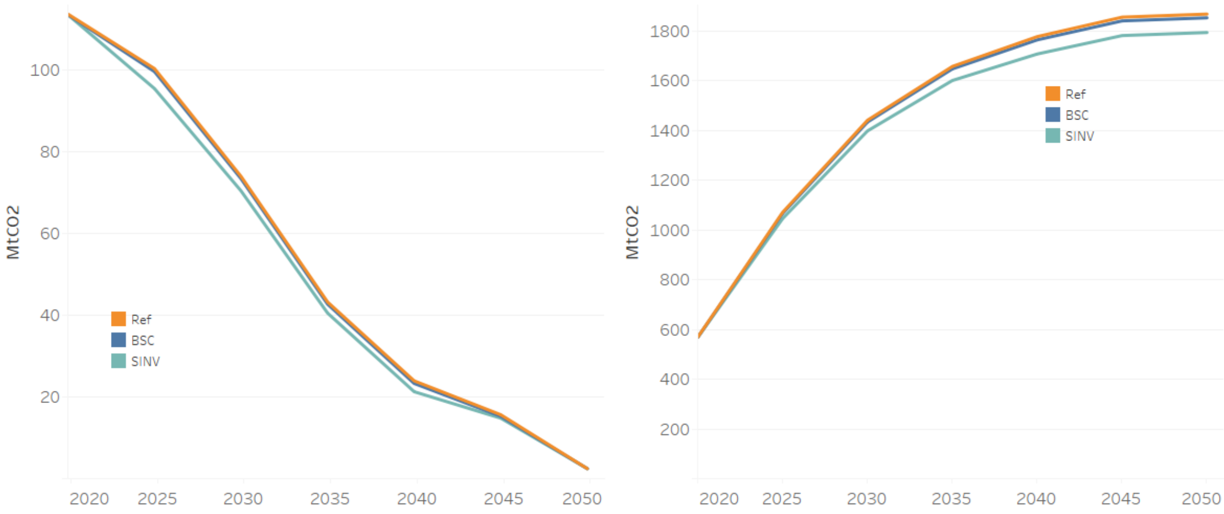


Figure 12. Total system emissions: annual emissions (left) and cumulative emissions 2018-2050 (right) per scenario.

Table 10. Energy system total CO2 emissions reduction by scenario (annual and cumulative 2018-2050) [$MtCO_2$]

Emissions	Scenario	2025	2030	2035	2040	2045	2050
Annual	BSC	0.73	0.57	0.53	0.63	0.39	0.00
	SINV	4.90	3.54	2.71	2.66	0.84	0.00
Cumulative	BSC	4.42	7.26	9.91	13.06	15.01	15.01
	SINV	25.27	42.98	56.55	69.82	74.04	74.04

As was mentioned in section 4, the presence of Steelanol and Torero reduces the total system cost. This cost reduction is due to multiple interactions in the system and therefore no simple answer can be provided. However, the main drivers for the system savings are the reduction of capital investment and O&M cost in the power sector and hydrogen production. Figure 13 shows the total yearly system cost difference compared to the REF scenario. These differences are split between operational costs (OPEX), capital investments (CAPEX) and carbon tax payments. Carbon tax payments –related to emission reductions– in the BSC and SINV scenarios are the main cause for the total system cost reduction. Note that the system perspective of our TIMES model interprets tax payments as part of the total system cost, as is necessary to drive the model to clean carbon solutions. However, from a societal point of view, tax payments are not a system cost, but merely a transfer of funds within the system itself.

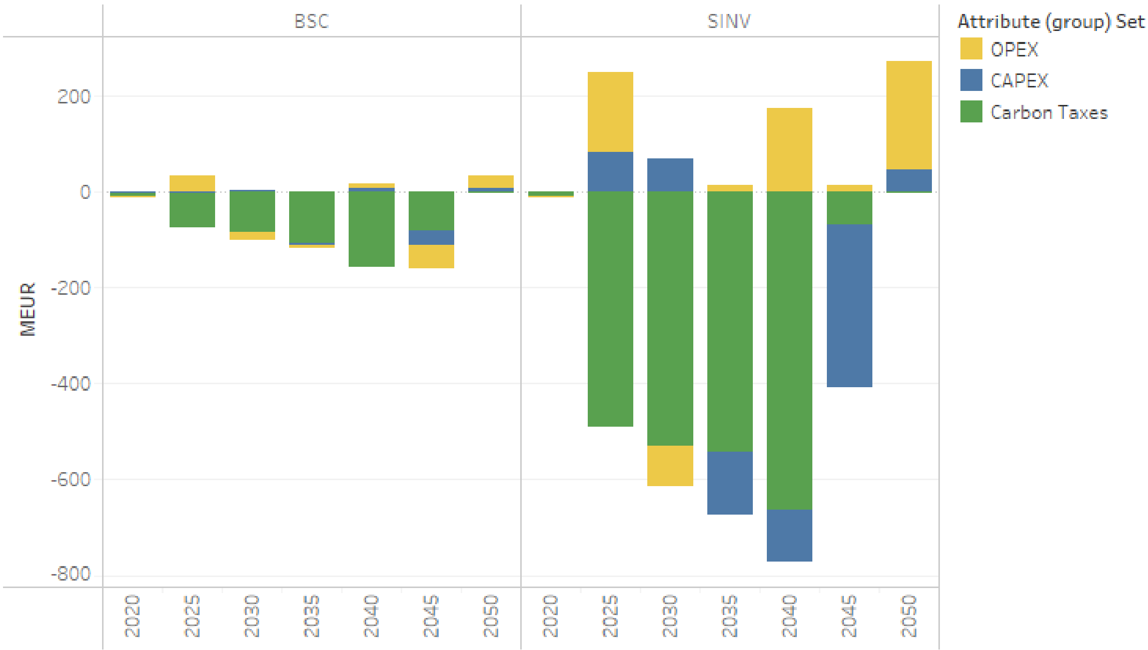


Figure 13. Total yearly system cost difference to REF

4.4. Indirect effects on other sectors

This section will discuss the impact of Torero and Steelanol in certain sectors in more detail. To this end, the solid and liquid biofuel consumption are investigated on a sectoral level as well as the power sector generation mix and corresponding electricity prices.

The implementation of Steelanol in the energy system model has an impact on all sectors due to Arcelor Mittal's large share in the energy-intensive Belgian industry. In general, the model's results show that there are minor technology differences in all scenarios, mainly due to the displacement of biomass in the model. The model contains a limitation on the amount of solid biomass which equals 13.9 PJ for all periods. This means the model will not increase its biomass consumption due to Torero, but rather reallocate the limited amount of solid biomass to comply with the required consumption in Torero. The findings supporting this conclusion are presented in Table 11, which shows the biomass consumption per sector and scenario.

Table 11. Solid biomass use per sector [TWh]

	2030			2035			2040			2045			2050		
	REF	BSC	SINV	REF	BSC	SINV	REF	BSC	SINV	REF	BSC	SINV	REF	BSC	SINV
Agriculture	6.07	6.06	4.93	4.73	4.71	4.51	3.83	3.84	4.18	3.23	3.23	3.26	3.64	3.64	3.56
Industry	4.09	4.11	5.45	5.58	5.59	5.81	6.78	6.74	5.83	7.57	7.29	5.62	6.30	6.26	5.50
Power/Heat	3.73	3.72	3.51	3.58	3.59	3.57	3.29	3.30	3.88	3.09	3.37	5.01	3.95	3.99	4.83
Residential	-	-	-	-	-	-	-	-	-	0.01	0.01	0.01	0.01	0.01	0.01
TOTAL	13.90	13.90	13.90	13.90	13.90	13.90	13.90	13.90	13.90	13.90	13.90	13.90	13.90	13.90	13.90

The model also contains a limitation on the import of liquid biofuels but due to the presence of Steelanol as an additional source for biofuels, the overall biofuel availability and consumption in the model increases compared to the REF scenario. Figure 14 shows biofuel consumption in the transport sector and its source. From the moment Steelanol is available, it starts competing with imported biofuels. During the transition phase, 2025-2040, the electrification of the transport sector –especially passenger vehicles– leads to a decline in the use of biofuels by 2040. Nevertheless, the scaling CO_2 price and the Net-zero constraint in 2050 trigger the use of biofuels –Steelanol in 2045 and imported Biodiesel in 2050. Steelanol is used in inland navigation and freight transport. In particular, in the BSC scenario, Steelanol use in inland navigation is limited by the technical constraints of diesel-ethanol blending. While with additional Steelanol capacity in the SINV scenario, the freight transport is prioritized to have access to it.

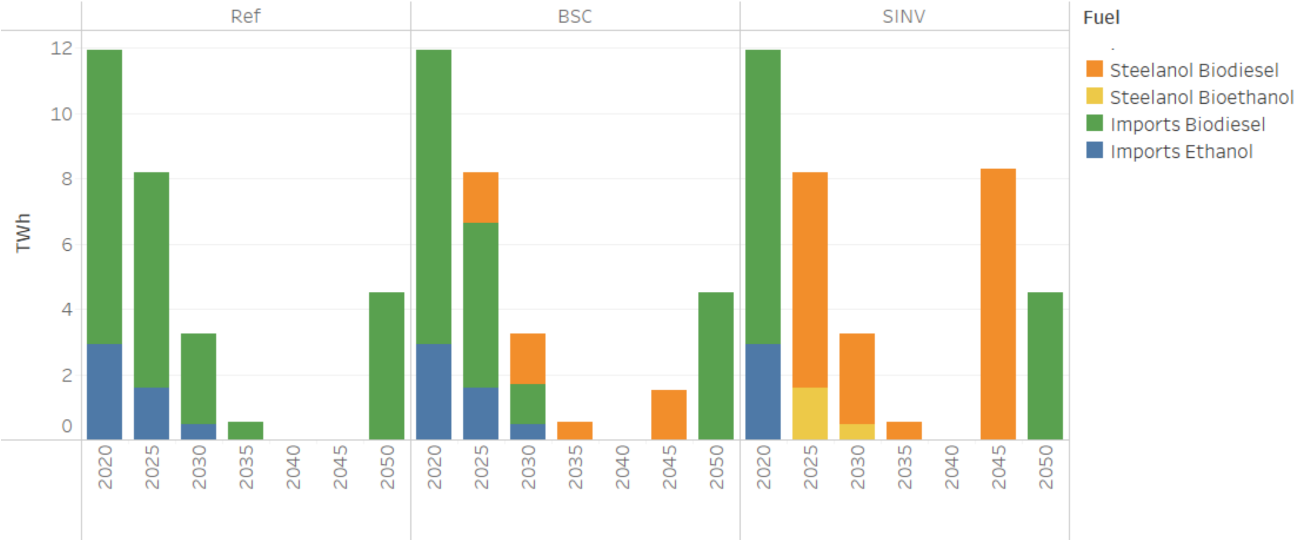


Figure 14. Biofuels use in the transport sector

Electricity demand in REF and BSC scenarios is similar. Nevertheless, from 2025 the influence of Steelanol in the electricity sector can be perceived as less blast furnace gas is used in the Knippegroen electricity plant, which is covered with additional natural gas, solar PV and imports as can be seen in Figure 15. Conversely, in the SINV scenario, the prolonged use of the BF in the production of steel postpones the commission of the EAF for the DRI route which leads to lower electricity demand and therefore lower requirements of power capacity. In this case, in 2040 and 2045, there is less solar PV generation, but higher participation of natural gas turbines and imports. The increase in the use of fossil fuels can be partially explained by the fact that the solar PV generation profile does not match the steel production profile and, on the other hand, CO_2 abatement in the steel sector allows the model to increase emissions in other sectors. When capturing the full influence of this behaviour, it is noted that electricity prices are reduced because of lower demand (see Table 12), which triggers a minor increase in electricity demand in buildings and an increase in local hydrogen production. Furthermore, by delaying the full transition to DRI, the average carbon dioxide content of grid electricity is lower in the case where steelanol is allowed, in both BSC and SINV scenarios, as can be seen in Table 13.

The inclusion of Steelanol influences the other sectors to a lesser extent. In the SINV scenario, the agriculture sector's use of biomass diminishes as it is allocated to the Torero plant, considering the upper limit of the total availability in the energy system. This leads to a slight increase of fossil fuel usage in the agriculture sector between 2025 and 2030. In the residential and commercial sectors, there is a minor increase in electricity consumption (0.1-0.7 TWh) between 2025 and 2040, which can be partially attributed to electricity price differences. Finally, in the freight transport sector, there is a lower consumption of fossil fuels, in particular in 2045 in the SINV scenario, as additional Steelanol is available for blending. However, the entire transport sector follows a similar electrification trend in all scenarios.

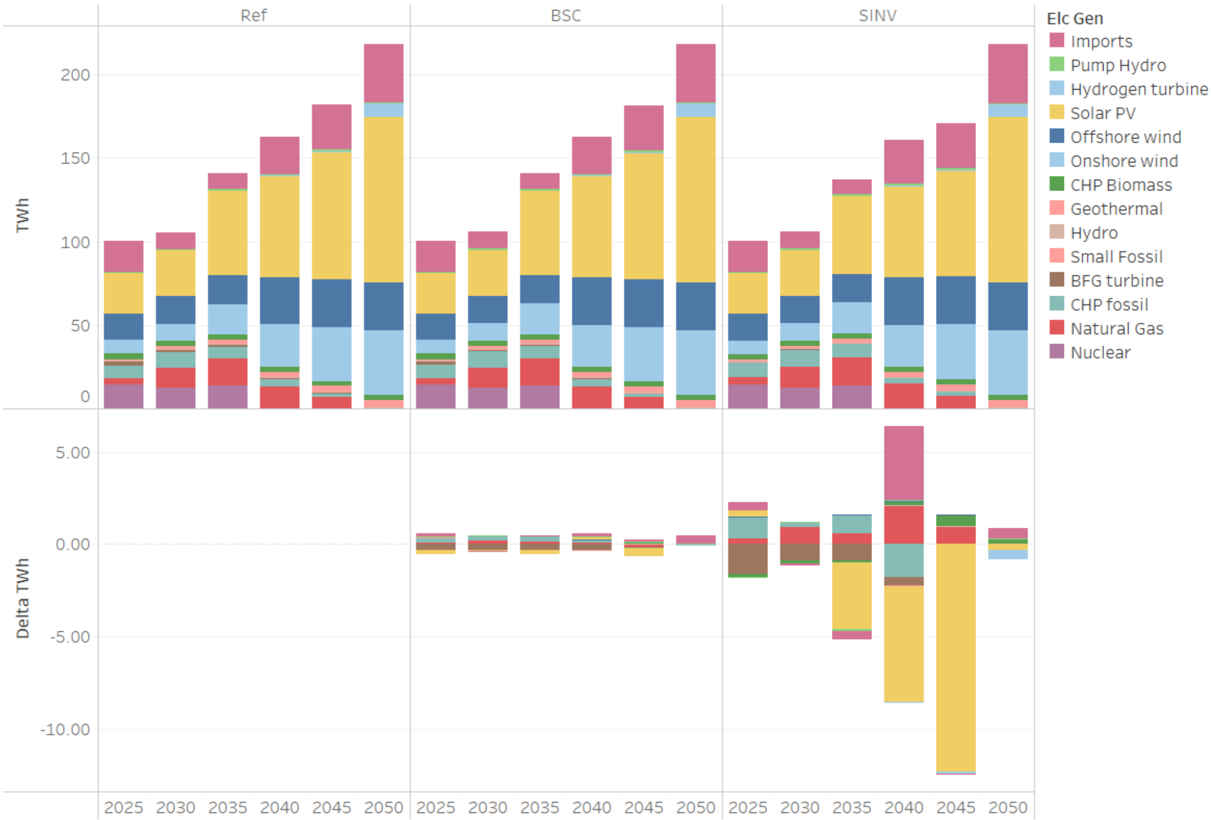


Figure 15. Electricity generation by technology.

Table 12. Electricity generation price per scenario [€2020/MWh]

	2025	2030	2035	2040	2045	2050
REF	136.14	112.31	114.74	106.44	102.90	118.67
BSC	135.87	112.26	114.61	106.14	102.09	118.08
SINV	136.33	111.99	114.50	97.61	93.12	115.66

Table 13. Emission Factor grid electricity [kgCO$_2$/MWh]

	2020	2025	2030	2035	2040	2045	2050
Ref	160.21	92.78	96.08	77.29	49.44	18.44	0.31
BSC	160.21	86.46	90.09	73.02	45.44	17.74	0.31
SINV	160.21	86.46	90.09	73.01	45.44	17.74	0.31

5 Conclusions and discussion

Steelanol has proven to be economically attractive as a transition technology towards a net-zero 2050 future. The model suggests that investing in additional Torero and Steelanol capacity, when possible, minimises the total system cost due to lower electricity demand and a reduction in carbon tax payments. Aside from being economically attractive, the technology has proven to be beneficial from a carbon budget perspective, reducing the cumulative total system emissions by 15.01 $MtCO_2$ with the current Torero and Steelanol setup, equivalent to 0.8% of the total cumulative Belgian energy system CO_2 emissions by 2050. With future investments in additional Steelanol and Torero capacity, the emissions abatement increases to 74.04 $MtCO_2$ (4.1%) in the investment scenario.

Steelanol is not economically viable for jet fuel production due to competition with hydrogen and synthetic aviation fuels. Steelanol for ethylene production was not selected by the model as there is currently no driver to decarbonise this production route. Further development of the model is required to provide a complete answer regarding ethylene production. Steelanol is used in the transport sector for diesel and gasoline blending. Steelanol is used in navigation and freight road transport for diesel blending and in passenger road transport for gasoline blending –only in 2025 and 2030 in the transition towards electric vehicles. Furthermore, the export of Steelanol is an attractive case as well depending on international prices and the local appetite for its use to decarbonize the transport sector.

In all scenarios, the model opts to not utilize the technology in 2050 due to the closing of the BF to comply with the net-zero constraint, which pushes the steel sector to further electrification or hydrogen use leading to the DRI-EAF route. However, if the Steelanol plant could be fed with an alternative biogenic carbon gas source in 2050, such as incinerator exhaust gasses or biomass plant flue gasses, it has the potential to remain operational, provided the microbial environment in the Steelanol bioreactor is adapted accordingly. Further research on the viability of these alternatives for Steelanol is recommended.

The use of Torero and Steelanol plants, particularly with additional capacity, could have a positive impact on the entire energy system as it reduces the system cost by mainly extending the use of the existing BF-BOF as well as making a clean biofuel available for the transport sector at competitive prices. Moreover, there are other minor indirect influences on decisions made in other sectors.

Finally, the presence of the Steelanol plant, as part of the Smart Carbon solution, can be evaluated within the same context of the Electrification scenario PATHS2050, which is more aligned with the Innovative DRI pathways. However, the investment scenario has been shown to produce near-identical results regarding the deployment of Torero and Steelanol capacity for both the Central and the Electrification storylines. The above-mentioned alternative gas input is expected to have a much greater influence on the dispatching of Steelanol and Torero.