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

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Abstract

Climate change is one of the most serious threats to the human habitat. The required structural change to limit anthropogenic forcing is expected to fundamentally change daily social and economic life. The production of iron and steel is a special case of economic activities since it is not only associated with combustion but particularly with process emissions of greenhouse gases which have to be dealt with likewise. Traditional mitigation options of the sector like efficiency measures, substitution with less emission-intensive materials, or scrap-based production are bounded and thus insufficient for rapid decarbonization necessary for complying with long-term climate policy targets. Iron and steel products are basic materials at the core of modern socio-economic systems, additionally being essential also for other mitigation options like hydro and wind power. Therefore, a system-wide assessment of recent technological developments enabling almost complete decarbonization of the sector is substantially relevant. Deploying a recursive-dynamic multi-region multi-sector computable general equilibrium approach, we investigate switches from coke- to hydrogen-based iron and steel technologies in a scenario framework where industry decisions (technological choice and timing) and climate policies are misaligned. Overall, we find that the costs of industry transition are moderate, but still ones that may represent a barrier for implementation because the generation deciding on low-carbon technologies and bearing (macro)economic costs might not be the generation benefitting from it. Our macroeconomic assessment further indicates that anticipated bottom-up estimates of required additional domestic renewable electricity tend to be overestimated. Relative price changes in the economy induce electricity substitution effects and trigger increased electricity imports. Sectoral carbon leakage is an imminent risk and calls for aligned course of action of private and public actors.

Keywords: Iron and Steel, Process Emissions, Mitigation, CGE, Macroeconomics

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1. Introduction

Deep decarbonization of socio-economic systems requires substantial reductions of greenhouse gas (GHG) emissions (Rockström et al., 2017) 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 decarbonization analysis has been in focus recently, for instance in Wollenberg et al. (2016). By contrast, industrial processes used in cement, chemicals, and iron and steel production are subject to delicate peculiarities rendering deep decarbonization of these industries an even more complex issue. For the case of the production of iron and steel, existing studies have investigated reductions of process-emissions focusing mostly on incremental changes. Exemplarily, Arens and Worrell (2014) focus on efficiency gain potentials. Bednar-Friedl et al. (2012) explore the effectiveness of unilateral climate policies due to international leakage effects, though the strenght of investigated measures fall far short of deep decarbonization. Nabernegg et al. (2017) examine variants of both dimensions, marginal technological improvements and supporting climate policy instruments. However, complying with the Paris Agreement and its long-term objectives necessitates more than marginal improvement but rather a *"fundamental structural transformation"* (Zenghelis, 2015, p. 174) of the prevailing socio-economic system.

A recent study by Fischedick et al. (2014) gives a sophisticated and detailed analysis of three promising almost process-emission-free 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 carbon capture and storage (CCS), (ii) hydrogen-based direct reduction and (iii) electrowinning. Oxygen reduction of iron ores is decisive for achieving high-quality steel grades, thus, the current process emissions can be (i) either captured, or the current reductant coke can be replaced by either (ii) hydrogen or (iii) electricity. 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 *"show[s] 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.s' (2014) analysis is rich in technological detail, it lacks the incorporation of salient 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 main contribution of the present article is the macroeconomic assessment of such industrial decarbonization pathways. By explicitly taking these economy-wide feedback effects into account, we are adding crucial dimensions to the existing techno-economic literature of 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 supply of many other products and services. This increases the importance of analyzing indirect effects and macroeconomic implications.

In addition, our paper contributes to the literature on CGE models analyzing technology switches in carbon-intensive economic activities. Gillingham et al. (2008) and Löschel (2002) separately provide surveys on macroeconomic models focusing on the interaction of technological change and climate policy. However, the extant literature mostly focuses on the required level and design of policy instruments like carbon taxes. We aim at addressing the question of macroeconomic impacts for an industry decarbonization pathway irrespective of whether the required level is met, and thus possibly facing a misalignment of industry decisions (technological choice and timing) and climate policies.

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 and fully formulated in 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 European Union (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 for a low-carbon future of socio-economic systems.

The paper is structured as follows. Section 2 states the basic climate policy challenge we address and provides a technological background on iron and steel production, followed by a literature review on the issue investigated. The data and methodological approach are given in Section 3. Beyond, the baseline path and the scenarios of the WEGDYN model simulation are explained. Section 4 presents the results, structured along sectoral (market prices and sector output), macroeconomic (gross domestic product and welfare) and social implications (unemployment of skilled and unskilled labor) 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 greenhouse gas (GHG) emissions (Serrenho et al., 2016), which represent about 7.5% of total global GHG emissions[1] (UNFCCC, 2017). It is among the sectors facing particular challenges in decarbonizing future production. Evidently, continuous process improvements and retrofitting measures

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[1] For Annex I parties, excluding emissions from 'Land-use, land-use change and forestry'.

have 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 CO_2 process-emission-intensity of BFs using coke and sinter is about 1.3 tons of CO_2 per ton of steel with the current European industry average being slightly above (about 1.5 tCO_2/t steel; IEA, 2007, Kirschen et al., 2011). Traditional mitigation options include not only efficiency measures (with CCS as silver bullet), but also general output decline or switches to scrap-based steel production.

Efficiency measures. Rootzén and Johnsson (2015) highlight the challenges of decarbonizing the iron and steel sector in a scenario analysis approach applied to Scandinavian iron and steel production. They investigate the opportunities of CO_2 emissions abatement taking best-available technologies (BAT) into account. 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. 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 and scrap-based EAFs, their model takes variations in production levels for the German iron and steel industry into account estimating energy consumption and the corresponding CO_2 emissions. In order to reach long-term targets, all of the three cited studies conclude that significant emission reductions are only achievable either with a combination of BATs and CCS or a major decline in sector output. However, in many EU member countries CO_2 underground storage is forbidden (Shogenova et al., 2013).

Output decline. 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 medium term, particularly because of the continuous high demand in industrialized countries and expectedly rising demand for steel's product properties especially in developing and emerging economies (van Ruijven et al.. 2016). Iron and steel are also basic inputs for other mitigation technologies (e.g. turbines for hydro and wind power).

Scrap-based steel production. Some scholars and experts in the field argue for rapid system change to scale up recycling of steel scrap which would render primary iron and steel production and its associated CO_2 process emissions obsolete. Morfeldt et al. (2015) present another technology-rich optimization study integrating secondary steel production. Their result points to the fact that the accumulation of steel and scrap is subject to a time lag and primary steel production will still make up a share of at least 50% globally in 2050 (even for stagnating demand levels). Applying a dynamic stock-model, Pauliuk et al. (2013) project that the scrap-age may eventually commence in the latter half of the 21^{st} century. In addition, another salient advantage of primary steel production relates to steel quality, since the scrap-based route lacks sufficient quality of the scrap feedstock (Arens et al., 2017).

All these options clearly show that decarbonizing the iron and steel sector is a complex issue. This is particularly true for 'rapid decarbonization' (Rockström et al., 2017) in order to prevent non-linear climate change impacts which increase in likelihood after surpassing the 2°C threshold. With global decarbonization needing to be achieved before mid-century (Rockström et al., 2017), we focus on primary steel production technologies that allow for such a process-emission-free pathway.

Table 1: Stylized representation of investigated iron and steel technologies based on IEA (2007), Napp et al. (2014) and Sabat and Murphy (2017).

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

Notes: Crude steel or hot metal, respectively, represents the final product of each route. *Process-emission-free. #One-step process not requiring significant raw material preparation. •For the amount of indirect emissions, the GHG-intensity of the used electricity mix is decisive.

Table 1 sketches the two globally most important iron and steel production routes. In 2015, the blast-furnace basic-oxygen-furnace route (BF-BOF) and the route of carbon-based direct reduced iron (which is fed into an electric arc furnace; DRI-C-EAF) accounted for 74.2% and 25.2% globally, measured in tons of crude steel produced (WSA, 2016). The table also describes two promising break-through alternatives in a stylized fashion which are the route of hydrogen based direct reduced iron (fed into an EAF) and the plasma-direct-steel-production route (DRI-H-EAF and PDSP, respectively). 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 (the carbon molecule of coke together with the oxygen from the ore forms CO_2). 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.[2]

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[2] For details on specific energy consumption of each route, we refer to existing literature (Fischedick et al., 2014; IEA, 2007; Kirschen et al., 2011) because, above all, comparability across BATs is not straightforward due to different system boundaries set in extant work. Kirschen et al. (2011) provide a range for the emission factor of the DRI-C-EAF route (0.8-

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 (the hydrogen with the oxygen now forms H_2O). The same applies for PDSP, with the main advantage compared to DRI-H-EAF that this route is even more integrated allowing for oxygen reduction that is even possible at low temperatures using *"vibrationally excited molecular, atomic, and ionic states of hydrogen"* ('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 for industry scales). By contrast, PDSP is currently at 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). Both process-emission-free technologies, DRI-H-EAF and PDSP, are assumed to use hydrogen derived from water electrolysis based on a polymer electrolyte membrane (PEM) which currently represents the most expensive means of hydrogen generation (0.16-0.30 EUR/Nm^3 of H_2; IEA-ETSAP, 2017) but with the advantage of being totally carbon-emission-free if renewable electricity is used. Incumbent technologies for hydrogen generation (natural gas steam reforming and coal gasification) are cheaper (0.05-0.10 EUR/Nm^3 of H_2) but carbon-emission intensive.

Summarizing, technological options to mitigate process emissions occurring from oxygen reduction processes of iron ores are available at various technology readiness levels. The switch to such 'radically innovative' production technologies represents another crucial lever for climate policy measures (Arens et al., 2017; Napp et al., 2014). However, the complexity and size of such switches raises challenging questions. Even though further improvements and cost reductions are conceivable, we analyze in the following the macroeconomic implications of technology switch pathways assuming current state of technologies and costs. We do so taking not only system-wide feedback effects into account but particularly focus on further important dimensions neglected by the existing techno-economic literature. We identify winners and losers of this technology switch and highlight potential risks that come along with such decarbonization pathways. Thus, our assessment employing the technological status-quo depicts a lower bound of positive (and, respectively, an upper bound of negative) macroeconomic implications.

1.2 tCO_2/t steel) which is much lower than for BF-BOF (around 1.5 tCO_2/t steel). In addition, exergy in the European iron and steel sector is very high since waste heat and gas recovery is highly advanced, which are either used in the iron and steel making itself or downstream in rolling, casting, and finishing. The assumption here is that this will also hold for hydrogen-based technologies.

3. Data, Methodology and Scenarios

3.1. Iron and steel technologies

In the following, we compare the currently most prominent technology (BF-BOF) with both process-emission-free technologies in terms of economic costs and process-emission intensities. The data are derived from and cross-verified by several sources (CEPS, 2013; Fischedick et al., 2014; IEA, 2007; Kirschen et al., 2011; Sabat and Murphy, 2017; UBA, 2017) as well as from a stakeholder dialogue and refer to a European perspective, especially with regards to resource and energy costs (Table 2).

The industry 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' 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 0.05 EUR/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 0.03 EUR/kWh.

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

Techno-economic specification	**Conventional**	**High-cost**	**Low-cost**
Electricity price [EUR/kWh]	-	0.05	0.03
Technology [EUR/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 labor	5	4	4
Skilled labor	44	40	40
Capital (wear and tear)	48	48	48
OPEX [EUR/t steel]	**415**	**624**	**452**
Difference to BF-BOF [EUR/t steel]	**-**	**209**	**37**
Process emissions [tCO_2/t steel]	**1.5**	**-**	**-**
Break-even CO_2 price [EUR/tCO_2]	**-**	**139**	**25**
Investment costs [EUR/t steel]	**-**	**1,113**	**1,043**
CAPEX* [EUR/t steel]**	**-**	**105**	**99**

Notes: *Electricity costs for hydrogen production (plus EAF in the case of DRI-H-EAF) for 4380 kWh/t steel. **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 0.05 EUR/kWh for the otherwise more expensive DRI-H-EAF route and 0.03 EUR/kWh for the PDSP route. ***'Greenfield' facility assumptions: 2% interest rate, 12 years lifetime and investment phase. Main sources: Stakeholder dialogue; CEPS (2013); Fischedick et al. (2014); IEA (2007); Kirschen et al. (2011); Sabat and Murphy (2017); UBA (2017).

The most salient point is that unit costs of DRI-H-EAF steel is about 50% costlier than BF-BOF steel in their operating expenditures (OPEX); for given prices of primary factors (capital and labor) and intermediate inputs. Although the use of DRI-H-EAF eliminates costs with respect to coke, the iron and steel industry in the here presented analysis switches to hydrogen by means of polymer electrolyte membrane based water electrolysis. Unit costs of hydrogen generation are subject to strong variations in the prevalent literature as industrial scale generation is yet to be developed (stakeholder dialogue; IEA-ETSAP, 2017). Here, we set the boundary such that within our system of analysis - be it the iron and steel sector itself, or some other agent supplying hydrogen to the market – on-site hydrogen is generated via electricity purchased from the power generation sector.

Hence, electricity costs include the electricity demanded to generate hydrogen, as well as electricity for steel production implied by the use of an electric arc furnace (EAF). We apply a net electricity price of 0.05 EUR/kWh representing current lower bound of EU electricity prices for industrial purposes (E-Control, 2017; EuroStat, 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 compared to the BF-BOF technology.

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. The intermediate step of producing iron pellets is obsolete for this technology (Table 1 and the zero unit-costs for iron pellets in Table 2). Additionally, we assume a lower electricity price of 0.03 EUR/kWh for PDSP, thus capturing a broader range of techno-economic specifications of process-emission-free alternatives to conventional iron and steel production.

If we compare the OPEX per ton of steel of PDSP with BF-BOF, differentials remain positive (37 EUR/t steel; 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. Beyond, 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. Additionally, policy makers also have much more traditional instruments at hand ('command and control').

The OPEX differentials net of taxes (209 EUR/t steel for DRI-H-EAF and 37 EUR/t steel for PDSP; Table 2) and the process emission factor of 1.5 tCO_2 for BF-BOF would imply CO_2 prices of about 139 EUR/tCO_2 for the high-cost specification and 25 EUR/tCO_2 for low-cost specification, in order to achieve cost competitiveness with the conventional technology ('break-even CO_2 price'). Regarding capital expenditures (CAPEX) the question is whether the existing capital stock needs to be rebuilt in regular intervals (re-investments) or not and whether any new (climate neutral) facilities would increase additional CAPEX. Based on extensive stakeholder consultation, we assume that for the existing BF-BOF stock no major re-investments are necessary, but only expenditures to accommodate for wear and tear in order to maintain production. For building up new, climate-neutral, facilities, however, additional investments would become necessary and thus also additional CAPEX (as compared to the prevailing technology). If we additionally consider the necessary investment costs for the new facilities of the process-emission-free technologies, the cost disadvantages of this transition are even higher. Table 2 shows the unit investment costs and the associated CAPEX for both process-emission-free technologies calculated as annuity payments.[3] 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.

Considering a linear investment phase and corresponding lifetime of each facility (we assume 12 years for both) the derived annuities (CAPEX) are 105 EUR/t steel for DRI-H-EAF and 99 EUR/t steel for PDSP for a construction period of 12 years (Table 2). 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 CAPEX for a full installation of 'Greenfield' facilities.[4]

Finally, assuming that European iron and steel producers intend to keep the level of crude steel production at current levels, a switch from coke to hydrogen would necessitate large amounts of electricity. With 4,380 kWh of electricity needed for producing a single ton of steel and about 102 million crude steel tons currently derived by the BF-BOF route (WSA, 2016), additional electricity demand would amount to 450 TWh. This constitutes around 14% of current European electricity demand (total demand of 3,300 TWh in 2011 according to Capros et al., 2016) for switching only European iron and steel production

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[3] The derivation of annuity payments A follows the usual specification,

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

with S being the loan amount, i being the interest rate and t being the financing term.

[4] The unit costs in terms of 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 CAPEX of DRI-H-EAF and PDSP are assumed to be higher (27% and 19%, respectively) due to the assumption of higher costs regarding hydrogen generation and underground storage.

towards carbon-neutrality.

3.2. *Macroeconomic assessment: WEGDYN CGE model*

The described cost structures from the previous section form the basis for the macroeconomic analysis that allows for economy-wide effects and for revealing repercussions. For our empirical investigation, we apply the WEGDYN model, which is a standard global multi-sector, multi-region, recursive-dynamic Computable General Equilibrium (CGE) model (calibrated to GTAP9 database with benchmark year 2011; Aguiar et al., 2016). It is based on the static version specified by and fully formulated in Bednar-Friedl et al. (2012). The model 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). We deploy standard recursive-dynamic modelling devices in order to sequentially solve for static equilibria that are connected through a time dependent process of capital stock accumulation and labor force growth (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 combustions of fossil fuels and industrial processes.

Table 3: 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
ELY	Electricity	NEU	Northern Europe
EXT	Extraction	SEU	Southern Europe
FTI	Food and textile industries	WEU	Western Europe
GAS	Gas	AFR	Africa
I_S*	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	Tech industries	RASI	Rest of South & East Asia
TRN	Transport	REU	Rest of Europe
CGDS	Capital goods	ROI	Rest of industrialized countries
		USA	USA

Notes: *Represented by two subsectors: (i) crude steel mix production and (ii) rolling, casting and finishing (Figure 1).

WEGDYN comprises 16 economic sectors (Table 3) with special emphasis on the depiction of the steel production technology to be replaced. The nesting of Leontief-type gross domestic iron and steel production is shown in Figure 1. We disentangle the BF-BOF-route (currently responsible for the bulk of process-emissions within established steel technologies) from the original GTAP sector 'Iron & Steel: basic production and casting' (I_S). Within the model the conventional technology is thus treated as a separate production sector, which uses capital for 'wear and tear', labor, energy and material inputs (KLEM) to produce output. Together with the output of remainder of the original I_S sector representing 'rolling, casting and finishing', the produced crude steel is aggregated to a final iron and steel sector which eventually supplies to the market. In the scenarios, we activate either the 'high-cost' or 'low-cost' technology phasing out the conventional one. Thus, there is an interim phase comprising a mix of both, conventional and process-emission-free crude steel which, additionally, necessitates additional CAPEX (calculated as annuities) for repaying new facilities.

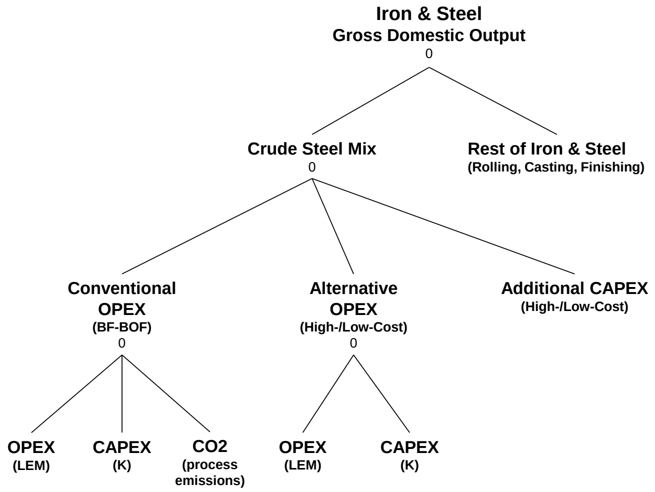

Figure 1: Leontief-nesting of gross domestic iron and steel production with distinct technologies using capital (K) for 'wear and tear', labor (L), energy (E) and material (M) inputs. Additional CAPEX (annuity-based repayments) accrue due to investments in new facilities.

Regarding the geographic aggregation, the model distinguishes between 17 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) 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 (Figure C.8 in Appendix C). 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 3 and C.5 in Appendix C for more details).

We differentiate between combustion based emissions (GTAP9, Aguiar et al., 2016) and process emissions (UBA, 2017; UNFCCC, 2017). Exogenous assumptions regarding CO_2 price and energy prices follow the projection of the World Energy Outlook 2016 (C.6 in Appendix C; IEA, 2016). Finally, the model is calibrated to World Bank unemployment rates of 2011 (Table C.7 in Appendix C; [dataset] WB, 2017), differentiating between skilled and unskilled labor, by introducing a minimum real wage (i.e. a fixed minimum ratio between nominal wages and the consumer price index). In the technology switch scenarios, changes in the unemployment rate emerge due to the endogenous real minimum wage. More details on model structure, macro closures and labor market modelling are given in Bednar-Friedl et al. (2012), Appendix A and Appendix B.

3.3. Scenario framework

The scenario framework is constructed by two different model simulation runs. 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 growth rates for gross domestic product (GDP) and labor force representing the second shared socio-economic pathway (SSP2; O'Neill et al., 2014) provided by 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) CO_2 price trajectory of the 'New policies scenario' (given for EU) reaching 46 EUR/tCO_2 in 2050 starting with 5 EUR/tCO_2 in 2015 (Table C.6 in Appendix C). The CO_2 price is modelled as fixed tax rate, hence there is no feedback, e.g. on emission allowance markets, and is implemented globally.

Further crucial baseline assumptions refer to generic energy market developments. We use the fossil fuel price forecast of the World Energy Outlooks (Table C.6 in Appendix C, IEA, 2016) 'New Policies Scenario' notwithstanding that the future development of coal, oil and gas prices is affected by large uncertainties. More specifically, there is uncertainty whether fossil energy prices decline or increase especially when it comes to phasing-out-fossils scenarios because not only demand but also supply might react. In a very illustrative manner, the demand curve for fossil fuels might shift downwards, for instance, due to political interventions like it is the case for coal in the German *'Energiewende'*. Contrary, also the supply curves of fossil fuels might shift, e.g upwards, because investors in the energy provision sector switch to e.g. renewable energy, thus reducing potential fossil output. Therefore, in the end the development of fossil energy prices will depend on whether, and if, how strong one effect dominates the other.

The second simulation (i.e. the technology switch scenario) introduces mitigation efforts exogenously via changes in the technological (and thus economic) structure. This simulation is then compared to the baseline simulation to isolate the economy-wide effects that are triggered by the exogenous introduction of technological changes in the iron and steel sector. Both simulations happen within the same 'baseline policy world', hence both simulations use the same CO_2 price trajectory in order to derive the isolated effect of the technology switch.

Applying such a scenario approach deviates from previous studies focusing on macroeconomic assessments of technology switches. Many macroeconomic studies investigate the design and thresholds of climate policy in order to derive the moment when ‘clean backstop technologies’ become competitive relative to incumbent technologies and, as consequence, begin to produce output (Gillingham et al., 2008, Löschel, 2002). By contrast, we analyze sectoral, macro and socio-economic effects when there is a misalignment of industry decisions (technological choice and timing) and climate policy, hence the competitive threshold might or might not yet be reached. To our best knowledge, there is no comparative study on macroeconomic implications regarding deep decarbonization of iron and steel production taking such misalignment into consideration.

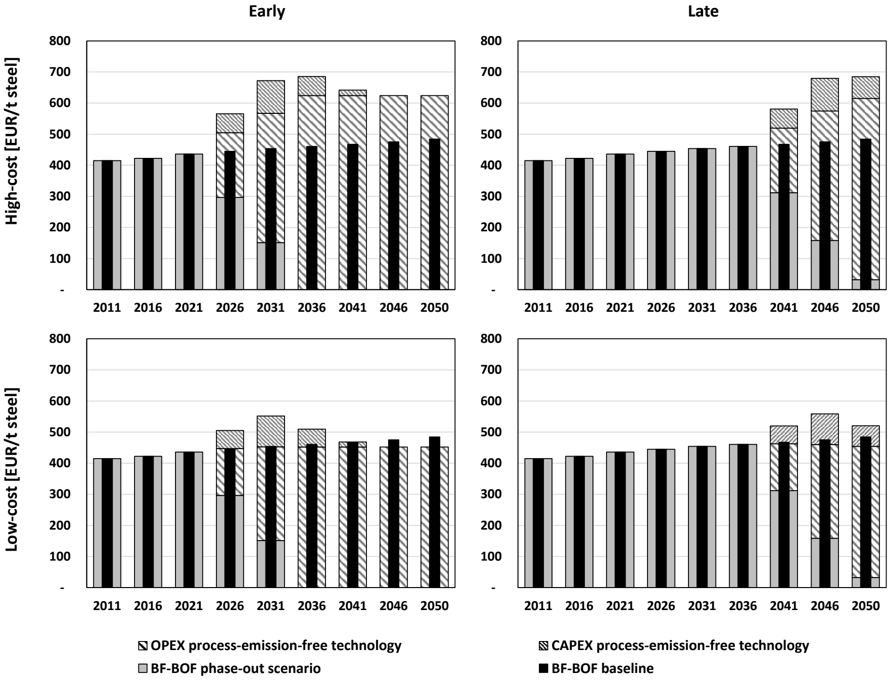

Figure 2: Operating and capital expenditures of the steelmix in EUR/t steel for the baseline and each scenario.

To capture uncertainty the imposed technological change distinguishes between four cases, constructed from combinations between (i)‘high-cost’ or ‘low-cost’ technological specifications and (ii) two industry timings – implementation starting in 2035 (‘late’) or in 2020 (‘early’) as shown in Figure 2. The investment into a process-emission-free technology is modelled to linearly substitute conventional iron and steel production over 15 years (while keeping capacities constant but allowing for endogenous feedbacks of demand). The incorporation of different timings allows us to estimate the implications of a more or less ‘ambitious’ (in the sense of ‘risk-taking’) industry behavior since the CO_2 price is increasing over time rendering a later technology switch more profitable.

Within our set of scenarios, the most plausible stakeholder-evaluated pathway of a technology switch is given by the late implementation of a ‘high-cost’ technological specification (shown in the right top panel of Figure 2) with the 3 alternative scenarios spanning up a range of future technology costs developments and industry decisions. For the detailed cost and CO_2 price assumptions, we see that only the implementation of a 'low-cost' specified technology would give a long-term (i.e. 2050) cost advantage compared to conventional iron and steel production (shown in the bottom left panel). As noted above, especially the temporary phase of additional CAPEX deteriorates relative costs of the steel mix compared to baseline iron and steel production across all scenarios. Hence, from this bottom-up perspective only the implementation of a 'low-cost' technological specification seems cost-competitive by mid-century.

4. Results

Throughout this section we report the results as deviation from the baseline scenario for each of the four scenarios. In general, the difference of relative costs for conventional and process-emission-free iron and steel production assumed in the four scenarios determine the sign and magnitude of macroeconomic implications across the various indicators. In addition, we are particularly interested in inter-sectoral implications in particular with regards to the switch in reductants from coke to electricity. Likewise, we report labor market effects and in macroeconomic feedbacks.

4.1. Sectoral implications

In the – according to stakeholders – most plausible scenario, an iron and steel industry transition starting in 2035 (labelled 'late') with a high-cost technology specification, the following market price implications for iron and steel, emerge for 2050: In the EU+3 (EU plus Norway, Iceland and Liechtenstein) market prices are higher as compared to the baseline in the range in between +0.7% (GRC) and +5.8% (EEU). When assuming a low-cost specification (but still starting in 2035) the price effects are in between -3.2% (WEU) and -0.5% (GRC). The assumptions on relative unit-cost developments of the conventional technology (including the underlying CO_2 price) and the 'high-cost' technological specification (including additional CAPEX) point to the misalignment of industry decisions and climate policy being ineffective to close the gap between conventional and 'high-cost' technologies by 2050. This is particularly the case during the phase of additional burdens regarding financing of new facilities. With a 'low-cost' technology specification, however, the CO_2 price trajectory levels out the cost disadvantage in OPEX of the alternative technology. In 2050, cost disadvantages accrueing from additional CAPEX are not relevant for early implementation (the period of repaying loans ends in 2043), and for late implementation are compensated by CO_2 prices cascading through the economy. Therefore, in this case we observe lower market prices for iron and steel relative to the baseline case. Note that in both techno-economic specifications, the strongest implications emerge in EEU and WEU, respectively, and the weakest in GRC. This is because the share of phased-out BF-BOF iron and steel production is high for the former and negligible for the latter region (Figure C.8 in

Appendix C). However, there are still small implications visible in GRC due to foreign trade.

If new technologies are implemented earlier (i.e. in 2020), we observe that in a 'high-cost' specification, iron and steel market prices are about +1.6% (GRC) to +10.6% (AUT) higher in 2031 than in the baseline case, however, the price-pushing effect during the transition declines thereafter. This is due to (i) the linearly increasing CO_2 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; ranging between +0.6% for GRC and +4.6% for EEU. By contrast, market prices for 'low-cost' iron and steel production range in between +0.6% (GRC) and +3.7% (EEU) in 2031 and between -5.0% (AUT) to -0.7% (GRC) in 2050.

Change in regional iron and steel market price

[%-diff to baseline]

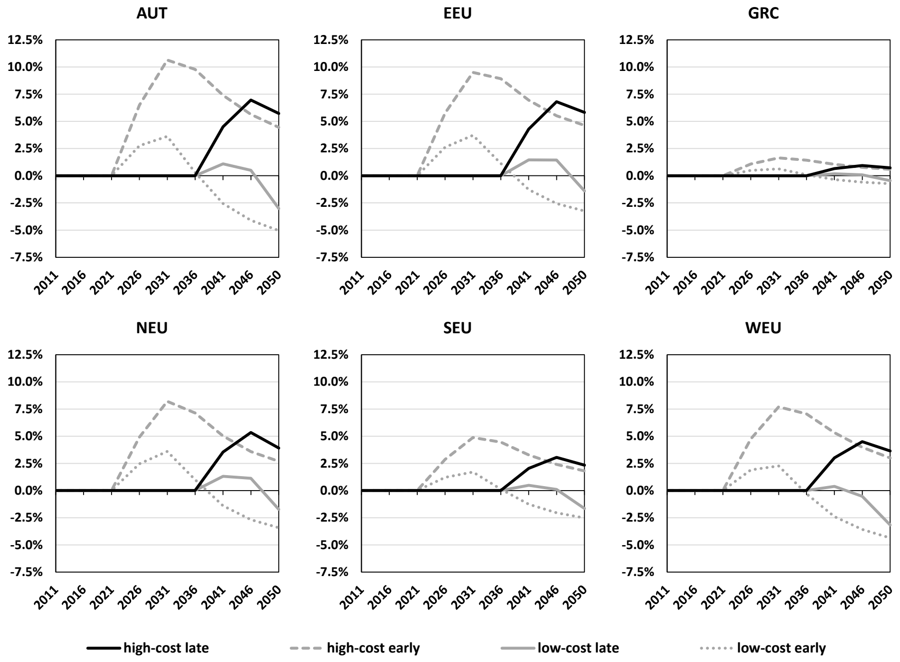

Figure 3: Regional iron and steel market price as percentage difference to baseline model run.

The relative market price changes for iron and steel translate into the following implications for sectoral outputs. In the 'high-cost' specification, regional market prices are higher than in the baseline scenario, demand for iron and steel decreases leading to lower sector output; measured in turnover (see respective bars labelled I_S in Figure 4). 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, these negative iron and steel sector output effects are getting smaller again.

The strongest relative output decreases are observed for AUT, since price effects are relatively strong in this region. For late (early) implementation of a ‘high-cost’ technology, iron and steel output implications range between -29.8% (-23.4%) for AUT and +5.3% (+3.7%) for GRC in 2050. In contrast, in the ‘low-cost’ specification regional market price effects for iron and steel lead to less severe and regionally redirected effects in 2050 with regional sector output changes in between -3.9% (-5.9%) in GRC and +11.7% (+28.7%) in AUT for late (early) implementation.

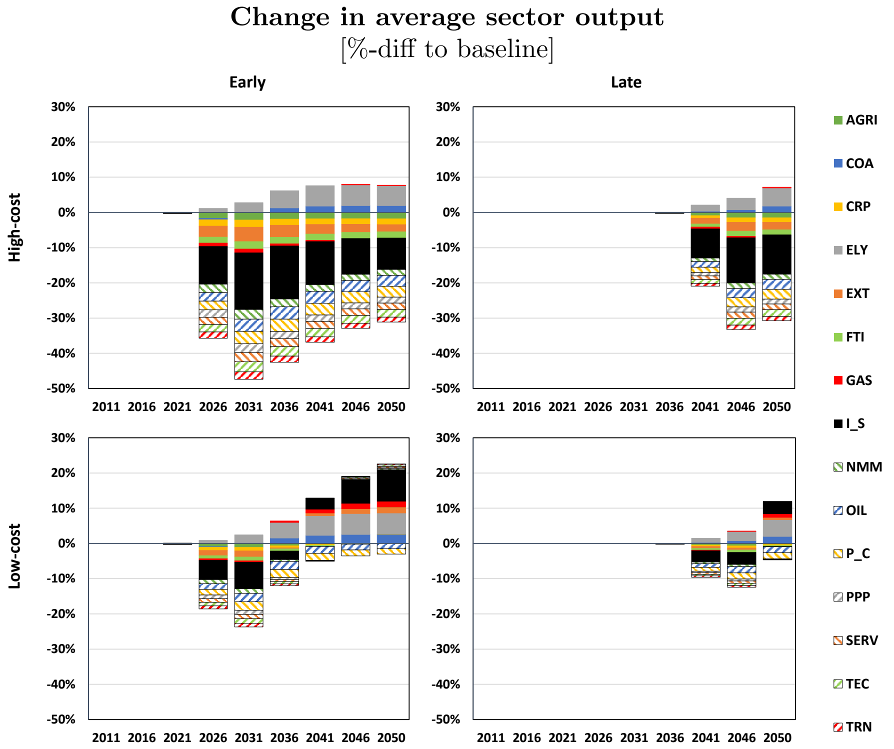

Figure 4: Winners and losers by sector (average of EU+3 countries) as output percentage difference to baseline model run. See online version for colors. Sector abbreviations: AGRI - Agriculture, COA - Coal, CRP - Chemical, rubber and plastic products, ELY - Electricity, EXT - Extraction, FTI - Food and textile industries, GAS - Gas, I_S - Iron & Steel: basic production and casting, NMM - Mineral products, OIL - Oil, P_C - Petroleum, coke products, PPP - Paper, pulp and paper products, SERV - Other services and utilities, TEC - Tech industries, TRN - Transport.

We now focus further on regional output implications of non-‘iron and steel’ sectors. The full trajectory for each scenario setting is given in Figure 4 but in the following we focus on effects in 2050. Due to higher prices for finished steel in the ‘high-cost’ technology switch scenarios (top row in Figure 4), the sectoral output 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 switch to ‘Electricity’ (ELY) in iron and steel production. This is why ‘Electricity’ gains the most in terms of sector output. Also sectors ‘Coal’ (COA) and ‘Gas’ (GAS) benefit marginally, since the assumed European electricity generation is still to some extent fossil-fuel based. All other sectors experience a loss because of the overall lower economic activity.

From a ‘low-cost’ perspective (bottom row in Figure 4), 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, and depending on the assumed electricity mix, the ELY, COA and GAS sectors 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. In general, all four scenarios reveal sectoral carbon leakage since the fossil intensity of electricity generation across regions is assumed to remain.

As highlighted in Section 3, the fuel switch from coke to hydrogen necessitates not only decarbonized, i.e. renewables based, electricity generation to prevent sectoral leakage, but might also involve large absolute increases in electricity demand across Europe. Refraining from system-wide effects of such a fuel switch, we would derive a substantial size of additional electricity demand as well as a significant regional spread (Table 4). Especially for countries like AUT, with high BF-BOF based crude steel production, such fuel switch scenarios in iron and steel would increase total economy-wide electricity demand by 45% from 66 to around 96 TWh. This highly questions whether such fuel switch in the iron and steel industry can take place using domestic potentials of renewables. For the case of AUT, the range of potentials for renewable electricity is estimated to be between 77 (Krutzler et al., 2015) and 103 TWh (Streicher et al., 2010), hence domestic potentials are only sufficient with the upper estimate, and this further neglects competition with increasing demand also from other sectors (electric mobility, housing appliances, other industry). Taking endogenous feedbacks across the economy into account puts these ‘additionality’ into perspective. Since domestic supply of electricity is composed of domestically generated and imported electricity (the ratio between both depends on relative prices and substitution possibilities), domestic electricity demand can react adaptively implying that the actual requirement for regional electricity generation is substantially lower amounting only to a range of 8-13% for AUT depending on the scenario. Thus, especially for countries with an overproportional BF-BOF share, where this barrier could apply, their embedding in the European electricity market could limit its relevance.

Table 4: Change of electricity (ELY) demand without (w/o) and with (w) system-wide feedbacks across regions.

	AUT	**GRC**	**EEU**	**NEU**	**SEU**	**WEU**
BF-BOF crude steel 2011* [Mio. t]	7	-	17	13	14	52
Additional ELY Demand** [TWh]	30	-	74	56	60	227
ELY demand 2011*** [TWh]	66	59	445	678	660	1,382
Total w/o feedbacks [TWh]	96	59	519	734	720	1,609
Change w/o feedbacks	**+45%**	**0%**	**+17%**	**+8%**	**+9%**	**+16%**
min of ELY demand feedback 2050#	8%	-1%	5%	3%	3%	9%
max of ELY demand feedback 2050#	13%	0%	6%	4%	5%	11%
Total w min of feedbacks [TWh]	71	59	465	696	681	1,508
Total w max of feedbacks [TWh]	74	60	471	704	691	1,530
Change w min of feedbacks	**+8%**	**-1%**	**+5%**	**+3%**	**+3%**	**+9%**
Change w max of feedbacks	**+13%**	**0%**	**+6%**	**+4%**	**+5%**	**+11%**

Notes: *WSA (2016); **4380 kWh/t steel (Table 2); ***Capros et al. (2016); #Min and max of ELY demand feedback effects in 2050 are taken across the four scenarios.

4.2. Macroeconomic implications

Figure 5 shows how the introduction of new iron and steel technologies translates into effects on regional GDP and welfare[5]. For a loss in relative sectoral cost competitiveness in terms of gross unit costs (including taxes on commodity inputs, primary factor inputs and CO_2) we reveal relative losses at the macroeconomic level in terms of GDP. This applies in particular to the 'high-cost' specification (shown in Figure 5) 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 -0.4% (-0.6%) for GRC and -2.3% (-2.7%) 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.

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[5] Welfare is calculated as Hicksian equivalent variation, representing the vector of consumption possibilities of the regional household.

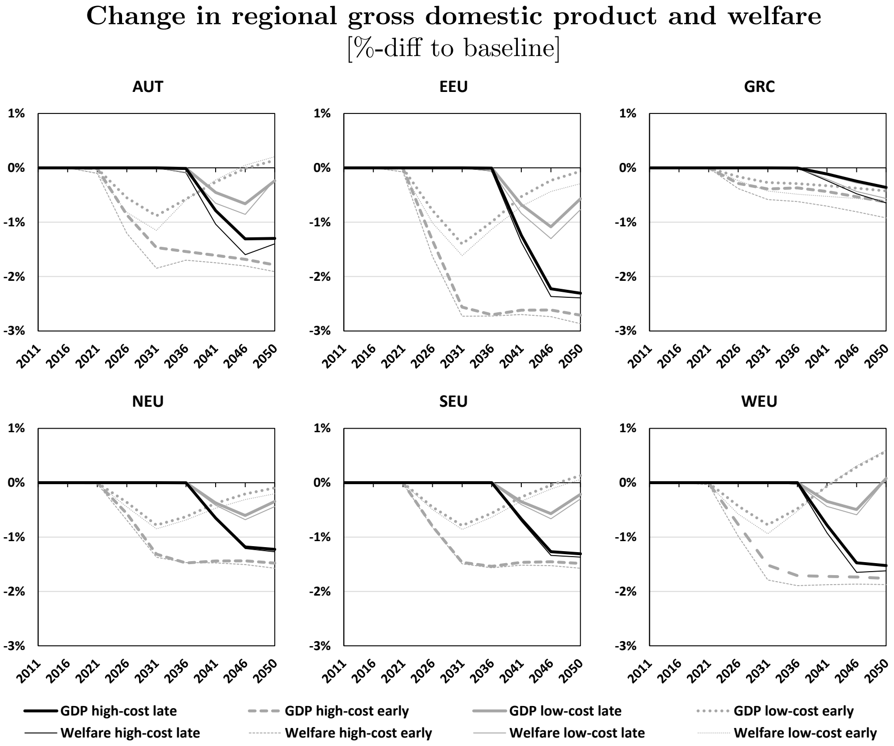

Figure 5: Regional gross domestic product and welfare as percentage difference to baseline model run.

For the ‘low-cost’ specification, long-term relative GDP range in between -0.6% in EEU (-0.4% in GRC) and +0.1% in WEU (+0.6% in WEU) for late (early) implementation. However, we see negative impacts in the interim phase of the transition pre-2050. This is due to the repayment of new facilities (vintage-based annuities) that drive up generation costs additionally, however only until 2036 with decreases afterwards. In addition, the CO_2 price is sufficiently high to re-establish cost competitiveness by 2050. Consequentially, long-term GDP levels converge to or are even higher than the baseline levels.

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 savings have to rise and thus consumption has to be reduced, leading to 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 favorable, 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. Labor 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 characterized by lower labor intensity (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), education and training of workers, power of unions, or market concentration. We model all but the last of these factors as 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 and unskilled labor (Figure 6).

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 labor intensity of the new technology. This is true for skilled and unskilled labor, with the effects being stronger for skilled labor.

By contrast, long-term unemployment rates tend to converge to baseline levels or are even lower in a ‘low-cost’ setting due to the stronger overall economic activity. However, during the capacity build-up and repayment period of 23 years (i.e. the repayments for PDSP facilities with 0.03 EUR/kWh), unemployment rates are slightly higher for EU+3 regions.

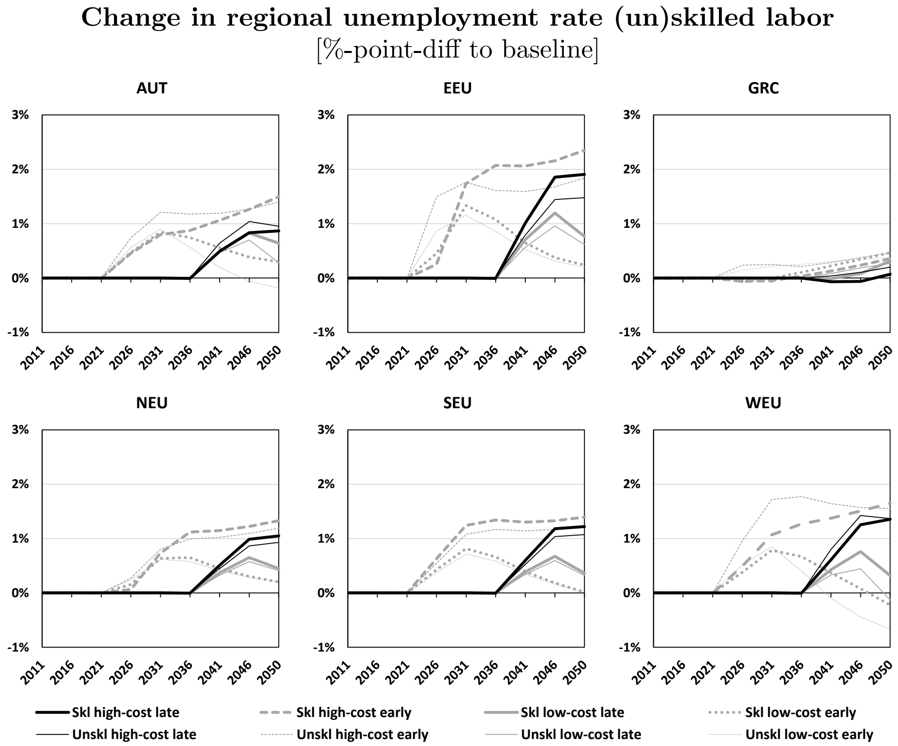

Figure 6: Regional unemployment rates of (un)skilled labor as percentage-point difference to baseline model run.

4.4. Foreign trade sensitivity

As shown by Alexeeva-Talebi et al. (2012), relaxing 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. Figure 7 shows sensitivities of GDP results by varying Armington trade elasticities[6] for the iron and steel sector. The benchmark development of an early implementation of a high- and low-cost technological specification is compared to scenarios where we strongly increase or decrease trade elasticities of the iron and steel sector by a factor of 10.

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[6] By using the Armington (1969) specification, we assume that domestic and foreign products are imperfect substitutes.

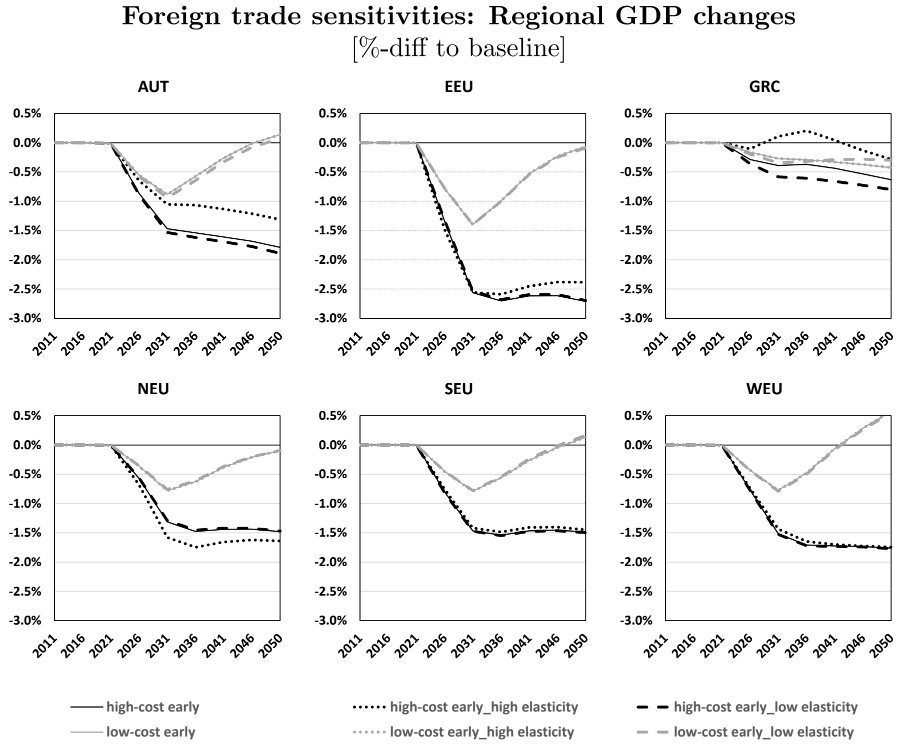

Figure 7: Foreign trade sensitivities: regional gross domestic product as percentage difference to baseline model run.

We find that decreasing the level of international trade integration regarding iron and steel in the model (i.e. decreasing Armington trade elasticities) leads to higher regional iron and steel market prices than in the benchmark comparison, due to decreased possibilities to substitute expensive domestic production with less expensive foreign supply. By contrast, opening these possibilities (i.e. increasing Armington trade elasticities) allows for this substitution effect and market price implications are less strong than in the benchmark comparison. We show that the shape and direction of regional market price implications are robust to variations in trade elasticity. 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 7) and *vice versa*. This holds across European regions, though we observe that stronger integration is at the expense of iron and steel production in NEU which is compensated by relatively more production in the remaining five regions (i.e. the relative market price increase is higher in NEU with stronger foreign trade integration).

5. Discussion & Limitations

A competitive (dis)advantage of technologies usually translates into respective GDP and welfare gains (losses). 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. We find that early implementation of a process-emission-free 'high-cost' technology increases the range of negative GDP implications in 2050 (-2.7% to -0.6% for early as compared to -2.3% to -0.4% for late implementation). If a 'low-cost' technological alternative can be established, long-term GDP implications seem to be more favorable and less sensitive to timing of the technology implementation (-0.4% to 0.6% for early compared to -0.6% to 0.1% for late implementation).

We derive similar conclusions for welfare effects (i.e. consumption possibilities). However, seen from a long-term position of economies (i.e. the rate of capacity utilization is assumed to coincide with its 'natural or 'normal rate), negative transition 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. Building up new capital stock with transition investments, and the associated initially negative welfare effects, might be a barrier 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 the labor factor crude steel production is more intensive in, skilled labor (Table 2), is more likely to suffer from an iron and steel transformation in terms of rising unemployment, especially in an early technology implementation scenario. Based on these system-wide implications, our analysis supports the bottom-up assessment of iron and steel technologies by Fischedick et al. (2014) stressing that increased research and development efforts are needed for driving down operating costs of process-emission-free iron and steel technologies. Supportive policy measures during the transition (in order to limit the additional repayment burden) should be a cornerstone of integrated climate and energy policy packages.

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. This finding coincides with the trans-disciplinary work of Lechtenböhmer et al. (2015) who investigated low-carbon re-industrialization scenarios in basic material sectors in the German region of North Rhine Westphalia. However, their study focuses on technological potentials and lacks (macro)economic dimensions which is why the authors acknowledge that *"system approaches are needed to advance understanding of how these [industry decarbonization pathways] impact other sectors [and consumers]"* (Lechtenböhmer et al., 2015, p. 11424; modification in brackets by the authors). Our study is a first step in providing such system approaches and stresses the importance of increased penetration of renewable electricity supply.

Considering the regional context, additional renewable electricity demand from the iron and steel sector due to the technology switch ranges in between 0% (GRC) up to 45% (AUT) if macroeconomic feedbacks are excluded. This large spread emerges because, currently, AUT is a country with comparably large iron and steel production using the conventional BF-BOF route. By contrast, steel production in GRC is mainly scrap-based, thus, the domestic steel sector is not affected by our assumed technology switch pathways. However, we show that excluding macroeconomic feedback effects leads to a substantial overestimation of additional electricity demand for hydrogen generation. Our model results reveal that the change in total domestic electricity demand only ranges in between -1% (GRC) up to 13% (AUT) because domestic demand can react to relative changes in electricity prices with increased electricity imports.

This finding adds a crucial dimension to discussions around domestic renewables potentials and dependency on electricity imports. The electrification of a single industry has far-reaching economy-wide implications, thus including feedback effects of other economic agents gives a more fully-fledged picture. We acknowledge that the assumption on electrifying only iron and steel production neglects further mitigation pathways e.g. electrifying other economic segments like transportation. For the sake of isolating macroeconomic implications of iron and steel decarbonization, we refrain from this aspect which certainly is a limitation.

As with every top-down assessment comparing structural changes at the scale of technologies, further caveats are relevant mentioning. In the analysis at hand, it is assumed that the produced iron and steel products are homogenous (i.e. there is neither a differentiation between rolled, casted or finished steel, nor a difference regarding qualities, i.e. steel grades). However, in order to be able to give insights into the economy-wide effects of such a transition of the iron and steel sector, such a trade-off between sectoral resolution and additional insight seems reasonable.

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 e.g. unilateral carbon pricing, the question of credibility, timing and extent of relocation due to unilateral top-down measures remains untouched in our analysis of very specific industry decision pathways. However, for the assumed global CO_2 price trajectory, our model shows relatively moderate increases in iron and steel production outside of Europe compensating for the output losses due to the technology switch within Europe. In modelling terms, this international leakage effect occurs mainly due to the assumed unit-cost disadvantage of alternative technologies (‘competitiveness’ channel of leakage; Bednar-Friedl et al., 2012) and the model specific assumption of fully flexible price adjustments. However, this price flexibility can be criticized because, in fact, BF-BOFs are characterized by very long lifetimes - experts in the field argue that there is no clear end-of-lifetime. Hence, immediate and overly extensive physical relocations of production (i.e. significant capacity additions) are at least restricted in the short term.

Future research directions could scrutinize three 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. In this respect, all four channels of leakage ('competitiveness and industrial relocation', 'international fuel market', 'terms-of-trade impacts', 'technology diffusion'; Bednar-Friedl et al., 2012) should be explored further for such technology-driven industry decarbonization pathways. 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). Lastly, the unclear end-of-lifetime of blast furnaces reflects a substantial advantage compared to new investment requirements in alternative technologies on a greenfield. Thus, the design of financial instruments (public and private) could be given a much more prominent role for incentivizing such fundamental structural transformation. Additionally, given the extraordinary long lifetime of blast furnaces, future investigation of climate policy design should explore the risk of stranding of assets when imposing such a fundamental re-structuration from coke-based to hydrogen-based technologies.

Despite the mentioned limitations of this study, we find that on a macroeconomic scale, the analysis is valuable regarding specific *a priori* defined scenarios. These represent a starting point for future investigations regarding uncertainties especially related to exogenously set model parameters and assumptions. To this end, variations in climate policies (e.g. CO_2 pricing) and socio-economic background characteristics (e.g. different SSPs) should be investigated in future work. The macroeconomic model choice is also a starting point for further research, as the CGE analysis assumes a supply-side constrained framework taking a long-run macroeconomic position (i.e. assuming long-run average capacity utilization in producing the aggregate of investment, intermediate and consumptions goods).

6. Conclusion

Iron and steel production in global economic value chains is of general purpose character because its versatile products serve directly as intermediate input and thus indirectly in many downstream production sectors (e.g. the automotive industry, fossil and renewable energy provision, buildings, *et cetera*). Fundamental structural changes in iron and steel production therefore raise the question of sectoral, macroeconomic and social implications. We carry out and present results of a top-down macroeconomic analysis of a currently contemplated technological change in the European iron and steel sector towards carbon-neutrality, based on existing techno-economic bottom-up literature.

Process emissions account for a significant share of iron and steel sector GHG emissions, with traditional mitigation options (i.e. efficiency measures, substitution possibilities, general output reduction, scrap-based steelmaking and end-of-pipe solutions like CCS) being insufficient or (legally) constrained for complying with long-term climate policy objectives. Our analysis investigates switches in the type of production process towards process-emission-free iron and steel technologies required for reaching climate targets, even though the current degree of alternative technology maturation varies considerably. We explore two alternative technologies: First, direct reduction, where hydrogen substitutes as reductant for coke in the current blast furnace route. Second, plasma-direct-steel-production, also based on hydrogen. With electricity as the new crucial input (needed for hydrogen generation), the electricity price is a core determinant for the competitiveness of a new route. For current industrial electricity prices (around 0.05 EUR/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, given current intermediate input prices. Plasma-direct-steel-production, however, is more competitive than even the conventional technology, when we can establish e.g. an industry electricity price of 0.03 EUR/kWh and modest CO_2 pricing (46 EUR/tCO_2 in 2050).

For the techno-economic variation investigated, we show respective sectoral (market price, sector output), macroeconomic (GDP, welfare) and labor market implications (employment of skilled/unskilled labor) while differentiating between relatively early (2020) and later (2035) implementation of process-emission-free iron and steel technologies phasing out the conventional blast furnace route. Our scenario setting allows analyzing macroeconomic implications of such technology switch pathways when industry decisions and climate policies are misaligned. The techno-economic cost specification of process-emission-free technologies relative to the conventional technology determines our macroeconomic results, however being complemented by macroeconomic feedback effects and policy (i.e. CO_2 price). Consequentially, we find that if thresholds of cost-competitiveness are met, macroeconomic benefits are possible. However, disregarding sectoral interdependencies implies shifts from process-related emissions in the iron and steel industry to combustion-based emissions in energy supply sectors (like coal and gas industries), particularly if electricity generation remains fossil fuel intensive. This clearly points to the requirement of an aligned course of action. A core finding of our assessment relates to the degree of additional renewable electricity demand due to the switch of reductants from coke to hydrogen and is shown to be substantially overestimated if macroeconomic feedbacks are neglected.

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Appendix A. Recursive-dynamics

Like the static version (Bednar-Friedl et al., 2012), the WEGDYN model includes one regional household eventually providing primary factors (labor 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 (the extensive database of IIASA, 2017) provided by KC and Lutz (2017). The calculated regionally-weighted labor force growth rates (15-64-year-old population) are shown in Figure C.9. Hence, labor endowment (representing income) in this analysis develops according to the calculated SSP2 labor force growth rate gr_{LF} assuming a time-constant participation rate. In order to ensure that labor endowment/income growth is positive (being a long-term fact) we additionally include a globally assumed labor-augmenting productivity growth rate of 1%. Hence, equations A.1-A.2 show the development of the regional specific labor endowment in our model with L being total labor income, t representing time and gr_L being the effective labor income growth rate:

$$L_{t+1} = (1 + gr_L)L_t; \tag{A.1}$$

$$gr_L = gr_{LF} + 0.01 \tag{A.2}$$

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:

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

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 C.9) with exogenous and constant effective labor 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 (Delpiazzo, 2010). A change in factor endowments (in our case increases in the capital stock, capital income and labor 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 labor 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. Labor market modelling

The baseline model runs are calibrated to benchmark 2011 regional unemployment rates retrieved from World Bank data ([dataset] WB, 2017) which are held constant throughout the simulation horizon. Hence, the share of labor hours actually employed is exogenously fixed and the real wage is endogenous. In order to look at labor 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 labor hours employed are endogenous. This allows to identify the labor market implications of installation of the new technologies. Hence, the implications given in Figure 6 represent the percentage-point deviation to the benchmark regional unemployment rates.

Appendix C. Additional data

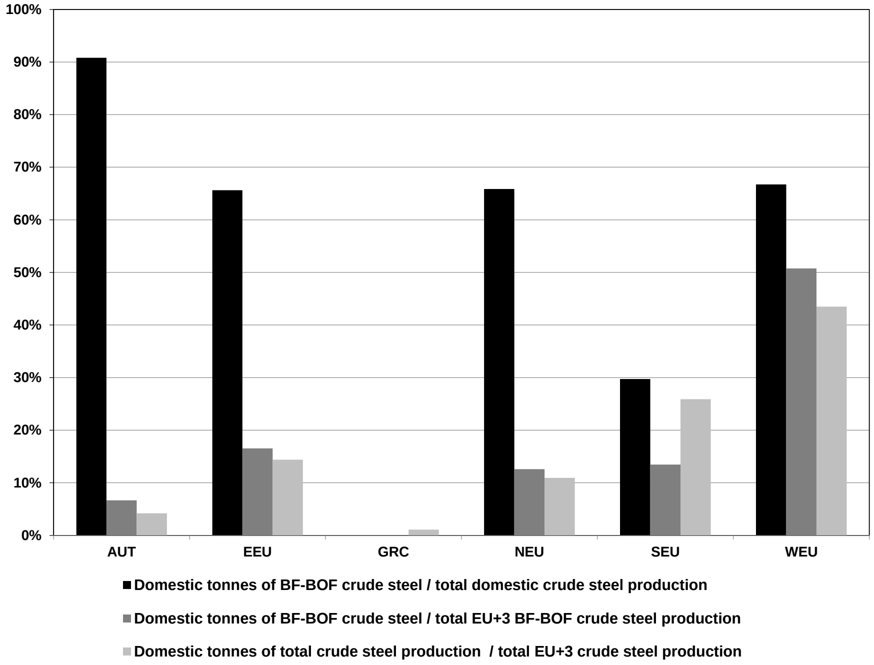

Figure C.8: BF-BOF crude steel production 2011 in EU+3 countries based on WSA (2016).

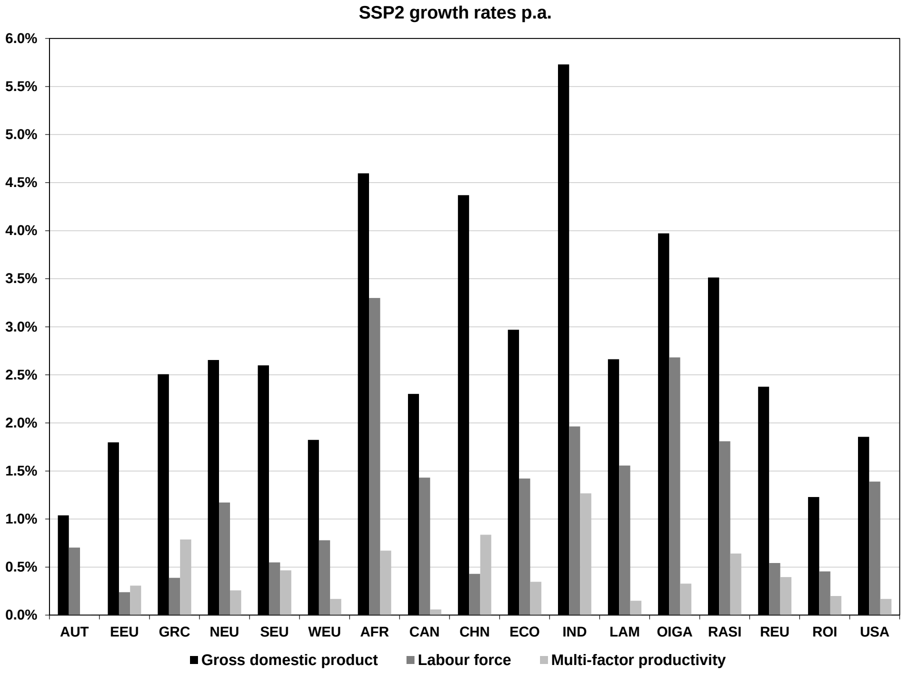

Figure C.9: Annual SSP2 growth rates; GDP data (based on Cuaresma, 2017) and labor force data (based on KC and Lutz, 2017) retrieved from the IIASA (2017) data base; multi-factor productivity calibrated.

Table C.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, Brunei 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, Makedonia, Serbia, Moldavia
ROI	Rest of industrialised countries	Australia, New Zealand, Japan
USA	USA	USA

Table C.6: CO_2-price and fossil fuel price forecast based on IEA (2016) assuming EUR_{2011}/USD_{2011} exchange rate of 0.7; EXT price growth rate assumed to be 0.009% p.a. based on stakeholder dialogue.

	Global CO2 price [EUR_{2011}/tCO2]	**Coal** [price index normalised to 2011]	**Oil**	**Gas**	**EXT**
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 C.7: Regional unemployment rates benchmark year 2011 for unskilled (ur_unl) and skilled labor (ur_skl) ([dataset] 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%			