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Department of Economics
Department of Public Economics
University of Graz

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Macroeconomic implications of switching to process-emission-free iron and steel production in Europe

Jakob Mayer1,*, Gabriel Bachner1, Karl W. Steininger1,2

1 Wegener Center for Climate and Global Change, University of Graz, Austria
2 Department of Economics, University of Graz, Austria

*Corresponding author, Tel.: +43(0)316/380 – 8457. E-mail adress: jakob.mayer@uni-graz.at

Abstract

Options to significantly reduce global greenhouse gas emissions in line with long-term political targets include switches in production technologies to those free of industrial process emissions. Exemplifying this transition, we analyse such a switch of the European iron and steel industry and its sectoral, macroeconomic and social implications. We employ a recursive-dynamic multi-region multi-sector computable general equilibrium approach in order to cover feedback effects originating from the integration of European sectors in a globally embedded context. Against the backdrop of a globally implemented CO2 price trajectory, we investigate how the range of macroeconomic implications depends on (i) the timing of the switch (either starting early in 2020 or late in 2035) and (ii) the investment and operating cost of two promising low-carbon technologies. We distinguish between high-cost and low-cost technological specifications, though both face cost disadvantages relative to conventional iron and steel production for current intermediate inputs and primary factors. An early implementation of a ‘high-cost’ technological alternative further reduces long-term GDP in 2050 among EU regions (-2.3% to -0.5% as compared to -1.4% to -0.3% for a late implementation starting in 2035). By contrast, GDP implications in 2050 seem to be unconstrained by early or late implementation of a ‘low-cost’ technology (regional range of -0.3% to 0.9% for both). However, welfare is reduced, particularly during the initial implementation phase since additional investment to build up new facilities reduces output available for other consumption needs. This ‘build-up’ might represent a barrier to such transitions, as the generation to decide on implementation and potentially bearing (macro)economic costs might not be the generation benefitting from it.
1. Introduction

The Paris Agreement to address climate change calls for a "fundamental structural transformation" (Zenghelis, 2015, p. 174) of the currently prevailing social and economic system. According to Rockström et al. (2017), going even ‘well below’ the agreed 2°C maximum target would require the inclusion of substantial amounts of anthropogenic CO₂ removals (i.e. negative emissions) by land-use changes and/or bioenergy carbon capture and storage. Raftery et al. (2017, p. 4) project that the agreed target to sufficiently cut greenhouse gas emissions is unlikely to be met, based on observational data of human population, gross domestic product (GDP) per capita, energy and carbon intensity (i.e. the KAYA identity).¹

Deep decarbonisation of socio-economic systems requires substantial reductions of greenhouse gas (GHG) emissions resulting from (i) the incineration of coal, oil and gas (combustion-based or energetic emissions), (ii) agricultural activities (cultivation of crops and livestock) and forestry, and (iii) industrial processes (process emissions). Much scientific emphasis related to near-zero GHG emission systems has been placed on energy-related GHG emission reduction, for instance in Johansson et al. (2012). Also, deep agricultural decarbonisation analysis has been in focus recently, for instance in Wollenberg et al. (2016). By contrast, deep decarbonisation of industrial processes like iron and steel production (mainly resulting from oxygen reduction in iron ores) has been analysed mostly in combination with ‘end-of-pipe silver

¹Though they emphasize that their model does not incorporate "sudden massive shifts", for instance in carbon-free technology usage.
1. INTRODUCTION

Technologies like carbon capture and storage (CCS, cf. Rootzén and Johnsson, 2015). To the authors' best knowledge (and disregarding CCS) existing studies have investigated process-emissions in the iron and steel sector regarding either incremental changes through marginal GHG-intensity gains (cf. Arens and Worrell, 2014) or policy instrument analyses to prevent carbon leakage (cf. Bednar-Friedl et al., 2012). However, to comply with the 2°C target, more radical than incremental changes are required with respect to currently process-emission-intensive iron and steel production.

A notable exception is a study by Fischedick et al. (2014), who present a sophisticated and detailed analysis of three promising low-carbon iron and steel technologies. They compare the process-emission-intensive and globally most widely applied technology (blast-furnace-basic-oxygen-furnace; BF-BOF) with (i) a combination of this conventional technology and CCS, (ii) hydrogen-based direct reduction and (iii) electrowinning. Investigating mass and energy flow simulations and a bottom-up economic evaluation for each route, the authors conclude that, in particular, the hydrogen-based direct reduction route "shows a great potential to allow economically viable emission reduction in line with climate targets and to substitute the conventional routes within the next 50 years" (Fischedick et al., 2014, p. 574).

While Fischedick et al. (2014)s analysis is rich in technological detail, it lacks the incorporation of salient indirect/feedback effects. For instance, a switch in the production process of finished steel eventually leads to a change in respective market prices. The extent to which other sectors’ demand for finished steel reacts depends on several factors, including substitution possibilities. However, changing market prices for finished steel trickle through different economic value chains and thus might in turn alter the unit costs of the iron and steel sector as well. The macroeconomic assessment in the present study explicitly takes these endogenous price effects into account and adds another dimension to the existing techno-economic literature of promising iron and steel mitigation technologies. This is particularly important since iron and steel have been categorized as one of few so-called general purpose technologies since the beginning of the industrialization (Rosenberg, 2013), which are used directly or indirectly in the production of many other

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2 Process-emissions in the cement industry are analysed in a macroeconomic framework in e.g. Jun et al. (2014).
3 Electrowinning represents oxygen reduction with electricity being the reductant instead of coke or hydrogen.
2. THE CHALLENGE OF PROCESS-EMISSION MITIGATION

products in interlinked sectors.

Methodologically we deploy WEGDYN, a dynamic-recursive multi-region multi-sector computable general equilibrium (CGE) model. It is based on the static version specified by Bednar-Friedl et al. (2012). We implement a transition path for the European Union iron and steel sector up to 2050. More precisely, we simulate a linear and bidirectional technology switch from BF-BOF-steel (blast-furnace derived pig iron which is fed into a basic-oxygen-furnace) to steel derived either by the DRI-H-EAF route (hydrogen-based direct reduced iron which is fed into an electric-arc-furnace) or PDSP (hydrogen-based plasma direct steel production). This technology switch is integrated in all EU member states (plus Norway, Iceland and Liechtenstein) in order to derive a system-wide and thus more fully-fledged picture of the transformational implications of a low-carbon future for socio-economic systems. Therefore, the paper contributes to the literature on CGE models analysing technology switches in carbon-intensive economic activities.4

The paper is structured as follows. Section 2 briefly motivates our research and provides technological background on iron and steel production, followed by a literature review on the issue investigated. The data and methodological approach is explained in Section 3. The explanation of the baseline path and the scenarios of the WEGDYN model simulation is also part of this section. Section 4 gives the results, structured along sectoral (market prices and sector output), macroeconomic (GDP and welfare) and social implications (unemployment of skilled and unskilled labour) of such a transition. We discuss the results of our analysis and associated limitations in Section 5 and conclude in Section 6.

2. The challenge of process-emission mitigation

We focus in this paper on the iron and steel sector, accounting for about 25% of global industrial emissions (Serrenho et al., 2016), which represent about 7.5% of total global GHG emissions5 (UNFCCC, 2017). It is among the sectors facing particular challenges in decarbonising future production. Evidently, continuous process improvements and retrofitting measures have

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4Gillingham et al. (2008) provide a survey on macroeconomic models focusing on the interaction of technological change and climate policy.

5For Annex I parties, excluding emissions from ‘Land-use, land-use change and forestry’.
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led to a relative decoupling of GHG combustion emissions and steel output in the past. However, especially in blast furnace (BF) pig iron production, which serves as the main feedstock in conventional primary steel production in EU-28 member states (share of 99% in 2015 according to WSA, 2016), process emissions represent essentially unavoidable GHG emissions under current conventional best-available technologies. The theoretical minimum CO₂ process-emission-intensity of BFs using coke and sinter is about 1.3 tons of CO₂ per ton of steel (Scholz et al., 2004; Kirschen et al., 2011) with the current European industry average being slightly above (about 1.5 tCO₂/t steel; ibid; IEA, 2007).

2.1. Conventional mitigation options

Rootzén and Johnsson (2015) highlight the challenges of decarbonising the iron and steel sector in a scenario analysis approach applied to Scandinavian iron and steel production. They investigated the opportunities of CO₂ emissions abatement taking best-available technologies (BAT) into account. In order to reach long-term targets, the authors conclude that significant emission reductions are only achievable either with a combination of BATs and carbon capture & storage (CCS) or a major decline in sector output. Also Schumacher and Sands (2007) assess variants of prevalent iron and steel technologies, but exclude CCS. Deploying a technology-based approach in a recursive-dynamic CGE framework, they arrive at a similar conclusion as Rootzén and Johnsson (2015). Only major output reductions - for instance, achievable by charging significant CO₂ prices - could bring about compliance with the 2°C target. However, unless relevant substitution possibilities for steel products are developed – e.g. polymers for automobile applications or wood (composites) for construction purposes – steel output decline is not to be expected in the short term, particularly because of the continuous high demand for steel’s product properties in emerging economies (cf. van Ruijven et al., 2016).

Arens et al. (2017) provide a more technology-rich assessment incorporating almost every German BF-BOF installation (including respective ages and capacities). Investigating the diffusion of 15 energy-efficient retrofitting technologies for BF-BOFs (e.g. top-pressure recovery turbine) and scrap-based EAFs (e.g. heat recovery), their model takes variations in production levels until 2035 for the German iron and steel industry into account and estimates energy consumption and the corresponding CO₂ emissions. In the
framework of their study, the authors confirm that it is unlikely that the current strategies of the German iron and steel industry follow a $2^\circ$C-compatible transition pathway.

However, some scholars and experts in the field argue for rapid system change to scale up recycling of steel scrap which would leave primary iron and steel production and its associated CO$_2$ process emissions obsolete. In this respect, another technology-rich optimization study is presented in Morfeldt et al. (2015) who integrate scrap-based secondary steel production in their ETSAP-TIAM model. Additionally, the authors assume two different medium- to long-term steel demand saturation scenarios, i.e. global demand for steel (virgin or scrap-based) stagnates in 2050 or 2100. Their result points to the fact that the accumulation of steel and steel scrap inhibits a time lag. Ultimately they conclude that virgin steel production has to make up a share of at least 50% globally in 2050 in order to meet even stagnating demand levels. Applying a dynamic stock-model, Pauliuk et al. (2013) arrive at a similar conclusion projecting that the scrap-age may eventually commence in the latter half of the 21st century. In addition, the study of Morfeldt et al. (2015) supports what the existing BAT literature suggests – if their ETSAP-TIAM model optimization is restricted to $2^\circ$C-compatibility, only combinations of BAT with the ‘silver-bullet’ CCS would allow for a solution.

Finally, another salient advantage of BF-BOF steel production relates to steel quality, since the scrap-based route is highly dependent on the quality of the feedstock (Arens et al., 2017). Currently, the secondary steel route is inferior to virgin iron and steel production from this perspective.

2.2. Best available technology options and promising innovations

The problem outlined above clearly shows that decarbonising the iron and steel sector is a complex issue. This is particularly true for ‘rapid decarbonisation’ (Rockström et al., 2017) in order to prevent non-linear climate change impacts which increase in likelihood after surpassing the $2^\circ$C threshold. With global decarbonisation needing to be achieved before mid-century (cf. Rockström et al., 2017), and given the above arguments related to secondary (i.e. scrap-based) steel production, this study focuses on primary steel production only. Let us first contrast conventional primary production technologies and currently promising break-through and, most importantly, process-emission-free alternatives.

Table 1 shows the two globally most important iron and steel production routes (BF-BOF and DRI-C-EAF with global shares in 2015 of about 74.2%
Table 1: Stylized representation of investigated iron and steel technologies based on Napp et al. (2014); IEA (2007).

| Abbreviation | Raw material preparation | Iron making | Steel making |
|--------------|-------------------------|-------------|--------------|
| BF-BOF      | Coal \(\Rightarrow\) Coke | Blast-furnace | Basic-oxygen-furnace |
|             | Iron ore \(\Rightarrow\) Sinter |             |              |
| DRI-C-EAF   | Coal / natural gas \(\Rightarrow\) Sinter | DRI plant | Electric-arc-furnace |
|             | Iron ore \(\Rightarrow\) Sinter |             |              |
| DRI-H-EAF*  | Electricity* \(\Rightarrow\) Hydrogen | DRI plant | Electric-arc-furnace |
|             | Iron ore \(\Rightarrow\) Pellets |             |              |
| PDSP*       | Electricity* \(\Rightarrow\) Hydrogen |             | Plasma smelting# |
|             | Iron ore |             |              |

Notes: *Process-emission-free. #One-step process not requiring significant raw material preparation (Sabat and Murphy, 2017). *Note that for the amount of indirect emissions the GHG-intensity of the electricity mix is decisive. Crude steel or hot metal, respectively, represents the final product of each route.

and 25.2% measured in tonnes of crude steel produced, respectively; WSA, 2016). It also depicts two promising break-through alternatives (DRI-H-EAF and PDSP) in a stylized fashion. In the case of BFs (or DRI-C plants, respectively), the reduction of oxygen molecules in iron ores by means of coke (or coal/natural gas) involves process emissions. This process is essential in order to derive high-quality pig iron (or direct reduced iron) from BFs (or DRI-C plants, respectively). Subsequently, the pig iron (DRI) is fed into a BOF (EAF) in order to derive crude steel (hot metal) which serves as feedstock for rolled, casted and finished steel products.

By contrast, the substitution of carbon in the DRI-C-EAF route with hydrogen – represented by the DRI-H-EAF process – would allow for almost process-emission free steel production. The only stoichiometric by-product for this route is water (vapour). The same applies for PDSP, with the main difference to DRI-H-EAF being that this route is even more integrated. Essentially, it is a one-step process indicated by only one box in Table 1 (‘Plasma smelting’; Sabat and Murphy, 2017). For DRI-H-EAF, the basic technologies (i.e. electrolysis, hydrogen-reduction, EAF) are already available but a sound integration of sub-processes is not yet explored sufficiently at scales suitable for industrial purposes. By contrast, PDSP is currently in a very early stage of development but it has been acknowledged to have various valuable characteristics, which is why major research and development efforts
are currently underway (Sabat and Murphy, 2017).

However, the process-emission-free technologies are assumed to use hydrogen derived from water electrolysis (PEM - polymer electrolyte membrane) which currently represents the most expensive means of hydrogen generation ($0.16\text{-}0.30 \text{€}_{2011}/\text{Nm}^3 \text{H}_2$; cf. IEA-ETSAP, 2017) but with the advantage of being totally carbon-emission-free if renewable electricity is used. Doing so is warranted, so that a shift in iron and steel technologies does not involve a mere shift from process-emissions in the iron and steel sector to combustion-emissions in the (hydrogen, and thus,) electricity generation sector.

Significant iron and steel output decline is not to be expected (at a global level) until mid-century and BAT do not offer the iron and steel sector any means to comply with the sectors’ contribution to reaching Paris Agreement targets. Hence, the switch to ‘radical innovative’ production technologies represents another crucial lever for climate policy measures (Napp et al., 2014; Arens et al., 2017). In this respect, Fischedick et al. (2014) present a sophisticated and detailed analysis of three promising iron and steel mitigation technologies. They compare the prevalent BF-BOF with (i) a combination of BF and CCS, (ii) hydrogen-based direct reduction and (iii) electrowinning. In addition to mass and energy flow simulations for each route, economic indicators are evaluated in three scenarios reflecting different spectra of the future German energy landscape. The authors conclude that hydrogen-based direct reduction is expected to become cost-competitive within the next 5 decades (Fischedick et al., 2014). However, they also point to the fact that the iron and steel sector is highly intertwined with domestic and foreign sectors. The macroeconomic assessment in this study explicitly takes endogenous price effects into account and thus adds another important dimension to the existing techno-economic literature.

3. Data, Methodology and Scenarios

3.1. Iron and steel technologies

In the following, we compare the unit costs (and their structures) of the currently most prominent technology (BF-BOF) and those of both process-emission-free technologies. The given costs, cost structures and technologically related process emissions are derived from several sources (Fischedick et al., 2014; NIR-AUT, 2017; CEPS, 2013) and a stakeholder dialogue and refer to a European perspective, especially with regards to resource and energy costs (Table 2).
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The most salient point is that DRI-H-EAF steel is costlier than BF-BOF steel by about 50% in per unit terms, for given prices of primary factors (capital and labour) and intermediate inputs. Although the use of DRI-H-EAF eliminates costs with respect to coke, the iron and steel industry in our analysis switches to carbon-emission-free derived hydrogen by means of PEM water electrolysis. Unit costs of hydrogen generation exhibit strong variations in the prevalent literature as industrial scale generation is yet to be developed (stakeholder dialogue; IEA-ETSAP, 2017). In the present analysis, we set the boundary such that within our system of analysis - be it the iron and steel sector itself, or some other agent supplying it as an intermediate product to the iron and steel sector – on-site hydrogen is generated via electricity purchased from the power generation sector.

Table 2: Unit costs of different iron and steel production technologies (net of taxes).

| Techno-economic specification     | Conventional | High-cost | Low-cost |
|-----------------------------------|--------------|-----------|----------|
| Electricity price [€-cents/kWh]   | -            | 5         | 3        |
| Integrated technology [€/t steel] | BF-BOF       | DRI-H-EAF | PDSP     |
| Coke                             | 84           | 0         | 0        |
| Electricity*                     | 0            | 219       | 131      |
| Iron pellets**                   | 0            | 84        | 0        |
| Iron ore                         | 189          | 189       | 189      |
| Services                         | 45           | 40        | 40       |
| Unskilled labour                 | 5            | 4         | 4        |
| Skilled labour                   | 44           | 40        | 40       |
| Capital (wear and tear)          | 48           | 48        | 48       |
| **Net total unit costs [€/t steel]** | **415**   | **624**   | **452**  |
| **Difference to BF-BOF [€/t steel]** | **-**      | **209**   | **37**   |
| **Process emissions [tCO₂/t steel]** | 1.5       | -         | -        |
| **Break-even CO₂ price [€/tCO₂]** | -           | 139       | 25       |

Notes: *Electricity costs for hydrogen production (and EAF in the case of DRI-H-EAF). **Additional costs due to the intermediate stage of producing iron pellets out of iron ore. In order to account for a techno-economic range of alternative technologies we assume an electricity price of 5€-cents/kWh for the otherwise more expensive DRI-H-EAF route and 3€-cents/kWh for the PDSP route. Main sources: Stakeholder dialogue; Fischedick et al. (2014); NIR-AUT (2017); CEPS (2013); Sabat and Murphy (2017).

Hence, electricity costs include the electricity demanded to generate hyd-
rogen, as well as electricity for steel production implied by the use of an electric arc furnace (EAF). We applied a net electricity price of 5\(\text{€-cents/kWh}\) representing current lower bound to average EU electricity prices for industrial purposes (EUROSTAT, 2017; E-Control, 2017). Another specific difference between BF-BOF and DRI-H-EAF relates to the raw material input, since the latter technology requires pre-processing of iron ore into iron pellets (IEA, 2007). The remaining cost elements, referring to costs for services and primary factors, are not substantially different.

The second technological alternative is PDSP, which shows high potential in regard to unit costs, flexibility in terms of industrial scale, product quality and zero climate impacts (Sabat and Murphy, 2017). Furthermore, it allows for a single-step production of steel, as the only raw material input in PDSP is iron ore. Hence, the intermediate step of producing iron pellets is obsolete for this technology (cf. Table 1 and the zero unit-costs for iron pellets in Table 2).

If we compare the unit costs of PDSP with BF-BOF, unit cost differentials remain positive (37 \(\text{€/t steel}\); cf. Table 2). Hence, the competitive advantage of BF-BOF in terms of unit cost raises the question of which possible incentives exist that would make an investment into the process-emission-free technologies a credible strategy. Climate policies could be such an incentive, for instance the anticipation of future stringency of climate regulations, or subsidies for hydrogen generation to achieve at least cost parity between the conventional and a process-emission-free technology. Additionally, policies related to inter alia foreign trade, energy or innovation might impact the constellation of competitive advantage, thus altering relative unit costs of steel for BF-BOF and DRI-H-EAF or PDSP, respectively.

It is important to note that the assumed electricity price is a key determinant of the ultimate unit costs. To capture a broad range of possible unit costs of process-emission-free iron and steel production, we construct two different techno-economic specifications. Representing the ‘high-cost’ techno-economic specification, we assume the iron and steel industry switches to the currently known costs of the DRI-H-EAF technology with an assumed future electricity price of 5\(\text{€-cents/kWh}\). As a ‘low-cost’ techno-economic specification, we instead switch the industry to PDSP technology (at the costs given in Table 2) with an assumed future electricity price of 3\(\text{€-cents/kWh}\).

The unit-cost differentials net of taxes (209 \(\text{€/t steel}\) for DRI-H-EAF and 37 \(\text{€/t steel}\) for PDSP; cf. Table 2) and the process emission factor of
1.5 t\textsubscript{CO}_2 (NIR-AUT, 2017; IEA, 2007; Kirschen et al., 2011) for BF-BOF would imply break-even CO\textsubscript{2} prices of about 139 \(€\)/t\textsubscript{CO}_2 for the high-cost specification and 25 \(€\)/t\textsubscript{CO}_2 for low-cost specification, in order to achieve cost competitiveness compared to the conventional technology. If we additionally consider the necessary investment costs for the new facilities of the process-emission-free technologies, the cost disadvantages deteriorate even more during the transition. Table 3 shows the unit investment costs and the associated capital expenditures (CAPEX) for both process-emission-free technologies calculated as annuity payments.\(^6\) The CAPEX for PDSP are assumed to be lower than for DRI-H-EAF because lower electricity prices allow for more profitable operating hours of PEM water electrolysis, requiring a lower number of facilities and thus lower costs.

| Generic assumptions                       |          |
|------------------------------------------|----------|
| Interest rate [%]                        | 2.00     |
| Investment phase [years]                 | 12.00    |
| Life time [years]                        | 12.00    |
| Annuity factor                           | 0.09     |

Table 3: Capital expenditures of ‘Greenfield’ facilities for DRI-H-EAF and PDSP.

| Technology    | DRI-H-EAF | PDSP |
|---------------|-----------|------|
| Electricity price \([€/kWh]\) | 0.05 | 0.03 |
| Gross investment unit costs \([€/t]\) | 1,113.00 | 1,043.00 |
| Annuity payments \([€/t steel]\) | 105.00 | 99.00 |

Considering a linear investment phase and corresponding lifetime of each facility (we assume 12 years for both) the derived annuities are 105 \(€\)/t steel for DRI-H-EAF and 99 \(€\)/t steel for PDSP for a construction period of 12 years (Table 3). With a stepwise adjustment of capital stock over a period of 12 years and a repayment period of 12 years for each vintage of this newly built up capital stock, this translates in total to a period of 23 years of additional capital expenditures (i.e. repayment) for a full installation of

\(^6\)The derivation of annuity payments \(A\) follows the usual specification shown in Equation 1,

\[
A = S \frac{(1 + i)^t}{(1 + i)^t - 1},
\]

with \(S\) being the loan amount, \(i\) being the interest rate and \(t\) being the financing term.
3. DATA, METHODOLOGY AND SCENARIOS

‘Greenfield’ facilities.\(^7\)

3.2. Macroeconomic assessment: WEGDYN CGE model

The WEGDYN model is based on the static version specified by Bednar-Friedl et al. (2012) and represents a global multi-sector, multi-country, recursive dynamic Computable General Equilibrium (CGE) model (calibrated to GTAP9 database; cf. Aguiar et al., 2016). It allows for a macroeconomic evaluation of system-wide effects originating from changes in the level of production of sectors or demand by households (public or private). It sequentially solves for static equilibria that are connected through a time dependent process of capital stock accumulation and labour force growth (cf. equations A.1-A.3 and the respective specification given in Appendix A). The production and consumption activities modelled in WEGDYN are associated with the emission of CO\(_2\), originating from both combustion of fossil fuels and industrial processes.

In total, WEGDYN comprises 16 economic sectors (Table 4) with special emphasis on the depiction of the steel production technology to be replaced. More precisely, we disentangle the BF-BOF-route (the specific process currently responsible for the bulk of process emissions within established steel technology) from the original GTAP sector ”Iron & Steel: basic production and casting” (IS). Within the model the BF-BOF-route is thus treated as a separate production sector, which supplies its output, together with the output of remainder of the original IS sector, to a final iron and steel sector aggregate which eventually supplies to the market.

Regarding the regional aggregation the model distinguishes between 16 regional aggregates, with Europe being represented as seven separate regions, namely: Northern Europe (NEU), Eastern Europe (EEU), Southern Europe (SEU), Western Europe (WEU), as well as Austria (AUT) and Greece (GRC).

\(^7\)The unit costs in terms of operating expenditures (OPEX given in Table 2) are validated mainly via data given in Fischedick et al. (2014). Although divergences exist in the declarations of cost data, they are negligibly small (OPEX for BF-BOF and DRI-H-EAF in our analysis are about 1.8% lower and 5.3% higher, respectively). Note that from a technological point of view, cost estimates for PDSP are a simplified approximation, the only difference being the omission of pre-processing iron ores (Sabat and Murphy, 2017). However for the transition itself, our analysis is more conservative, compared to Fischedick et al. (2014) because capital expenditures (CAPEX given in Table 3) of DRI-H-EAF and PDSP are higher (27% and 19%, respectively) due to the assumption of higher costs regarding hydrogen generation and (underground) storage.
as separate regions, taken together representing EU-28 member states plus Norway, Liechtenstein and Iceland (EU+3). We consider Austria and Greece separately as two exemplary countries on either end of a spectrum, Austria with basically all its iron and steel production currently in the BF-BOF route, Greece with no production outside of scrap-based EAF (cf. Figure B.9 in Appendix B). The seventh regional aggregate Rest of Europe (REU) represents those countries which are not part of the EU-ETS. The rest of the world is represented by 9 further regional aggregates (Table 4 and B.5 in Appendix B for more details).

Table 4: Aggregate sectors and regions of the WEGDYN CGE model.

| Model code | Aggregated Sectors                  | Model code | Region Name       |
|------------|-------------------------------------|------------|-------------------|
| AGRI       | Agriculture                         | AUT        | Austria           |
| COA        | Coal                                | GRC        | Greece            |
| CRP        | Chemical, rubber, plastic products  | EEU        | Eastern Europe    |
| EXT        | Extraction                          | SEU        | Southern Europe   |
| FTI        | Food and textile industries         | WEU        | Western Europe    |
| GAS        | Gas                                 | AFR        | Africa            |
| IS*        | Iron & Steel: basic production and casting* | CAN | Canada           |
| NMM        | Mineral products                    | CHN        | China             |
| OIL        | Oil                                 | ECO        | Emerging economies|
| P_C        | Petroleum, coke products            | IND        | India             |
| PPP        | Paper, pulp and paper products      | LAM        | Latin America     |
| SERV       | Other services and utilities        | OIGA       | Oil and gas exporting countries |
| TEC        | T eck industries                    | RASI       | Rest of South & East Asia |
| TRN        | Transport                           | REU        | Rest of Europe    |
| CGDS       | Capital goods                       | USA        | USA               |

Notes: *Represented by two subsectors: (i) conventional BF-BOF iron and steel production and (ii) rolling, casting and finishing.

We differentiate between combustion based emissions (GTAP9, Aguiar et al., 2016) and process emissions (UNFCCC, 2017; NIR-AUT, 2017). Exogenous assumptions regarding CO₂ price and energy prices follow the projection of the World Energy Outlook 2016 (cf. B.6 in Appendix B; IEA, 2016). Finally, the model is calibrated to World Bank unemployment rates of 2011 (cf. Table B.7 in Appendix B; WB, 2017) differentiating between skilled and unskilled labour. To this end we introduce a minimum real wage (i.e. a fixed ratio between nominal wages and the consumer price index). In the technology switch scenarios, changes in the unemployment rate emerge due to the calibrated real minimum wage (reflecting inter alia union power). More details on the model structure, macro closures and the modelling of the labour market are given in Appendix C.
3.3. Scenario framework

In general, the intention of the WEGDYN CGE analysis is to compare two distinct simulations. The first simulation refers to a baseline path, assuming a given economic structure (e.g. conventional iron and steel production) and a specific socio-economic background development. We apply SSP2 growth rates for GDP and labour force (IIASA, 2017) and long-term capital depreciation rates derived from Feenstra et al. (2015). The baseline calibration using multi-factor productivity growth rates is specified in detail in Appendix A. Additionally, the baseline scenario assumes the IEA (2016) CO₂ price trajectory of the ‘New policies scenario’ (given for EU) reaching globally €46/tCO₂ in 2050 starting with €5/tCO₂ in 2015 (cf. Table B.6 in Appendix B. The CO₂ price is modelled as fixed tax rate, hence there is no feedback, e.g. on emission allowance markets. It is implemented globally.

The second simulation (i.e. the technology switch scenario) introduces mitigation efforts exogenously via changes in the technological (and thus economic) structure (process-emission-free iron and steel production). The scenario is then compared to the baseline path to see the economy-wide effects that are triggered by the introduced exogenous changes. Both simulations happen within the same ‘baseline policy world’, which reflects the institutional framework or stringency of climate policy (with the latter specified as the level of the CO₂ price). The underlying ‘policy world’ might also be changed to see whether economy-wide effects of mitigation efforts look different in a different policy world.

In a nutshell, technology switch scenarios are differentiated by four distinct combinations. First, they refer either to ‘high-cost’ or ‘low-cost’ technological specifications. Second, we investigate two industry timings – implementation starting in 2035 (‘late’) or in 2020 (‘early’) – of investment into the respective technology linearly substituting conventional iron and steel production over 15 years while keeping capacities constant but allowing for endogenous feedbacks. The incorporation of the latter scenario feature allows us to estimate the implications of a more or less ‘ambitious’ (in the sense of ‘risk-taking’) industry behaviour since the CO₂ price is increasing over time.

4. Results

If not otherwise stated, the panels referred to below give regional indicators differentiating between the techno-economic specification (i.e. ‘high-
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cost’ DRI-H-EAF with an assumed electricity price of 5€-cents/kWh and ‘low-cost’ PDSP with 3€-cents/kWh) staying within a climate policy world represented by a linearly increasing CO₂ tax reaching 46€/tCO₂ in 2050. Results are given relative to a baseline model run where conventional iron and steel production persists by means of BF-BOFs which is also confronted with the same CO₂ price trajectory. This allows for isolating the pure effect of switching to process-emission-free iron and steel technologies.

4.1. Sectoral implications

For a iron and steel industry transition starting in 2035 (labelled ‘late’), the specific manifestation of unit costs for new technologies determines the sign of implications for regional iron and steel market prices in 2050 as shown in Figure 1. The EU+3 (EU plus Norway, Iceland and Liechtenstein) implications of market price increases in 2050 range in between +0.3% (GRC) and +3.5% (AUT) in a ‘high-cost’ specification and in between -6.4% (AUT) and -0.9% (GRC) in a ‘low-cost’ specification. Thus, the underlying CO₂ price trajectory is insufficient to close the gap between conventional and ‘high-cost’ technologies, especially since the latter is affected by additional burdens regarding financing of new facilities. This changes when using a ‘low-cost’ technology specification where the CO₂ price trajectory leads to lower market prices for iron and steel relative to the baseline case. Note that in both techno-economic specifications, the strongest implications are in AUT and the weakest in GRC, particularly pointing to the fact that the share of phased-out BF-BOF iron and steel production is highest for the former and negligible for the latter region (cf. Figure B.9 in Appendix B). However, there are still small implications visible in GRC due to the country’s high integration in the EU domestic market.

If new technologies are implemented earlier (we use 2020), we see that in a ‘high-cost’ specification, iron and steel market prices are about +1.0% (GRC) to +7.5% (AUT) higher in 2036 than in the baseline case. However, after 2036 the price-pushing effect during the transition declines until 2050 (ranging in between 0.6% for GRC and 5.2% for AUT) due to (i) the linearly increasing CO₂ price and (ii) the decline in additional CAPEX for the new facilities. Both effects slowly reduce the unit cost disadvantage of the ‘high-cost’ technological specification but prices in 2050 remain higher than in the baseline case. By contrast, market prices for ‘low-cost’ iron and steel are lower throughout the model horizon leading to an EU+3 range of -5.5% (AUT) to -0.7% (GRC) in 2050.
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Regional iron and steel market price

[\%\text{-diff to baseline}]

Figure 1: Regional iron and steel market price as percentage difference to baseline model run.

The relative market price changes for iron and steel translate into the following implications for sector output (Figure 2). In the ‘high-cost’ specification, regional market prices are higher than in the baseline scenario, demand for iron and steel adjusts accordingly and is mirrored by lower sector output (measured in quantities). This effect gets stronger during the construction of each additional vintage of the process-emission-free technology. After all new capital vintages have been installed, the decline relative to the baseline case tends to get smaller.

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Regional iron and steel sector output

[\%\text{-diff to baseline}]

Figure 2: Regional iron and steel sector output as percentage difference to baseline model run.

The strongest relative output decreases can be seen for AUT and EEU, since price effects are also strongest in these regions. For late (early) implementation, output implications range between \(-15.4\%\) \((-18.7\%)\) for AUT and \(+2.1\%\) \((+3.7\%)\) for GRC in 2050. In contrast, in the ‘low-cost’ specification the continuously lower regional market price for iron and steel leads mainly to increased regional sector output and ranges between \(-6.9\%\) \((-5.7\%)\) in GRC and \(+25.2\%\) \((+23.8\%)\) in AUT for late (early) implementation in 2050.
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Average regional sector output 2050

(a) ‘High-cost’ (‘Late’)  
(b) ‘Low-cost’ (‘Late’)

The introduction of new iron and steel technologies leads to the following inter-sectoral implications (Figure 3a for ‘high-cost’ and Figure 3b for ‘low-cost’) in a late implementation scenario. Due to higher prices for finished steel in a ‘high-cost’ technology switch scenario (Figure 3a), the sectoral output (turnover) of the iron and steel sector declines relatively strongly as demand is being reduced. Also ‘Petroleum and coke products’ (P.C) turnover declines relatively strongly due to the input switch to ‘Electricity’ (ELY) in the iron and steel sector, which is why ELY gains the most in terms of sector output. Also sectors ‘Coal’ (COA) and ‘Gas’ (GAS) benefit marginally, since European electricity generation is to a significant extent fossil-fuel based.
This clearly points to the requirement of an aligned course of action in order to prevent a switch from process-emissions in the iron and steel sector to combustion-based emissions in the electricity generation sector. All other sectors experience a loss because of the overall weaker economic activity.

From a ‘low-cost’ perspective (Figure 3b), the P_C sector loses the most due to decreased demand from the iron and steel sector. By contrast, the gain in competitiveness of the iron and steel sector in terms of lower market prices translates into higher demand and results in the highest increase in turnover compared to other sectors. Again, ELY, COA and GAS belong to the main winners in such a scenario. All the remaining sectors gain marginally with the exception of OIL which suffers from decreased intermediate demand from the oil-intensive P_C sector.

4.2. Macroeconomic implications

Figure 4 shows how the introduction of new iron and steel technologies translates into effects on regional GDP. For a loss in relative sectoral cost competitiveness in terms of gross unit costs (including taxes on commodity inputs, primary factor input and CO\textsubscript{2}) we reveal relative losses at the macroeconomic level in terms of GDP. This applies in particular to the ‘high-cost’ specification in Figure 4) independently of the timing of action of the iron and steel industry. The relative GDP losses in the aggregate EU+3 region range in between -0.3% (-0.53%) for GRC and 1.4% (-2.4%) for EEU in 2050 for late (early) implementation. The iron and steel sector in the EEU region represents a high share of regional output (about 2%) in comparison with the remaining EU+3 regions (AUT 1.5%, GRC 0.9%, NEU 0.9%, SEU 1.3%, WEU 1.3%) (Aguiar et al., 2016). Hence, on an aggregate level the induced change in market prices for iron and steel (due to the technology switch) has larger implications there.
For the ‘low-cost’ specification, long-term relative GDP effects are positive except for GRC, and range between -0.3% in GRC up to 0.9% in WEU for late, respectively early implementation. However, we see small negative impacts in the early phase of the transition (2021-2036) in AUT, EEU, NEU and SEU for the early implementation case (in between -0.2% and 0%). This originates from lower short-term aggregate consumption due to short-term increases in unemployment and thus aggregate (labour) income (cf. Section 4.3), which is stronger in magnitude than the increase in aggregate investment (including new facilities of the process-emission-free technology), until the CO$_2$ price is sufficiently high to re-establish cost competitiveness.
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Consequentially, aggregate consumption only picks up afterwards.

Regional welfare
[\%\text{-}diff to baseline]

Figure 5: Regional welfare as percentage difference to baseline model run.

A crucial issue not captured in GDP is the shift of national income use from consumption to additional investment. To allow for additional investment, aggregate consumption is reduced, reflected in a welfare reduction that can be seen during the investment period of 12 years (2035-2047 for the late and 2020-2032 for the early implementation). Each kink in the regional time-series for the welfare measure shown in Figure 5 is the point in time when the last facility investment takes place. Especially in the ‘low-cost’ specification, where from a bottom-up perspective the option seems to be
4. RESULTS

favourable, this ‘early transition and capacity build-up phase’ (in terms of relative welfare losses) has to be taken into account if decision makers intend to support such a transition in the iron and steel industry.

4.3. Labour market implications

The switch from the conventional BF-BOF technology to one of the two carbon-free alternatives (‘high-cost’ or ‘low-cost’ specification) involves a change of steel production characterised by lower labour intensity (cf. Table 2). Principally, this could give rise to either job creation or job displacement tendencies, depending on factors like inter alia cost competitiveness of the new technology relative to prevailing technologies (employed domestically and abroad), market concentration, education and training of workers, or power of unions. For the examples listed, we compare unit costs of steel technologies embedded in a highly competitive industry. Although the focus is on Europe, the model explicitly captures the global context. We distinguish between skilled (Figure 6) and unskilled labour (Figure 7).

In the case of the ‘high-cost’ specification, it has been shown that the underlying CO$_2$ price trajectory is insufficient to warrant cost competitiveness relative to the conventional technology. Hence, the lower demand for steel and its strong interdependency with other sectors translates into higher regional unemployment rates relative to the baseline case, also due to the lower labour intensity of the new technology. This is true for skilled (Figure 6) and unskilled labour (Figure 7), with the effects being stronger for skilled labour. In 2050, the ranges for the (un)skilled unemployment rates are depicted as percentage-point difference to the baseline case in Figure 8.
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Regional unemployment rate skilled labour

\[%\text{-point-diff to baseline}\]

Figure 6: Regional unemployment rates of skilled labour as percentage-point difference to baseline model run.
By contrast, long-term unemployment rates tend to be lower in a ‘low-cost’ setting due to the stronger economic activity overall. However, during the capacity build-up and repay period of 23 years (i.e. the repayments for PDSP facilities with 3€-cents/kWh), unemployment rates are slightly higher for most EU+3 regions. Figure 8 provides the corresponding (un)skilled unemployment implications in 2050 for EU+3.
5. **DISCUSSION & LIMITATIONS**

**EU+3 unemployment rates 2050**

[\%\text{-point-diff to baseline]}

(a) Early implementation (2020)  
(b) Late implementation (2035)

![Graph showing unemployment rates](image)

Figure 8: Range of EU+3 unemployment implications (percentage point change to baseline unemployment rate) in 2050 for (8a) early and (8b) late implementation.

5. **Discussion & Limitations**

The inclusion of endogenous market effects supports the bottom-up analysis of Fischedick et al. (2014) to some extent. Comparing the two studies, we find that the underlying CO\textsubscript{2} price trajectory of Fischedick et al.s’ (2014) conservative scenario is in line with our analysis (45\(\text{€/tCO}_2\) by mid-century). However, exogenously assumed coal prices increase more in Fischedick et al. (2014) (1.6% p.a. as compared to 1.0% p.a. in WEGDYN) and peak electricity prices decrease strongly (-12.7% p.a.) whereas in WEGDYN endogenous electricity prices remain almost constant (5 and 3\(\text{€-cents/kWh}\), respectively). Additionally, CAPEX assumptions are higher in our analysis. These main exogenously-defined differences favour the process-emission-free technology in the analysis of Fischedick et al. (2014) and essentially lead to their conclusion that even in a conservative scenario, conventional BF-BOFs iron and steel production will be outperformed by DRI-H-EAF around mid-century.
By contrast, a similar conclusion in our analysis only applies for PDSP which calls for (i) increased research & development efforts in order to substantially drive down operating costs of process-emission-free iron and steel technologies and (ii) supportive policy measures during the transition in order to limit the additional repayment burden of new facilities.

Our analysis presented is based on the assumption that the production of iron and steel is homogenous with respect to the specific final steel product (i.e. there is neither a differentiation between rolled, casted or finished steel, nor a difference regarding qualities, i.e. steel grades). However, in reality there exists a wide range thereof which may eventually change the results at a more highly resolved level (i.e. at firm- or specific application-level). However, higher resolution would come at the cost of lower computability, restricting the analysis of macroeconomic implications.

An ongoing and highly controversial debate surrounds the risk of carbon leakage in heavy industries such as the European iron and steel sector. Although companies heavily stress the imminent loss in competitiveness when there is a regional disparity in the magnitude of carbon pricing, the credibility, timing and extent of re-location measures remain uncertain. In fact, BF-BOFs inhibit very long lifetimes - experts in the field argue that there is no clear end-of-lifetime and it would theoretically be possible to apply retrofitting measures on a regular basis. Additionally, Europe has a long tradition and knowledge base regarding this process-emission-intensive route. Hence, the issue of carbon leakage rather relates to the question of whether geographic divergence in the stringency of climate policies leads to a downturn of European producers and a corresponding rise for non-European suppliers. In this respect, a sensitivity analysis regarding fundamental foreign trade model assumptions of iron and steel is presented in Appendix D.

Future research directions should scrutinise two issues in this respect. First, the quality and shape of iron and steel produced and demanded varies considerably and carbon leakage due to climate policy divergences could be negligible if European iron and steel products offer significant added value, for instance in terms of quality. Second, the direction and magnitude of otherwise induced changes in production levels represent another type of influencing factor for carbon leakage, with the rate and direction of (macro)economic implications remaining uncertain, in particular if substitution possibilities for specific steel applications are taken into account (e.g. wood for construction purposes or polymers for automobile parts).

While stating a non-exhaustive list of plausible limitations, we find that
6. CONCLUSION

on a macroeconomic scale, the analysis is valuable regarding specific \textit{a priori} defined scenarios. These represent a starting point for future investigations regarding uncertainties related to exogenously set assumptions in the WEGDYN CGE analysis. To this end, variations in climate policies (e.g. CO$_2$ pricing) and socio-economic background characteristics (e.g. different SSPs) are investigated in future work. Model choice is also a starting point for further research, as the CGE analysis assumes a supply-side constrained framework taking a long-run position of the macroeconomy (i.e. assuming long-run average capacity utilization in producing the aggregate of investment, intermediate and consumptions goods).

Finally, a crucial issue arose in the course of a comprehensive ‘desired futures’ process involving relevant stakeholders regarding the low-carbon transition in Austria. It is acknowledged that the initiation of transitions requires policy support (e.g. a sufficient and globally uniform CO$_2$ price), otherwise it would have commenced already; but many stakeholders show concern about system stability after the low-carbon or carbon-free transformation has been completed. For instance, changes in governance might lead to ‘re-switching’ incentives ultimately undermining the transformed systems’ stability. Thus, mechanisms for a permanent anchoring of such systems should be scrutinized in more depth.

6. Conclusion

For a transition to process-emission-free iron and steel production in Europe, there are various technological pathways available, although the degree of current technology maturation varies considerably. As process emissions are a significant share of sector GHG emissions, a switch in the production process is required for reaching climate targets. We explore direct reduction, where hydrogen substitutes as reductant for coke in the current blast furnace route. An alternative is plasma-direct-steel-production. With electricity as the new crucial input, in fact substituting for coke, the electricity price is a core determinant for the competitiveness of the new route. For current industrial electricity prices (around 5€-cents/kWh, with differentiations across Europe), we find that hydrogen-based direct reduction (with electric-arc furnaces producing crude steel) is not competitive with the conventional blast-furnace basic-oxygen furnace (BF-BOF) route at current intermediate input prices. Plasma-direct-steel-production, however, is more competitive than
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even the conventional technology, when we can establish e.g., an electricity price not above 3€-cents/kWh and modest CO\textsubscript{2} pricing (46€/tCO\textsubscript{2} in 2050).

In macroeconomic analyses (we deploy the WEGDYN CGE model), a competitive (dis)advantage usually translates into respective GDP and welfare (dis)advantages. Impacts from the introduction of a process-emission-free iron and steel technology tend to be strongest in those European countries with highest shares of BF-BOFs. For the techno-economic variation investigated, we show respective sectoral (market price, sector output), macroeconomic (GDP, welfare) and labour market implications (employment of skilled/unskilled labour) while differentiating between relatively early (2020) and later (2035) implementation of process-emission-free iron and steel technologies. We find that early implementation of a process-emission-free technology representing a ‘high-cost’ alternative increases the range of negative GDP implications (-2.3% to -0.5% for early as compared to -1.4% to -0.3% for late implementation in 2050). If a ‘low-cost’ technological alternative can be established, long-term GDP implications seem to be invariant to industry timing (-0.3% to 0.9% for both, early and late implementation).

We derive similar conclusions for welfare effects (i.e. consumption possibilities). However, seen from a long-term position of economies (i.e. no under-utilization) negative short-term effects on welfare are stronger than for GDP since the additional investment in process-emission-free iron and steel technologies restricts the usage of income for consumption purposes. From the analysis, we can conclude that building up new capital stock with transition investments, and the associated initially negative welfare effects, might be a barrier (or ‘implementation risk’ for initiating a transition) for environmentally-benign technologies such as process-emission-free iron and steel production. This barrier might be even more difficult to be overcome when possible technological transitions take longer than the lifespan of a human generation, since the generation carrying the (macroeconomic) costs might not benefit at all from the transition. In this respect it is noteworthy that skilled labour is more likely to suffer from an iron and steel transformation compared to unskilled labour in terms of rising unemployment, especially in an early technology implementation scenario.

Finally, aligning the investigated iron and steel industry transformation with the expansion of renewable electricity generation is of decisive character, otherwise the shift from process to combustion-based emissions undermines the effectiveness of the intended climate change mitigation effort.
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Appendix A. Recursive-dynamics

Like the static version (cf. Bednar-Friedl et al., 2012), the WEGDYN model includes one regional household eventually providing primary factors (labour and capital) to the market and using factor income in order to demand products and services from supplying sectors. The models’ government balance is reflected by government revenue due to fixed tax rates and flexible tax income. Savings and investments balance according to a fixed savings rate. Additionally, the balance of payments is fixed at benchmark (2011) levels. Foreign trade of each commodity supplied follows the Armington (1969) assumption of not perfectly substitutable goods produced in different regions.

For the recursive-dynamic calibration of the baseline model run, we deploy SSP2 population growth projections separated by gender and age (cf. the extensive database of IIASA, 2017) provided by KC and Lutz (2017). The calculated regionally-weighted labour force growth rates (15-64-year-old population) are shown in Figure B.10. Hence, labour endowment (representing income) in this analysis develops according to the calculated SSP2 labour force growth rate $g_{LF}$ assuming a time-constant participation rate. In order to ensure that labour endowment/income growth is positive (being a long-term fact) we additionally include a globally assumed labour-augmenting productivity growth rate of 1%. Hence, equations A.1-A.2 show the development of the regional specific labour endowment in our model with $L$ being total labour income, $t$ representing time and $g_{LF}$ being the effective labour income growth rate:

\[ L_{t+1} = (1 + g_{LF})L_t; \]  
\[ g_{LF} = g_{LF} + 0.01 \]  
(A.1) \hspace{1cm} (A.2)

Taking regional capital stock levels $KS$ for the benchmark year 2011 from the Penn World Table (Feenstra et al., 2015) and regional investment levels $I$ and depreciation rates $\delta$ from GTAPv9 (Aguiar et al., 2016), the available regional capital stock in 2012 follows:

\[ KS_{t+1} = KS_t(1 - \delta) + I_t \]  
(A.3)

From this the regional growth rate of the capital stock between 2011 and 2012 can be derived. Since we assume constant interest and depreciation rates, the rental price of capital is constant and capital stock growth equals
capital income growth. However, investment levels differ in each period and, consequentially, the capital income growth rate is not a constant. In order to ensure that the reference path is calibrated to the SSP2 economic growth rate (as shown in Figure B.10) with exogenous and constant effective labour income growth but endogenous capital income growth, we adapt multi-factor productivity (i.e. factor-neutral technological progress).

This procedure of updating factor endowments represents a Keynesian closure of the saving-investment balance. Hence, it induces investment-led economic growth (cf. Delpiazzo, 2010). A change in factor endowments (in our case increases in the capital stock, capital income and labour supply) results in a change in income to the household (in our case an increase over time) the use of which is split among consumption and savings at each time step. This has no influence on the production technology and the shape of the production function remains. In our case, factors have become more abundant and, as a consequence, factor prices decrease. The ratio of decreased factor prices and increased factor endowments decides whether the households’ new balance of payments allows for increased consumption and savings. If so, the absolute value of savings increases deterministically since the fraction of income saved is, as explained previously, assumed to be fixed (fixed savings rate).

Thus, savings adjust to available capital and labour income, which in turn is (co-)determined by the size of the capital stock and thus by investments. Note that in the counterfactual simulations, we introduce additional investment, necessary to build up the new iron and steel capital stock financed by cuts in aggregate consumption and aggregate investment. Finally, we solve sequentially for ‘new’ static equilibria and recalibrate the capital stock and capital income growth from which the multi-factor productivity growth factor is derived.

We consider a linear investment phase and a corresponding life time of each new process-emission-free facility of 12 years for both. With a stepwise adjustment of the capital stock over a period of 12 years, and repayments of 12 years for each vintage of this newly built up capital stock, this translates, in total, to a period of 23 years of additional capital costs for a full installation of the new technologies. Hence, 12 years after the first vintage is built, repayments are highest and linearly decline afterwards until all vintages are repaid.
## Appendix B. Supplementary material

Table B.5: Regional aggregates of the WEGDYN model.

| Model code | Aggregate name                     | Aggregated countries                                      |
|------------|------------------------------------|------------------------------------------------------------|
| AUT        | Austria                            | Austria                                                    |
| GRC        | Greece                             | Greece                                                     |
| EEU        | Eastern Europe                     | Bulgaria, Czech Republic, Hungary, Poland, Romania, Slovakia, Slovenia |
| NEU        | Northern Europe                    | Estonia, Lithuania, Latvia, Denmark, Finland, United Kingdom, Ireland, Norway, Sweden |
| SEU        | Southern Europe                    | Croatia, Cyprus, Spain, Italy, Malta, Portugal              |
| WEU        | Western Europe                     | Belgium, Germany, France, Liechtenstein, Iceland, Luxembourg, Netherlands |
| AFR        | Africa                             | Benin, Benin, Burkina Faso, Botswana, Cte d’Ivoire, Cameroon, Ethiopia, Ghana, Guinea, Kenya, Madagascar, Mozambique, Mauritius, Malawi, Namibia, Rwanda, Senegal, Togo, United Republic of Tanzania, Uganda, Zambia, Zimbabwe, Mongolia, Burundi, Central African Republic, Congo, Comoros, Cape Verde, Djibouti, Eritrea, Gabon, Gambia, Guinea-Bissau, Equatorial Guinea, Liberia, Lesotho, Mali, Mauritania, Niger, Sierra Leone, Somalia, Swaziland, Chad |
| CAN        | Canada                             | Canada                                                     |
| CHN        | China                              | China                                                      |
| ECO        | Emerging economies                 | South Africa, Hong Kong, Armenia, Azerbaijan, Georgia, Kazakhstan, Kyrgyzstan, Russian Federation, Tajikistan, Turkmenistan, Ukraine, Uzbekistan, Brazil, Mexico, Indonesia, Republic of Korea, Pakistan, Belgium, Turkey |
| IND        | India                              | India                                                      |
| LAM        | Latin America                      | Argentina, Belize, Bolivia, Chile, Costa Rica, Dominican Republic, Guatemala, Honduras, Jamaica, Nicaragua, Panama, Peru, Paraguay, El Salvador, Trinidad and Tobago, Uruguay, Puerto Rico, Bahamas, Barbados, Cuba, Guyana, Haiti, Suriname |
| OIGA       | Oil and gas exporting countries    | Angola, Democratic Republic of the Congo, Nigeria, Ecuador, Venezuela, United Arab Emirates, Bahrain, Algeria, Egypt, Iran, Iraq, Israel, Jordan, Kuwait, Lebanon, Libya, Morocco, Oman, Occupied Palestinian Territory, Qatar, Saudi Arabia, Syrian Arab Republic, Tunisia, Yemen |
| RASI       | Rest of South & South East Asia    | Cambodia, People’s Democratic Republic, Lao, Macao, Special Administrative Region China, Vietnam, Brunet Darussalam, Malaysia, Philippines, Singapore, Thailand, Bangladesh, Sri Lanka, Nepal, Fiji, New Caledonia, Papua New Guinea, French Polynesia, Solomon Islands, Vanuatu, Samoa, Afghanistan, Bhutan, Maldives, Myanmar, Timor-Leste |
| REU        | Rest of Europe                     | Albania, Switzerland, Bosnia-Herzegovina, Macedonia, Serbia, Moldavia |
| ROI        | Rest of industrialised countries   | Australia, New Zealand, Japan                              |
| USA        | USA                                | USA                                                        |
Figure B.9: BF-BOF crude steel production 2011 in EU+3 countries based on WSA (2012).

Figure B.10: Annual SSP2 growth rates; GDP data (based on Cuaresma, 2017) and labour force data (based on KC and Lutz, 2017) retrieved from the IIASA (2017) data base; multi-factor productivity calibrated.
Table B.6: CO2-price and fossil fuel price forecast based on IEA (2016) assuming EUR2011/USD2011 exchange rate of 0.7; EXT price growth rate assumed to be 0.009% p.a. based on stakeholder dialogue.

| Year | Global CO2 price [2011/tCO2] | Coal | Oil | Gas | EXT [price index normalised to 2011] |
|------|-------------------------------|------|-----|-----|-------------------------------------|
| 2011 | 0.00                          | 1.00 | 1.00| 1.00| 1.00                                |
| 2015 | 5.00                          | 1.05 | 1.19| 1.10| 1.05                                |
| 2020 | 14.00                         | 1.11 | 1.43| 1.21| 1.09                                |
| 2025 | 20.00                         | 1.17 | 1.70| 1.33| 1.14                                |
| 2030 | 26.00                         | 1.23 | 2.04| 1.46| 1.20                                |
| 2035 | 30.00                         | 1.29 | 2.43| 1.60| 1.25                                |
| 2040 | 35.00                         | 1.36 | 2.90| 1.76| 1.31                                |
| 2045 | 40.00                         | 1.43 | 3.47| 1.94| 1.37                                |
| 2050 | 46.00                         | 1.51 | 4.14| 2.13| 1.43                                |

Table B.7: Regional unemployment rates benchmark year 2011 for unskilled (ur_unl) and skilled labour (ur_skl) (WB, 2017); own calculations.

| Region | ur_unl | ur_skl | Region | ur_unl | ur_skl |
|--------|--------|--------|--------|--------|--------|
| AUT    | 9.10%  | 3.10%  | ECO    | 6.40%  | 7.90%  |
| EEU    | 27.20% | 8.10%  | IND    | 2.20%  | 5.00%  |
| NEU    | 15.80% | 6.50%  | LAM    | 5.70%  | 6.60%  |
| SEU    | 20.40% | 10.60% | OIGA   | 10.90% | 8.40%  |
| WEU    | 13.40% | 5.40%  | RASI   | 2.50%  | 7.70%  |
| GRC    | 16.20% | 18.40% | REU    | 20.90% | 6.10%  |
| AFR    | 5.60%  | 13.70% | ROI    | 6.70%  | 4.30%  |
| CAN    | 14.40% | 6.30%  | USA    | 12.00% | 8.50%  |
| CHN    | 4.30%  | 4.30%  |        |        |        |

Appendix C. Labour market modelling

The baseline model runs are calibrated to benchmark 2011 regional unemployment rates retrieved from World Bank data (WB, 2017) which are held constant throughout the simulation horizon. Hence, the share of labour hours actually employed is exogenously fixed and the real wage is endogenous. In order to look at labour market implications in the counterfactual model runs (when a process-emission-free alternative replaces the conventional iron and steel technology) the modelled causality is reversed, meaning that the trajectory of real minimum wages is fixed which implies that labour hours employed
Appendix D. Sensitivity analysis - foreign trade of iron and steel

As has been in shown in Alexeeva-Talebi et al. (2012), fundamental model assumptions particularly related to the degree of global trade integration for energy-intensive and trade-exposed sectors can lead to diverging results in terms of magnitude and direction. The following Figures D.11-D.12 show results for the regional iron and steel market price and GDP, respectively, emerging from variations in Armington elasticities for the iron and steel sector. The benchmark development for an early implementation of a high-cost technological specification – presented in Section (4) – is compared to scenarios where we strongly increase trade elasticities of the iron and steel sector by a factor of 5 (‘tela-up\textunderscore 5’) and 2.5 (‘tela-up\textunderscore 2.5’), respectively, and a scenario where trade elasticities are strongly decreased by a factor of ten (‘tela-down\textunderscore 10’).

Decreasing the level of international trade integration regarding iron and steel in the model (‘tela-down\textunderscore 10’) leads to higher regional iron and steel market prices (Figure D.11) than in the benchmark, due to decreased possibilities to substitute expensive domestic production with less expensive foreign supply. By contrast, opening these possibilities allows for this substitution effect and market price implications are less strong than in the benchmark (for both ‘tela-up\textunderscore 5’ and ‘tela-up\textunderscore 2.5’). However, the shape and direction of regional market price implications are quite robust.
Accordingly, decreasing foreign trade integration forces each economy to use more expensive domestically-produced iron and steel leading to stronger negative GDP implications compared to the benchmark (Figure D.12) and vice versa. This applies for all EU+3 regions except for GRC in cases where the level of foreign trade liberalization for iron and steel is much higher than in the benchmark.
Figure D.12: Sensitivity analysis: regional gross domestic product as percentage difference to baseline model run.
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