Macroeconomic implications of a 2°C-compatible transition path in the European iron and steel industry

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Abstract

1. Introduction

The Paris Agreement to address climate change entered into force on the 4th of November 2016. Nonetheless, taking recent research on the nonlinearity of climate sensitivity into account (cf. Timmermann et al., 2016), the urgency of climate mitigation action can not be exaggerated. The iron and steel sector, accounting for 25% of global industrial emissions in 2012 (Serrenho et al., 2016), is among the sectors facing particular challenges in decarbonizing future production. Evidently, continuous process improvements and retrofitting measures have led to a decoupling of greenhouse gas (GHG) *combustion* emissions and steel output in the past. However, in steel production another emission category, *process* emissions, accounts for about half of global GHG emissions of the iron and steel sector. This is due to the current technology used, the blast furnace (BF) route. It is the globally most utilized steel-making technology (with a share of about 90%) (CCC, 2015; WSA, 2016) and uses coke as reducing agent which results in GHG process emissions. These process emissions can only be reduced i) by reducing BF-steel production, ii) by increasing the efficiency of BF-steel production, or iii) by switching to a different production process (Napp et al., 2014). Today, steel serves as an input in a vast range of downward applications, from plates, bars and stripes to automobile chassis or rotor blades of wind power plants (CCC, 2015; BCG, 2013). In the following we assume a continuous demand for and use of steel in the forthcoming decades, and analyse the macroeconomic implications of switching to a carbon-free production technology.

In Austria, a country with a large iron and steel sector (2.7% of gross value added to GDP in 2014; Statistik Austria, 2016a), the major steel producer already anticipates the requirement for such a technological regime shift. Its publicly available firm policy credibly promotes a strategy of net zero GHG emissions by 2050. Within the EU-H2020 project *TRANSrisk*[1] a specific transition path up until 2050 was developed in the course of a comprehensive *´desired futures´* process involving all relevant stakeholders, a path that is in compliance with the Austrian contribution to achieve the global 2°C target. Taking the steel producers' strategy as a piece of a broader transition pathway, we here ask: *What are the macroeconomic implications of a 2°C-compatible transition pathway in the European iron and steel industry and which consequential risks and uncertainties can be derived?* Consequential risks refer to *ex post* risks of an implemented policy or transition technology, respectively.

[1] Transitions Pathways and Risk Analysis for Climate Change Mitigation and Adaption Strategies (http://transrisk-project.eu).

Methodologically we deploy a dynamic-recursive multi-region multi-sector computable general equilibrium (CGE) model (based on the static version specified by Bednar-Friedl et al., 2012) and implement a transition pathway for the iron and steel sector up to 2050. More precisely, we simulate a linear and bidirectional technology switch from BF-steel to steel derived from direct reduced iron which uses hydrogen from electrolysis (DRI-H_2). This switch is integrated in all countries participating in the European Unions' Emission Trading Scheme (EU-ETS). The bottom-up cost assessment of a representative European DRI-H_2 technology is based on a stakeholder dialogue. The background characteristics of the model are driven by socio-economic pathway assumptions (SSP2) (O'Neill et al., 2014; van Vuuren et al., 2011).

The paper is structured as follows. Section 2 briefly discusses the technological background and the specificities of the transition in European iron and steel production up until 2050. The methodological approach is explained in Section 3 where we also briefly present research related to data and the applied model as well as the model calibration. The reference path development of the model simulation is also part of this section. The presented analysis is work in progress which is the reason why we restrict this working paper to a preliminary discussion of results (Section 4) and refrain from generic conclusions.

2. Low carbon transition in the iron and steel sector

2.1. Technological background

Blast furnaces are the traditional means of steel making (approximately 90% of global applications according to CCC, 2015 and WSA, 2016) and reduce iron ore into pig iron with coke being the reducing agent. This chemical process removes oxygen molecules and is decisive for the final quality of steel. The pig iron is refined in a basic oxygen furnace and the resulting steel is processed for a wide range of down-stream applications. The essential usage of coke in this traditional production route can be seen in the salient and recently rising share of *process* emissions, for instance in the Austrian iron and steel sector where, in 2014, 85.5% of the sectors' total GHG emissions are attributable to the described reduction process (Figure 1). Simultaneously GHG emissions from *combustion* declined. Note, that in 2014 the Austrian iron and steel sector accounted for 15.5% of national GHG emissions (without LULUCF[2]/without indirect emissions) with absolute emissions rising since decades, although output per emissions improved – the "classical" rebound effect.

The primary technological alternative is represented by conventional Direct Reduced Iron (DRIconv). It traditionally uses natural gas derived methane and converts it into a mix of carbon monoxide and hydrogen. The latter component then serves as reducing agent for the iron ore. Thereafter the directly reduced iron is refined into steel in an electric arc furnace (CCC, 2015; BCG, 2013). The accompanying GHG *process* emissions primarily stem from the part of the chemical reaction in which carbon monoxide reacts with oxygen resulting in carbon dioxide emissions. The remaining part of the reaction refers to hydrogen and oxygen which results in water (vapour). To avoid the carbon dioxide process emissions of the chemical reaction, several currently ongoing research projects investigate prototype plants which open the possibility to derive hydrogen solely from electricity (electrolysis, or "power-to-gas", respectively) and not from methane. Hence, successful research and development, in particular, concerning purely hydrogen-based DRI, electrolysis-based hydrogen as well as renewable electricity technologies, could make the 21st century steelmaking fully decarbonized.

[2] Land use, land use change and forestry.

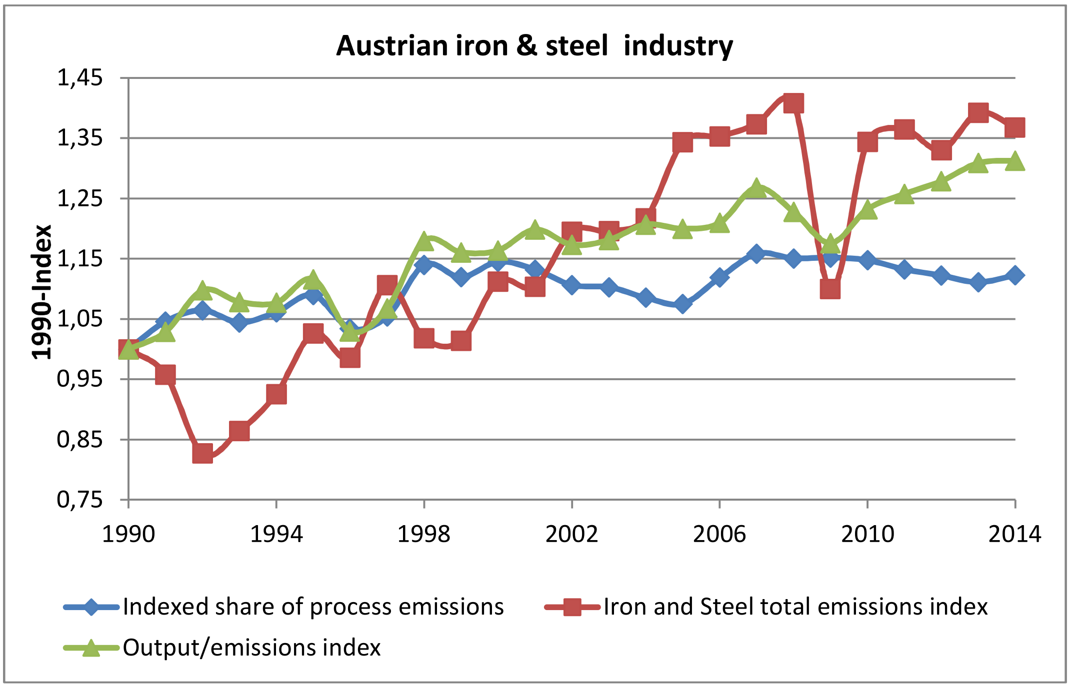

Figure 1: 1990 based index showing the development of: (i) the share of process-related GHG emissions in the Austrian iron and steel sector, (ii) GHG emissions of the Austrian iron and steel sector and (iii) GHG emission efficiency (output/emissions) (Sources: EEA (2016); World Steel Association (2016); own calculation and representation)

Complementing this perspective with technological background information originating from the GTAPv9 data base, in 2011 the Austrian and Greek iron and steel sector has been relatively more capital intensive than the corresponding sectors in the remaining European regions. Additionally, the Austrian and Eastern Europe iron and steel sector has been relatively more important in terms of their contribution to gross domestic production (Figure 2).

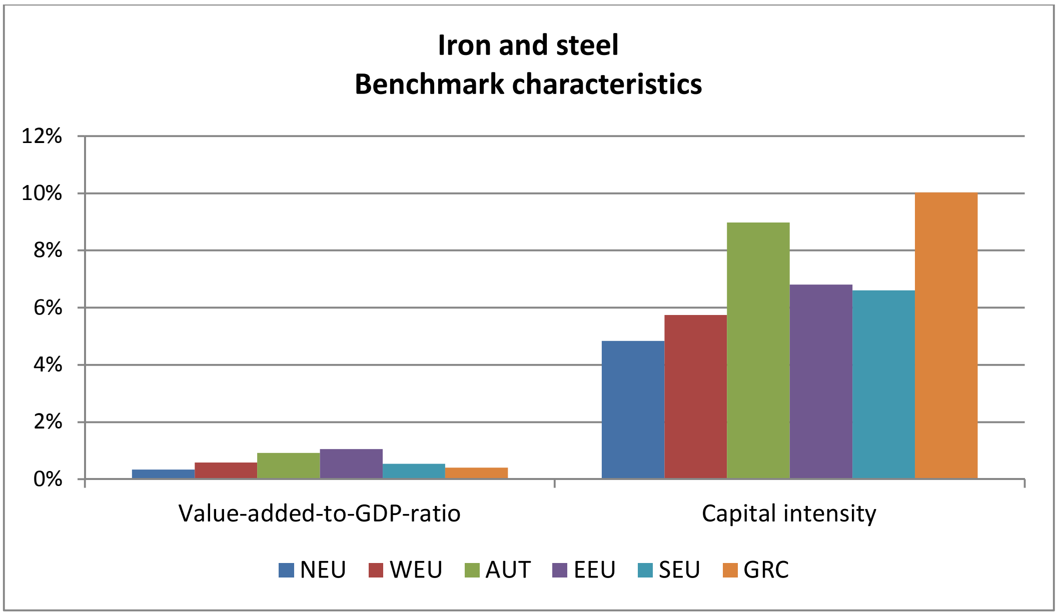

Figure 2: Value added of the iron and steel sector relative to GDP and capital intensity of the iron and steel sector in the European model regions (GTAPv9) in 2011.

2.2. Transition in the iron and steel sector

The pursued window of opportunity in the iron and steel sector relates to the already mentioned technological reorientation towards DRIconv. The conventional technology uses a mix of carbon monoxide and hydrogen derived from methane. Hence, a switch from BF to DRIconv would still mean profound reliance on GHG process emissions in the first place. However, the strategy of the Austrian (but also other European) iron and steel producer(s) is to substitute methane-based hydrogen by hydrogen produced by means of electrolysis, using 100% electricity from renewable energies. In this respect it is crucial to distinguish between barriers of implementation for DRIconv based on methane and for DRI-H_2 based on hydrogen.

For the production of hydrogen, central natural gas reforming (CGR) still outperforms central water electrolysis (CWE) in terms of conversion efficiencies (DOE, 2017). The former directly releases GHG emissions. For the latter grey emissions depend on the prevalent electricity mix. However, the comparably higher energy intensity of CWE comes with higher costs. In Northern America, a significant higher share of iron and steel production comes from DRIconv than in Europe (CCC, 2015; WSA, 2016). This partly stems from lower methane prices due to the massive uptake of shale gas extraction in recent years (EIA, 2017, EC, 2016). Thus, without political interventions or technological breakthroughs the prospect for large scale CWE-derived hydrogen production appears questionable. In the EU the vast majority of iron and steel is derived from BF (CCC, 2015; WSA, 2016). This relates partly to the historically accumulated BF capacity and knowledge stock (*'path dependency'*). Hence, a similar prospect for CWE-derived hydrogen applies for Europe, where, in the first place, the switch from BF to DRIconv is prevented by relatively low coal prices (compared to methane). However, even converging coal and methane prices would still mean that CWE derived hydrogen is in the cost perspective inferior to CGR.

We can report this barrier by the analysis and difference in technology-specific unit costs of steel which are reported in Table 1 and represent direct costs without overheads. These cost data are derived from publicly available sources (cf. WSA, 2016; CEPS, 2013) and a stakeholder dialogue. They refer to a European perspective especially with regards to energy markets (cf. EC, 2016).

Technology-specific cost component	**BF**	**DRI-H_2 Scenario Ia**	**DRI-H_2 Scenario Ib**	**DRI-H_2 Scenario II**
Fossil fuels (coal, oil gas)	84	0	0	0
Electricity	0	219	219	131
Resource extraction	189	273	189	157
Services	45	40	40	40
Unskilled labour	5	4	4	4
Skilled labour	44	40	40	40
Capital goods / (Re-)Investment	131	131	131	126
Total	**498**	**707**	**623**	**498**

Table 1: European and technology-specific unit costs of steel (stakeholder dialogue and CEPS, 2013). For DRI-H_2 two distinct scenarios are applied. Differences in totals are due to rounding.

The most salient point is that DRI-H_2-steel is more costly than BF-steel by about 42% in per unit terms (Table 1), for given prices of primary factors and intermediate inputs, which refers to Scenario Ia in our analysis. Although the usage of DRI-H_2 cuts down costs with respect to fossil fuels (FOS), the iron and steel industry needs now hydrogen for the reduction of iron ore. Unit costs of hydrogen exhibit strong variations in the current literature as industrial scale production of hydrogen is yet to develop (stakeholder dialogue, and CCC, 2015). This grounds our decision to work with two scenario settings for the DRI-H_2 route, where the costs of hydrogen are covered under electricity costs, together with the electricity for steel production implied by the use of an electric arc furnace. The second reason is the uncertainty in costs for primary resources. While we know that they increase, as the switch to DRI-H_2 necessitates the use of the relatively more expensive Hot Briquetted Iron (HBI) instead of (sintered) iron ore (cf. the "Steel Production Scheme" in IEA, 2007, p. 98, Fig. 5.2), there is no reliable information on the level of this increase in the long term. The remaining technology-specific unit cost components are differentiated between services, unskilled labour (about 10% of overall labour input) as well as skilled labour, and capital costs.

	Scenario	
	Ia / Ib	**II**
Gross investment [Bn. €]	8.00	7.50
Interest rate [%]	2.00	2.00
Investment phase [y]	20	20
Life time [y]	15	15
Capacity [1000 t]	7.50	7.50
Annuity factor	7.80	7.80
Annuity costs [€/t]	83	78

Table 2: Investment unit costs for BF and DRI-H_2 are equal in Scenario Ia and Ib. Scenario II assumes higher full load hours for electrolysis plants leading to lower investment unit costs for DRI-H_2 only.

The difference in the technology-specific investment unit costs of steel originates in the components attributable to financing new plant capacities. Costs of maintenance and repair (about 48 €/t) on the other hand are roughly the same across technological routes. For financing costs we calculated the annuity payment per tonne of steel at about 83 €/t for both technological routes (Scenarios Ia and Ib). This is based on bottom-up stakeholder information about gross investment, plant capacity, construction time, life time and an assumed long term macroeconomic interest rate, all as shown in Table 2. We derive total investment costs which exceed the regional specific value of total investment (the principal debt) by about 17%. Note that the total unit costs for DRI-H_2 include those for hydrogen which is based on the assumption that electrolysis plants operate at 4,000 full load hours. In Scenario II we assume that low-cost renewable electricity is available sooner than expected which increases the electrolysis operation up to 6,500 full load hours. This corresponds to lower electrolysis plant capacities and decreases capital costs to 78 €/t. Together with costs of maintenance and repair of about 48 €/t, this adds up to investment unit costs of about 126 €/t (cf. Table 1).

By assumption steel production in EU member states remains constant throughout the time horizon (Table 3) using regional specific crude steel production data from WSA (2016). Additionally we assume that all steel producers in EU member states face the same technology-specific unit costs as presented in Table 1. Note that gross investment for DRI-H_2 is assumed to start in 2031, such that production along this route commences five years later, i.e. in 2036. Overall construction time is assumed to take until 2050. Hence, in the period of 2031-2050 the model sector "TEC" (comprising subsectors 'construction', 'machines', 'tools', etc.; cf. Table 6 in the Appendix) receives annually a linearly computed payment (annuity) from the iron and steel sector.

Benchmark year 2011	**AUT**	**GRC**	**NEU**	**WEU**	**EEU**	**SEU**
Crude steel production [Mio. t]	7.47	1.93	19.50	77.55	25.68	46.21
Gross domestic output [Mio. €]	8 354	2 987	45 228	127 616	39 267	68 967
Full costs [€/t]	1 117.79	1 544.54	2 319.16	1 645.65	1 528.86	1 492.61

Table 3: Regional specific full costs of steel production in the benchmark year 2011. Crude steel production (WSA, 2016); Gross domestic output (GTAPv9).

Additionally, it has to be noted that a combined full costs index (representing unit costs and overheads of a mix of steel derived from BF and DRI-H_2 during the phase out) increases faster in Austria as compared to the remaining European model regions (Figure 3). This stems from the fact that in 2011 the Austrian iron and steel sector exhibits the lowest gross domestic sector output (i.e. full costs) per tonne of steel according to GTAPv9 as compared to the remaining European model regions (full costs measure in Table 3).

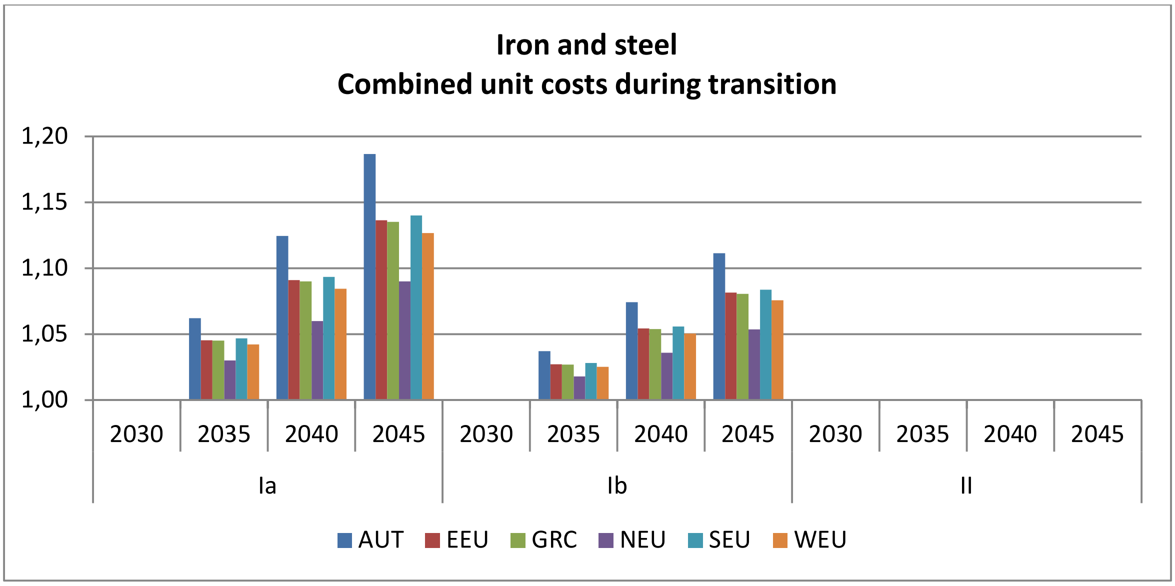

Figure 3: Combined unit costs index of iron and steel production during the phase out of blast furnace production and its substitution by DRI-H_2-production in the three scenario specifications. Note that the unit cost parity assumption in scenario II has no influence on the combined unit costs index.

The competitive advantage of BF in terms of unit cost raises the question which incentives there are that would make an investment into the DRI-H_2 route a credible strategy (compare the unit cost increase in the EU during the phase out of BF-steel and its substitution by DRI-H_2 in the period 2036-2050 in Figure 3). Climate policies could be such an incentive, for instance the anticipation of future stringency of climate regulations or subsidizing hydrogen production such to achieve cost parity. Additionally, also 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 and DRI-H_2. In terms of electricity the switch to DRI-H_2 requires an additional (renewable) electricity generation of about 33 TWh/a by 2050. This equals an expansion of Austria's current electricity generation by more than the half (62 TWh in 2014 according to Statistics Austria, 2016b). Hence, such an investment plan also necessitates substantial development and EU-wide integration of national electricity markets.

According to Grossmann et al. (2012) and Steininger et al. (2016), global electricity prices might potentially drop to about 3 €cents/kWh under high-penetration scenarios of PV. Taking this as lower bound for electricity costs in scenario II (cf. Table 1) we assume equal competitiveness of steel technologies by altering unit costs for electricity and resources. For the latter, this conforms to an annual reduction in resource expenditures of about 1.9% (which comprise mainly Hot Briquetted Iron) between years 2011 and 2035. This could be seen as crude but plausible assumption about an economy of scale development representing learning effects with respect to Hot Briquetted Iron usage, effects stemming from additions to capacities and overall efficiency gains.

We note that the distinct steel technologies are separately modelled deploying fixed-coefficient production functions which then are combined in a Leontief nest.[3] Although we assume a fixed amount of steel produced along the transition path – we apply a non-expansionary strategy (in terms of tonnes of steel produced) to the European context – the *direct* upstream and downstream effects will be different. Consequentially, relative prices will change which will induce *indirect* sectoral, as well as domestic and foreign macroeconomic effects. Therefore, we here highlight consequential risks of a 2°C-compatible transition pathway in the European iron and steel sector. The here presented cost-benefit analysis of *action* could serve as reference case for a comparison with the cost-benefit appraisal of *inaction* (for instance, conducted by Steininger et al., 2015, for the case of Austria, or by evaluating the abated process emissions by using social costs of carbon measures derived by the Interagency Working Group, 2016).

As explained previously, a technology switch in the iron and steel sector necessitates an expansion of *renewable* electricity to prevent a mere shift from *process* emissions in the iron and steel sector to *combustion* emissions in the electricity supply sector. Especially photovoltaics and wind power capacities will have to expand in a way never seen before. For the moment, this is out of scope for the purpose of this working paper but points to complementary investigations in the future.

3. Methodology and Data

3.1. Recursive dynamic CGE model

Springer (1998) supplies a comprehensive characterization of dynamic CGE models, which we shortly summarise here and build upon. They are *computable* since they use numerical data and provide numerical results. They are *general equilibrium* as opposed to the *ceteris paribus* convention used in *partial equilibrium* analysis. The model includes households, firms, governments and importers as well as exporters. Therefore these models serve to find a vector of prices for factors and commodities such that supply and demand for all actors are simultaneously balanced. The major advantage of CGE models, hence, is the capability to include sectoral interdependencies – impacts in one sector potentially affect down- and upstream value chains. This represents the major analogy to conventional input-output models. However, the latter lack the incorporation of international/sectoral competition through spatially differentiated endogenous prices and international/sectoral mobility of factors (Rose, 1995).

[3] Schumacher and Sands (2007) applied a similar approach and analysed the impact of climate policies on steel production using a steel mix which is composed of steel from BFs and scrap-based electric arc furnaces.

Our particular model is based on a static version of a multi-regional multi-sectoral CGE model developed by Bednar-Friedl et al. (2012). Their focus has also been on industrial process emissions and their incorporation into the assessment of the effectiveness of policy instruments like border carbon adjustments. As low-carbon transition is an inherently dynamic issue, we extend the characteristics of the pure static model and solve it in a recursive dynamic fashion. This refers, first, to the time dependent process of the development of the core model variable which is the capital stock. Second, this approach sequentially solves static equilibria. Hence, we restrict the option of fully forward-looking rationality of economic actors, but apply adaptive expectations in building up the capital stock (and, depending also on the closure of the capital balance, corresponding consumption levels). While this neglects intertemporal substitution possibilities, the recursive dynamic setting can be argued on the grounds of agents not acting with full foresight, but rather on the basis of adaptive expectations. Obviously there is also a computational advantage, as this intertemporal structure is less complex, posing less computational requirements and thus allows for higher sectoral and regional resolution (Springer, 1998).

Applying a recursive dynamic CGE model, the analysis compares two simulation runs: that of the reference path development – assuming that institutional or technological characteristics do not change – with that when new policies or technologies are introduced.

GTAP region	**Description**	**Economic growth rate p.a.**	**Labour force growth rate p.a.**	**Depreciation rate p.a.**	**TFP growth p.a.**
- EU-ETS region					
AUT	Austria	1.04%	-0.30%	4.42%	1.20%
EEU	Eastern Europe	1.80%	-0.76%	4.74%	1.55%
GRC	Greece	2.51%	-0.61%	3.35%	1.70%
NEU	Northern Europe	2.66%	0.17%	4.00%	1.20%
SEU	Southern Europe	2.60%	-0.45%	3.77%	1.43%
WEU	Western Europe	1.82%	-0.22%	3.93%	1.32%
- Rest of the World					
AFR	Africa	4.60%	2.30%	5.03%	0.16%
CAN	Canada	2.30%	0.43%	3.71%	1.30%
CHN	Peoples Republic of China	4.37%	-0.57%	5.30%	2.60%
ECO	Emerging economies	2.97%	0.42%	4.34%	1.24%
IND	India	5.73%	0.96%	5.58%	1.90%
LAM	Latin America	2.66%	0.56%	4.14%	0.21%
OIGA	Oil and gas exporting countries	3.97%	1.68%	5.43%	0.56%
RASI	Rest of South & South East Asia	3.51%	0.81%	5.49%	2.01%
REU	Rest of Europe	2.38%	-0.46%	5.18%	1.30%
ROI	Rest of industrialized countries	1.23%	-0.54%	4.50%	1.57%
USA	United States	1.86%	0.39%	4.75%	1.50%

Table 4: Economic growth rates p.a. (Cuaresma, 2015) and labour force growth rates p.a. (15-64 year old population; KC and Lutz, 2014) for the shared socio-economic pathway 2 retrieved from IIASA (2016). Regionally weighted depreciation rate calculated from the Penn World Table (Feenstra et al., 2015). Regionally average total factor productivity (TFP) growth rates per anno (Poncet and Fouquin, 2006).

3.2. Data

We apply GTAPv9 benchmark data with reference year 2011 and incorporate 16 aggregated economic sectors (Table 6 in the Appendix) within 17 aggregated regions (Table 7, *ibid*). Furthermore we integrate core development path information drawn from analyses of the *'New scenario framework for climate change research'* (O'Neill et al., 2014). We implement a specific *'shared socio-economic pathway'* (SSP) underlying the reference development. Such SSPs represent future projections of in particular population, urbanization and gross domestic product. For our analysis we use SSP2. The corresponding economic growth rates for the regional aggregates of our analysis are given in Table 4. SSP2 represents a 'middle of the road' background development posing medium socio-economic challenges for adaptation and mitigation (O'Neill et al. 2015).

3.3. Reference path development

The reference path is the recursive dynamic calibration of the static multi-region CGE model presented in Bednar-Friedl et al. (2012). As given in Springer (1998), a dynamic calibration has to satisfy two requirements and can be broken down into six steps. The first requirement is to replicate the benchmark data. The second requirement refers to the selection of exogenous variables which represent a specific reference path.

After having ensured these two requirements, seven steps lead to a recursive dynamic reference path (cf. Table 5). First, we assume benchmark equilibrium and apply unit conventions to the value terms data in the benchmark. Second, we formulate the behaviour of the economic agents using the *'general algebraic modelling system'* (GAMS) with the *'mathematical programming system for general equilibrium analysis'* (MPS/GE) subsystem. In the third step we calibrate the benchmark period, in this case given by our data source to be the year 2011. After the first three steps the model is completely formulated for comparative static analysis. Hence, the additional three steps in Table 5 confine the recursive dynamic setting from the pure static one.

Step	Procedure
I	Assuming benchmark equilibrium • Value terms data in benchmark • Unit conventions
II	Analytical formulation of economic agents' behaviour (MPS/GE)
III	Calibration of benchmark period
IV	Update of factor endowments
V	New static equilibria and recalibration capital income growth rate and total factor productivity growth factor
VI	Return to step IV

Table 5: Recursive dynamic calibration approach (based on Springer, 1998).

In step four we update the factor endowments of the regional household (capital income and labour income). KC and Lutz (2014) provide SSP population growth projections separated by gender and age (cf. the extensive database of IIASA, 2016), from which we calculate the regionally weighted labour force growth (15-64 year old population) as shown in Table 4. Hence, within step four of the reference path, labour endowment (representing income) develops according to the calculated SSP2 labour force growth rate gr_{LF} assuming a time-constant participation rate (cf. Table 4). In order to ensure that labour endowment growth is positive we additionally include a globally assumed labour-augmenting productivity growth rate of 1%. Hence, equation 1 shows the development of the regional specific labour endowment in our model with L being total labour income, t representing time and gr_L being the labour income growth rate:[4]

$$L_{t+1} = (1 + gr_L)L_t;\ gr_L = gr_{LF} + 0.01 \quad (1).$$

Taking regional capital stock levels for the benchmark year 2011 and regionally weighted long term depreciation rates from the Penn World Table (Feenstra et al., 2015), the available regional capital stock in 2012 follows

$$KS_{t+1} = KS_t(1 - delta) + I_t. \quad (2),$$

from which the regional growth rate of the capital stock between 2011 and 2012 can be derived. Since we assume constant interest rates 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 the capital income growth rate is consequentially not a constant. In order to ensure that the reference path is calibrated to the SSP2 economic growth rate with exogenous constant labour income growth but endogenous capital income growth, we introduce total factor productivity (factor-neutral technological progress) which adapts also endogenously according to the following procedure. Taking a conventional constant elasticity of substitution production function

$$Y_{t+1} = A_{t+1}[\alpha K_{t+1}^{\rho} + \beta L_{t+1}^{\rho}]^{\frac{1}{\rho}} \quad (3),$$

with production Y, productivity index A, capital input K, labour input L, value shares α and β, and substitution parameter ρ, it can be shown that the total factor productivity growth factor gf_A follows

$$gf_A = \frac{gf_Y}{gf_L gf_K} \quad (4).$$

This procedure of updating factor endowments represents a Keynesian closure of the saving-investment balance. Hence, it induces investment-led economic growth (cf. Delpiazzo, 2009). 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 assumed to be fixed (fixed savings rate).

Savings thus adjust to available factor 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 which is financed by cuts in consumption. Finally, in step five we solve sequentially for 'new' static equilibria and recalibrate the capital stock and capital income growth from which the total factor productivity growth

[4] Note that we suppress regional sub-indices in the following equations to alleviate readability.

factor follows (Equation 4). Step six tells the model to go back to step four to calculate for the next period until the end of the time horizon (in our case 2050) is reached.

4. Results and discussion

The effects shown in the forthcoming Figures Figure 4-Figure 7 depict the development of indicators within each of the scenarios (Section 0) relative to that of the reference path (Section 3.3). Results from simulation runs so far show that there are no effects on the iron and steel price in Scenarios Ia and Ib in the year 2035 (representing period 2031-2035) since by assumption investment costs are identical for both technologies (Figure 4). By contrast, as there are lower investment costs in Scenario II, we see small effects already in 2035. Lower investment needs in the iron and steel sector allows for higher consumption levels and higher demand for iron and steel induces a slightly higher price in 2035 compared to the reference path.

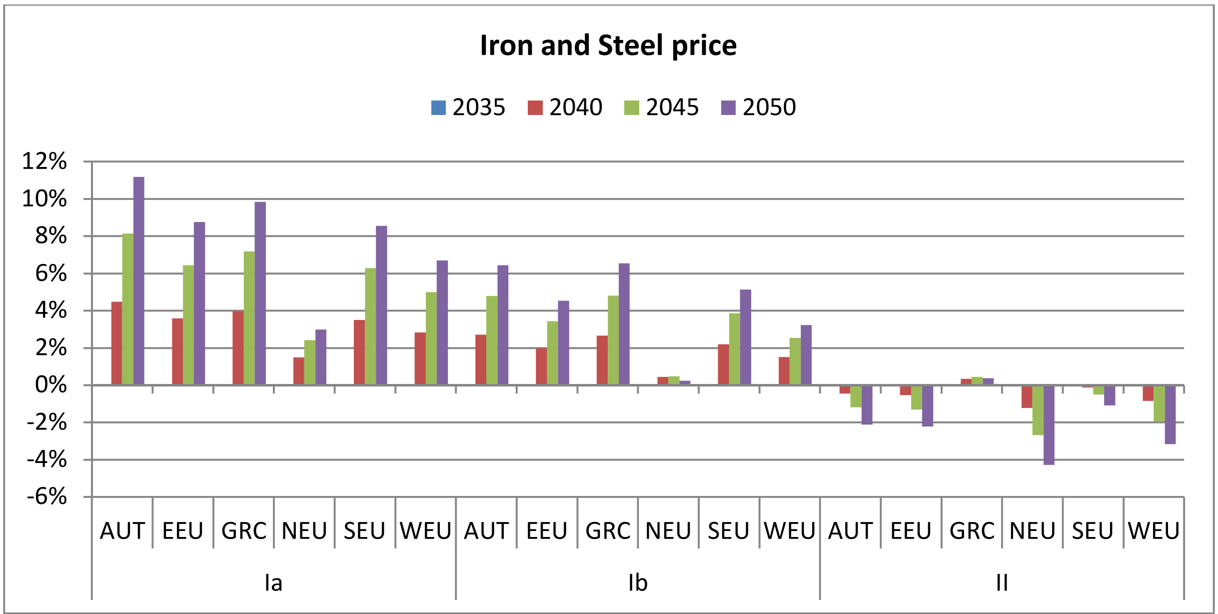

Figure 4: Iron and steel price in the European model regions (scenario development relative to reference path).

Effects originating in distinct unit costs and a distinct input structure (cf. Table 2) are twofold (Figure 4). Compared to a generically decreasing iron and steel price in the reference path, the price is higher and increasing in Scenarios Ia and Ib from 2036 onwards (2040 represents 2036-2040). Regional effects point in the same direction but are strongest for Austria (AUT) and weakest for Northern Europe (NEU). This reflects the relatively higher capital intensity and higher value share of the Austrian iron and steel sector as compared to the remaining European regions (cf. Figure 2).

In Scenario II the assumed unit cost parity between BF and DRI-H_2 leads to a stronger decreasing iron and steel prices than in the reference path, except for Greece (GRC) (Figure 4). This development results from more effective capital inputs i) due to productivity gains from positive total factor productivity growth and ii) due to lower capital needs in the iron and steel industry as a result of the switch from BF to DRI-H_2 (cf. Table 2).

The most salient regional impacts from changed unit costs and a changed input structure exist in AUT, thus in the following we focus on AUT and the aggregate European Union (EU) development. In

Scenarios Ia and Ib, effects on investment levels in AUT and the EU are inexistent because investment costs for BF and DRI-H2 are by assumption equivalent (Figure 5). The lower domestic consumption levels (compared to the reference path) are due to the increase in the iron and steel price. By contrast, the lower investment needs in Scenario II and the stronger decrease in iron and steel prices (compared to the reference path) allows for a steadily increasing consumption level.

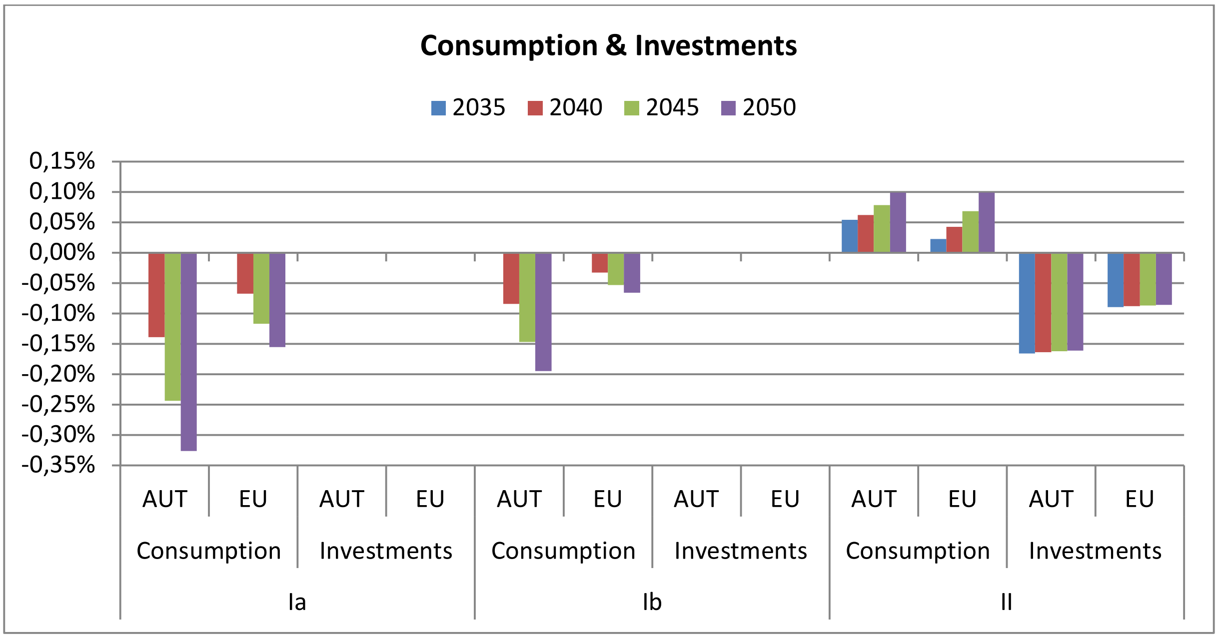

Figure 5: Consumption and investment in the Austrian and European Union model regions (scenario development relative to reference path).

Finally, these effects lead to lower GDP and welfare[5] levels in Scenarios Ia and Ib than in the reference path for AUT and the EU, and *vice versa* in Scenario II (Figure 6). In particular, the positive effects on GDP and welfare levels in Scenario II are traceable to the stronger decrease in the iron and steel price in EU member states relative to non-EU countries and the lower capital intensity of the DRI-H_2 route.

One further crucial aspect concerns distributional impacts resulting from the analyzed transition path in the iron and steel industry. In the reference path the capital rent decreases due to the relatively strong capital accumulation. The price of labor (wages) increases because labor supply is scarce relative to capital supply. Compared to this reference path the income gap in all three Scenarios diverges less because capital rents are higher and wages are lower than in the reference path (Figure 7).

[5] Hicks'ian equivalent variation measure.

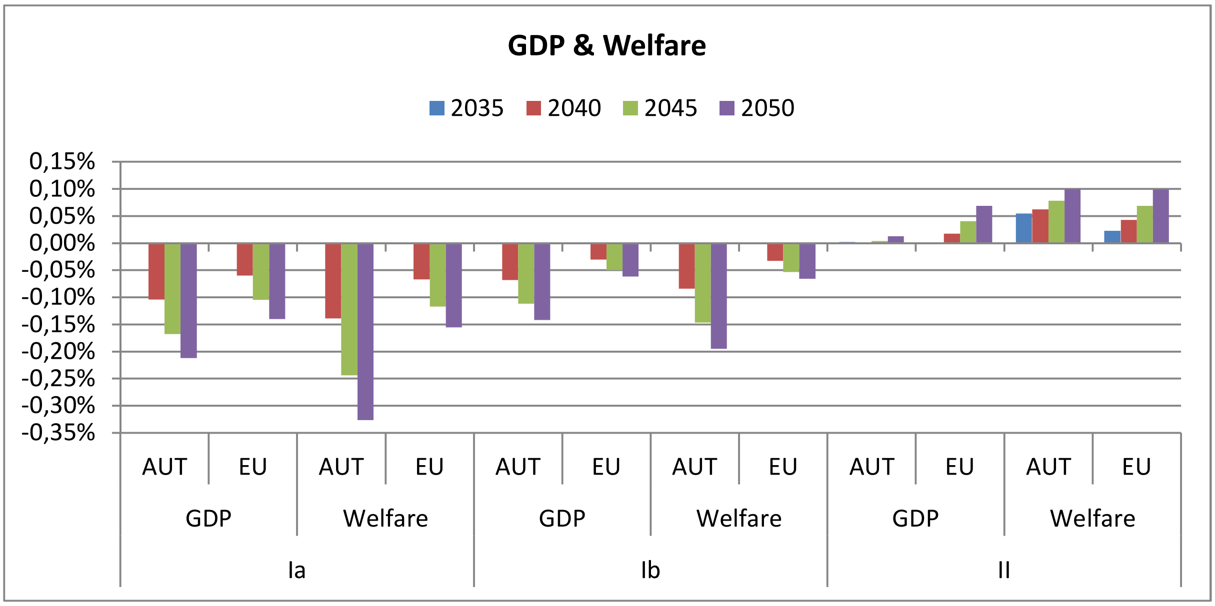

Figure 6: Gross domestic product and welfare (Hicks'ian certainty equivalent measure) in the Austrian and European Union model regions (scenario development relative to reference path).

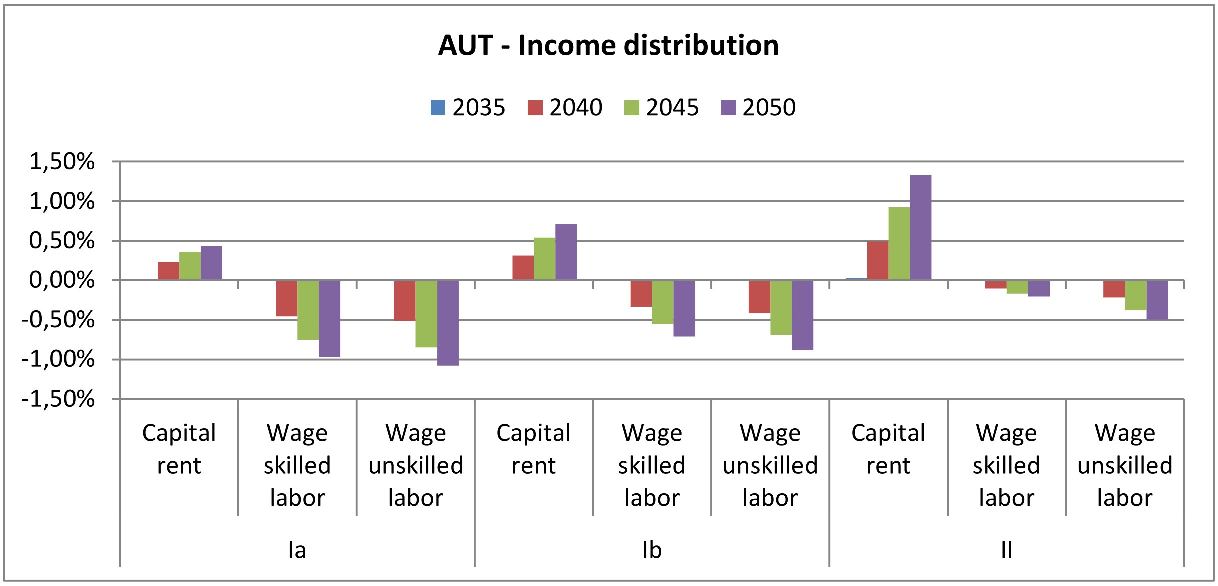

Figure 7: Capital rent and wages (unskilled and skilled labor) in the Austrian model region (scenario development relative to reference path).

We also note that the definition of unit costs of the hydrogen route relies on specific assumptions on the regional electricity mixes and, most importantly, (renewable) electricity generation costs as well as market prices evolvement over time. With the "2030 Energy Strategy" by the European Commission (EC, 2014), clear signs of significant expansions of renewables in Europe are in the pipe.

Finally, the results from our model point to the *costs of action* from implementing a specific decarbonisation path in the iron and steel sector which can be contrasted with the *costs of inaction* taking into account the social cost of carbon (SCC) assessed by the Interagency Working Group (2016, p. 4, Table ES-1).

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Appendix

Model code	Aggregated Sectors
coa	Coal
oil	Oil
gas	Gas
ppp	Paper, pulp and paper products
p_c	Refined oil products
crp	Chemical, rubber, plastic products
nmm	Mineral products nec
i_s	Ferrous metals
ely	Electricity
CGDS	Capital goods
TEC	Tech industries
FTI	Food and textile industries
SERV	Other services and utilities
TRN	Transport
EXT	Extraction
AGRI	Agriculture

Table 6: List of economic sectors.

Model code	Aggregate name	Aggregated countries
CHN	China	China
IND	India	India
CAN	Canada	Canada
USA	USA	USA
AUT	Austria	Austria
GRC	Greece	Greece
NEU	Northern Europe	Estonia, Lithuania, Latvia, Denmark, Finland, United Kingdom, Ireland, Norway, Sweden
WEU	Western Europe	Belgium, Germany, France, Liechtenstein, Iceland, Luxembourg, Netherlands
EEU	Eastern Europe	Bulgaria, Czech Republic, Hungary, Poland, Romania, Slovakia, Slovenia
SEU	Southern Europe	Croatia, Cyprus, Spain, Italy, Malta, Portugal
REU	Rest of Europe	Albania, Switzerland, Bosnia-Herzegovina, Makedonia, Serbia, Moldavia
ROI	Rest of industrialized countries	Australia, New Zealand, Japan
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
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
AFR	Africa	Benin, Benin, Burkina Faso, Botswana, Côte 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

Table 7: List of model regions.