The economy-wide effects of deep decarbonization and its uncertainties - The case of the European iron and steel industry

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Abstract

The climate target of limiting global mean surface temperature rise "well below 2°C" renders deep decarbonization of energy- and emission-intensive industries crucial. Policy makers are particularly interested in the macroeconomic consequences of such decarbonization pathways and often rely on integrated bottom-up-top-down modelling studies. However, the underlying assumptions and uncertainties involved often remain unquestioned or invisible, although they may govern the models' results. For the case of a zero-process emission pathway of the European iron and steel industry, we demonstrate how different assumptions on different layers of uncertainty (technology, socio-economic, policy, macro-economic) influence results. We show that the effects depend strongly on the technological choice, regional characteristics as well as the assumed macroeconomic states (either full capacity utilization or output gap), with the latter even leading to a different direction of macroeconomic effects in certain cases. Also, the underlying socio-economic development (SSP) and the climate policy trajectory play an important role, both by themselves and in their interaction. Our main conclusions are that the model choice for policy analysis might pre-determine the outcome of the analysis and thus this choice should be well reflected by both, modelers and policy makers. From the perspective of researchers we emphasize that model assumptions and documentations should be transparent. Also, results should be presented in the right context.

Keywords: Climate change mitigation, Uncertainty, Low carbon transition, Iron and steel, Macroeconomic modelling, Computable General Equilibrium

1. Introduction

By mid-century, the net balance of annual greenhouse gas emissions must be negative (or at least neutral), in order to stabilize global temperatures at levels agreed to in the Paris Agreement. For Annex I countries, the utmost share of GHG emissions[1] relates to the combustion of fossil fuels; in 2015 about 81% of emissions were energy-related, according to UNFCCC (2017). A further, non-negligible, portion was comprised of emissions associated with industrial processes (about 7% in 2015).[2] Thus, achieving the political goal of "well below 2°C" also necessitates the management of industrial process emissions.

In comparison to the analysis of combustion-based emissions, a narrow strand of literature focuses on the macroeconomic implications of various (technological or political) measures to tackle industrial process emissions (examples are Bednar-Friedl et al. (2012), Schinko et al. (2014), Pang et al. (2014)). A system-wide perspective in this context is essential because of potential feedbacks of measures affecting other economic sectors and (private and public) households. When applying general, as opposed to partial, analysis the possible economy-wide impact channels of local system interventions, in synergy or conflict to the desired outcome, can be identified. However, such channels are affected by a broad spectrum of uncertainties. Consequentially, the 'hard' concept of *synergies* and *conflicts* 'softens' either to (i) measurable *opportunities* and *risks*, respectively, or even (ii) non-measurable "uncertainty".

In general, there are many different definitions of *uncertainty*, most often with *risk* as a subset that can be defined as "measurable uncertainty" (Knight, 1921, p. 20). The IPCC defines uncertainty as "a cognitive state of incomplete knowledge that results from a lack of information and/or from disagreement about what is known or even knowable" (Kunreuther et al., 2014, p. 155). Risks are closely connected to the concept of uncertainty, as both emerge due to (measurable) uncertain states of the world. Kunreuther et al. further differentiate uncertainty of three different types: First, *epistemic uncertainty* emerges from the "lack of information or knowledge for characterizing phenomena". Second, *paradigmatic uncertainty* results from the "absence of prior agreement on the framing of problems and ways to scientifically investigating them". Third, *translational uncertainty* "results from scientific results that are incomplete or conflicting so that they can be invoked to support divergent policy positions". *Translational* uncertainty thus results from *paradigmatic*

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[1] Without Land use, land use change and forestry.

[2] The remaining shares for Annex I parties refer to Agriculture (about 8%), Waste (about 3%) and other activities (UNFCCC, 2017). For non-Annex I parties GHG emissions data by sector are either incomplete or vary considerably.

uncertainty, in cases where scientists disagree on model assumptions or how to model processes and come to contradictory conclusions due to different methodological (including modelling) approaches.

In our analysis of uncertainties we build upon the techno-economic analysis of Mayer et al. (2017) who analyze the economy-wide implications associated with a low-carbon transition pathway of iron and steel production in Europe. As steel demand is deeply interwoven in modern economies, the iron and steel sector serves as a good case for analysis of uncertainties. While Mayer et al. (2017) only indicate the presence of large uncertainties, the objective of the present contribution is to narrow down plausible epistemic, paradigmatic and translational uncertainties that exist for economy-wide effects of low-carbon transitions.

Our approach is motivated by the existing literature on low-carbon transitions, which is mostly using the concept of sensitivity or scenario analysis for uncertainty appraisal, but rarely going beyond epistemic uncertainty. More sophisticated approaches deploy Monte Carlo simulations and other probabilistic approaches in order to analyze a behavior space of parameter combinations drawn from statistical distributions; e.g. Abler et al. (1999) who investigate economic and sectoral policies impacting environmental indicators or Babonneau et al. (2012) and Wang and Chen (2006) who focus on climate policies. Another approach to address uncertainty is multi-model comparison, as was done, for example, in the Energy Modeling Forum 29 (Böhringer et al., 2012), however all of the models used have been general equilibrium models, which all share the same basic functional relationships and assumptions. The same is true for a more recent analysis by Guivarch et al. (2016), who test for uncertainty within the Shared Socioeconomic Pathways (SSP) framework. Thus, current approaches most often do not go beyond the epistemic uncertainty pillar. Yet, for a more fully-fledged assessment it is essential to also analyze the remaining uncertainty pillars, i.e. paradigmatic and translational uncertainty. These two types of uncertainties ultimately lead to discussions on very fundamental macroeconomic questions or principles, such as whether the economy is supply or demand driven. When assuming a supply-driven economy, general equilibrium modeling is state-of-the-art, whereas the assumption of a demand-driven economy leads to the application of post-Keynesian models. However, as general equilibrium and post-Keynesian modeling groups mostly work in parallel streams of literature, rather than in cooperation, paradigmatic and translational uncertainties are barely addressed in economic research. Notable attempts for such an integrated analysis in the context of climate change mitigation are Edenhofer et al. (2010), Jansen and Klaassen (2000) and Kober et al. (2016). Edenhofer et al assess the technological feasibility and associated macro-economic consequences of reaching greenhouse gas concentration targets and focus on (epistemic) uncertainty in technology costs and climate sensitivity. Jansen and Klaassen address epistemic uncertainty via sensitivity analysis in terms of different ways of taxing recycling, and Kober et al. via different CO_2 price scenarios. Implicitly the three cited studies also address the paradigmatic and translational pillars by deploying fundamentally different macro-economic model types. However, to the authors' best knowledge, a systematic and comprehensive analysis of uncertainties as it is presented here has not been published thus far, as we go beyond the current state of research by addressing a multitude of uncertainties at different layers in one consistent framework, including all three pillars of uncertainty, discussing them explicitly and making them visible and comparable.

In the present analysis, we start with the definition of various parameter and scenario variations regarding (i) alternative technologies, (ii) underlying assumptions on socio-economic background narratives and (iii) climate policies (i.e. all addressing the epistemic pillar). Particularly, we address paradigmatic and translational uncertainties by comparing the results of two different macro-economic modelling approaches. Both of them – a dynamic-recursive general equilibrium model and a dynamic macro-econometric post-Keynesian model – represent different model families dealing with the prevailing macro-economic states, reflected by different degrees of capacity utilization. In doing so, one of the goals of this paper is to pinpoint the epistemic, paradigmatic and translational layers which drive uncertainties regarding the magnitude and direction of economy-wide effects for low-carbon transitions.

2. Uncertainty Framework and Methods

In the analysis we address all three types of uncertainties by variations on four *uncertainty layers*. First, on the *technological* uncertainty layer we vary between two different process-emission free iron and steel production technologies. Second, on the *socio-economic* layer we vary across three possible socio-economic background developments (shared socio-economic pathways, SSPs). Third, on the *climate policy* uncertainty layer we vary the stringency and geographic scope of climate policy, implemented as three *climate policy-worlds*. Fourth, on the *macro-economic* uncertainty layer we change the assumption of the prevailing macro-economic state, reflected by different degrees of capacity utilization, with one extreme case depicting a macroeconomic state of *full capacity utilization* and another extreme case depicting an *output gap* (or idle capacities). The specific configurations of the four layers are given in sections 2.1-2.4.

Table 1 summarizes the different layers and assigns the type of uncertainty to each, as defined by the IPCC. Most of the variations address epistemic uncertainty; however we also address paradigmatic and translational uncertainty, as we change the assumption on the degree of capacity utilization by deploying two fundamentally different macroeconomic modelling approaches.

Table 1 Overview of the uncertainty framework used in the analysis

Uncertainty layer	Implementation via…	IPCC type of uncertainty addressed
Technology	…two different iron and steel production technologies	epistemic
Socio-economic	…three different shared socio-economic pathways (SSPs)	epistemic
Climate policy	…three different climate policy worlds (stringency and geographic scope)	epistemic
Macroeconomic state	…the degree of capacity utilization	paradigmatic (and translational)

The general methodology proceeds as follows. First, a baseline path is specified by (i) the choice of a specific socio-economic background development (SSP), (ii) the definition of a specific *climate policy-world,* and (iii) the iron and steel production technology as we observe it currently (i.e. "conventional" iron and steel production). Second, the introduction of climate change mitigation efforts determines the counterfactual path, in this case a switch to a process-emission-free iron and steel production technology, with all other assumptions identical as in the baseline path. By comparing the baseline and the counterfactual pathway we isolate the economy-wide effects of the technology switch. To capture uncertainty we then systematically change assumptions (in the baseline *and* counterfactual paths respectively) on the four uncertainty layers and do the same comparison between baseline and counterfactual path.

2.1. Technological Uncertainty

There are several technological options to produce process-emission-free iron and steel, opening up the first uncertainty layer. We specify two different process-emission-free technologies, replacing the current CO_2-emission-intensive blast-furnace basic oxygen furnace route (BF-BOF), presumably at the two cost-extreme ends of the spectrum (at least according to current knowledge). The first technology comprises a route using hydrogen-based direct reduced iron which is fed into an electric arc furnace (DRI-H-EAF). This technology is mature and already currently in use, yet not based on hydrogen, but natural gas (CH_4). The most important uncertainty regarding DRI-H-EAF is thus the supply of hydrogen. The second technology is plasma-direct-steel-production (PDSP), which is characterized by a single-step production, with iron ore as the only raw material input. PDSP is still in the experimental phase, but seems promising in regards to unit costs, flexibility of scale, steel quality and greenhouse gas emissions (Sabat and Murphy, 2017). By analyzing a rather mature technology and one which is still in its infancy, we cover a broad range of uncertainty on the technological layer.

Table 2 Unit cost structures of different iron and steel production technologies (net of taxes). In order to account for a techno-economic range of alternative technologies we assume an industrial electricity price of 5€-cents/kWh for the otherwise more expensive DRI-H-EAF route and 3€-cents/kWh for the PDSP route. (Sources: Stakeholder dialogue; CEPS (2013); Fischedick et al. (2014); NIR-AUT (2017))

	Techno-economic specification	**Conventional**	**High-cost**	**Low-cost**
	Electricity price [EUR/kWh]	-	0.05	0.03
	Integrated technology [EUR/t steel]	BF-BOF	DRI-H-EAF	PDSP
OPEX	Coal products (esp. coke)	84	0	0
	Electricity*	0	219	131
	Iron pellets	0	84**	0
	Iron ore	189	189	189
	Services	45	40	40
	Unskilled labour	5	4	4
	Skilled labour	44	40	40
	Capital (wear and tear)	48	48	48
	Net total unit costs [EUR/t steel]	**415**	**624**	**452**
	Difference to BF-BOF [EUR/ t steel]	**-**	**+209**	**+37**
	Process emissions[tCO_2/t steel]	**1.5**	**-**	**-**
	Implicit break-even CO_2 price excl. CAPEX [EUR/tCO_2]	**-**	**139**	**25**
	CAPEX [EUR/t steel]	**-**	**105**	**99**

*Electricity costs for hydrogen production (and EAF in the case of DRI-H-EAF)
**Additional costs due to the intermediate stage of producing iron pellets out of iron ore

The respective operation cost structures are given in Table 2 as central values of available ranges (cf. Mayer et al., 2017). It is apparent that DRI-H-EAF steel is much costlier than BF-BOF steel in per unit terms, for given prices of primary factors (capital and labor) and intermediate inputs. The most salient difference is the switch from coke costs to electricity purchased from the electricity generation sector, in order to generate on-site hydrogen for DRI-H-EAF iron and steel production. Operating expenditures (OPEX) for electricity thus include electricity needed for hydrogen generation and operating an electric arc furnace. Note that DRI production requires the pre-processing of iron ore to iron pellets (IEA, 2007), whereas all remaining elements of operating expenditures are not substantially different. In contrast, the pre-processing of iron ore is made obsolete by the PDSP route, which highlights a crucial advantage relative to DRI-H-EAF. The production cost structure for PDSP, as it is assumed here, thus represents the lower bound of the uncertainty range regarding technology costs. However, our assumption is still conservative, as e.g. Hiebler and Plaul (2004) conclude that the costs of PDSP[3] might be by 20% lower than the BF-BOF technology.

In order to investigate a broad range of technological alternatives – capturing a large economic range of technological uncertainty – we focus in the present analysis on two techno-economic specifications referring either to *high-cost* (DRI-H-EAF with electricity costs of 0.05 EUR/kWh) or *low-cost* (PDSP with electricity costs of 0.03 EUR/kWh).

Capital expenditures (CAPEX) for new facilities of each respective technology are determined by annuity payments (105 EUR/t of steel for the high-cost, 99 EUR/t of steel for the low-cost specification). We assume a linear investment phase and a corresponding life time of each facility, both of which are assumed to be 12 years. The stepwise accumulation of new capital and the respective repayment for each vintage leads to a period of 23 years of additional CAPEX (peaking when reaching the middle of the repayment phase) until full installation of new process-emission-free technology facilities is completed. During the investment phase, these additional capital expenditures increase the unit cost disadvantage of new technologies relative to the BF-BOF.

2.2. Socio-Economic Uncertainty

As point of reference, we use SSP2 (O'Neill et al., 2017, 2014) for the main scenario setting, the narrative of which reflects a "Middle of the road" socio-economic background development, meaning that the challenges for both mitigation and adaptation are moderate. In order to capture socio-economic uncertainties, we evaluate ranges of macro-economic indicators by SSP variation. Each SSP is defined across six broad categories: demographics, human development, economy and lifestyle, policies and institutions (excluding climate policies), technology, and environment and natural resources (O'Neill et al., 2017). We follow an approach which incorporates a wide range of aspects given data requirements, as well as suitability and compatibility between different SSP narratives and our model framework.

From Figure A1 in the Appendix it is apparent that SSP3 and SSP5 span the range of regional economic growth rates for EU regions (retrieved from the SSP data base provided by IIASA (2017)). Accordingly, we deploy SSP3 and SSP5 (and its different characteristics) as additional background developments in order to reflect a large range of socio-economic uncertainty. Although both alternative SSPs 3 and 5 are affected by high challenges to mitigation (which we model by lower multi-factor productivity; see Figure A1 in the Appendix), SSP3 is affected in addition by high challenges to adaptation (whereas SSP5 inhibits low adaptation challenges). To account for the

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[3] Hydrogen Plasma Smelting Reduction (HPSR), as they call it.

difference in adaptation challenge, we increase capital depreciation for SSP3 model simulations (by 50% across regions) and decrease it for SSP5 simulations (by -25%), both relative to SSP2. This should serve as a representation of higher or lower climate change impacts on capital formation and durability relative to SSP2. The employed long-term capital depreciation rates for SSP2 are given in Table A1 in the Appendix.

2.3. Uncertainty of Climate Policy

To capture uncertainty on the climate policy layer, we specify three different *climate-policy worlds* in which the switch to a process-emission-free iron and steel technology takes place. First, *reluctant policy* means that the global community sticks to the currently prevailing Nationally Determined Contributions (NDCs), reflected in the model by a modest global CO_2 price, reaching 46 EUR_{2011}/tCO_2 globally by 2050 (Figure 1; based on IEA, 2016). In contrast, *ambitious policy* means that we follow a more stringent policy by tripling the CO_2 price trajectory, hence reaching 138 EUR_{2011}/tCO_2 globally by 2050, seeking not to exceed +2°C of global warming. This assumption is in line with IWGSCC (2015)[4] and the 450ppm scenario by the IEA (2016).[5] Our assumption for the *ambitious policy* world thus may reflect an upper bound of politically feasible CO_2 taxation. In addition, we set up an *EU-ambitious* case in which only the EU implements an *ambitious* policy (138 EUR_{2011}/tCO_2 by 2050) with the rest of the world remaining *reluctant* (46 EUR_{2011}/tCO_2 by 2050) (i.e. when only the EU follows the ambitious policy depicted in Figure 1).

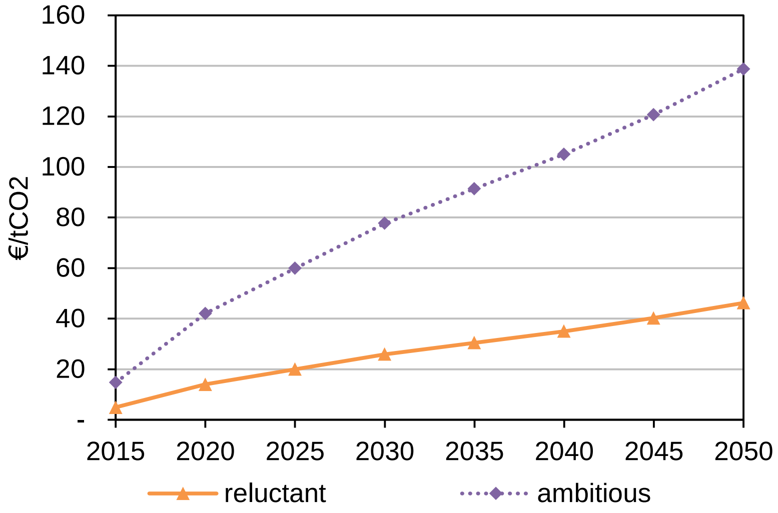

Figure 1 Different CO_2 price trajectories in different policy worlds [EUR_{2011}/tCO2]

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[4] Social Costs of Carbon of USD 212/tCO_2 in 2050 (95th percentile)

[5] Reaching USD 140/tCO_2 in 2040.

2.4. Macroeconomic Uncertainty

In order to address paradigmatic and translational uncertainty, we use two fundamentally different macroeconomic models, which reflect different macroeconomic states, or perspectives on the degree of macroeconomic capacity utilization. More specifically, we deploy a computable general equilibrium model, which is well suited to describe an economy with average long-run *full capacity utilization*. Second, we deploy a post-Keynesian macro-econometric model that assumes a macroeconomic *output gap*, best depicting an economy with idle factors; e.g. temporary idleness during a recession.

Despite the fundamental differences, the two models also have similarities, namely, the high level of sector disaggregation and sector interconnectedness depicted by an input-output framework, which makes both approaches capable of examining the potentially differing impacts on each sector, both directly and indirectly (through changes in demand from other sectors). These economy-wide – as opposed to partial – approaches recognize that there may be implications for sectors that are not specifically targeted by a particular greenhouse gas emission mitigation measure.

2.4.1. Full Capacity Utilization (General Equilibrium Model)

For the case of average long-term *full capacity utilization* we deploy the WEGDYN model, which is a global multi-sector, multi-country, recursive dynamic computable general equilibrium (CGE) model. From a macro-economic modelling point of view, WEGDYN is supply-side driven, meaning that capacities (capital, labor and resource endowment) are fully utilized, constraining macro-economic expansion via scarcity. This assumption of full utilization of existing capacities refers to a long-run position of the economy. For more details on the structure of WEGDYN, the associated closure rules and background assumptions we refer to Mayer et al. (2017) and Bednar-Friedl et al. (2012).

WEGDYN is based on social accounting data of the GTAP9 database (Aguiar et al., 2016) and the static specification developed by Bednar-Friedl et al. WEGDYN allows for a macro-economic assessment of system or feedback effects triggered by either changes of the level of production of economic sectors or changing consumption patterns of households (public or private). The model sequentially solves for static equilibria in five-year steps, connected through capital stock accumulation, labor force growth and multi-factor productivity growth over time. Activities of production and consumption involve the emission of carbon dioxide (CO_2) originating either from the incineration of fossil fuels or from industrial processes.

The sectoral resolution of WEGDYN distinguishes between 16 economic sectors (Table A2) whereas special emphasis is given to the sector “Iron & Steel: basic production and casting”. There, we differentiate between three disaggregated parts representing either: (i) a conventional and process-emission-intensive technology (BF-BOF), (ii) a new process-emission-free technology (as discussed in Section 2.1) and (iii) the casting, rolling and finishing of crude steel. The former two technologies supply crude steel, which is combined with the activity of the casting, rolling and finishing subsector to a final iron and steel sector aggregate. The latter then eventually supplies the final product to the market.

For the spatial resolution WEGDYN differentiates between 17 regional aggregates (Table A3). We focus on EU-28 member states (plus Norway, Liechtenstein and Iceland) for the purpose of our analysis, represented by 6 distinct aggregated regions. We keep Austria (AUT) and Greece (GRC) as separate model regions, in order to contrast implications of high process-emission-intensive iron and steel production of the former country with no process-emissions-intensive production of the latter (see Figure A2).

2.4.2. Output Gap (Post-Keynesian Model)

For the case of a macroeconomic *output gap,* we deploy the post-Keynesian energy-environment-economy macro-econometric model E3ME (see also www.E3ME.com). It shares many similarities with the CGE model, however there are fundamental differences. In contrast to the CGE model, the post-Keynesian model is based on the theory of effective demand, implying that there are idle capacities available for increasing production, if stimulated. Additional investment, for example, would thus not crowd out other investments or consumption (Pollitt et al., 2015). In other words, there is an *output gap*, emerging from the difference between potential economic output (with full capacity usage) and the observed economic output. Methodologically it can be described as a system of dynamic econometrically-estimated equations, capturing short-term impacts followed by medium-term adjustment to a long-run steady state.

The model is characterized by a high level of disaggregation in terms of the sectors of the economy and the categories of final household expenditure identified. Like CGE models, it is based on an input-output framework that explicitly identifies the interdependencies between sectors, final demand agents and regions. E3ME covers 14 atmospheric pollutants (GHGs and non-GHGs) from 50 emission sources. The main data sources are OECD Structural Analysis database, International Energy Agency, Edgar emissions database, Eurostat, World Bank and United Nations.

In terms of regional resolution, it covers 59 world regions. The European Union is represented at Member State level, which allows for a study of the impacts of EU (unilateral) climate policies. E3ME is based on annual data covering the period since 1970, and the model projects forward annually to 2050. For more details see Anger et al. (2016) and Barker et al. (2012).

3. Scenario Definitions

Table 3 summarizes how the different uncertainty layer variations, as described in section 2, are combined. As a point of reference we refer to a “main scenario” which is characterized as follows. For the socio-economic layer we assume GDP growth according to SSP2, for the climate policy layer we assume a globally reluctant climate policy (reflecting current NDCs, reaching 46 EUR/tCO_2 by 2050 globally) and for the macro-economic layer we assume *full capacity utilization* as model closure (represented by the deployment of the WEGDYN CGE model). The analysis aims at tackling epistemic uncertainties regarding technologies, policies and the socioeconomic future. The deployment of fundamentally different macroeconomic models addresses paradigmatic uncertainty, by changing the assumption regarding the macroeconomic state from *full capacity utilization* to the assumption of an *output gap* (*ceteris paribus*).

Table 3 Uncertainty space, emerging from different combinations of climate policy ambitiousness and different socio-economic background developments.

Climate policy world	**Socio-economic background development**		
	SSP2	**SSP3**	**SSP5**
Globally reluctant: Modest global CO_2 price reaching €46/tCO_2 by 2050 (IEA, 2016, “New Policies Scenario”)	**Main scenario** (model closure: full capacity utilization)	Variations of main scenario → socio-economic uncertainty	
EU ambitious: EU follows CO_2 price trajectory with €138/tCO_2 by 2050. Rest of the world: €46/tCO2 by 2050	Variations of main scenario → climate policy uncertainty		
Globally ambitious: Global CO_2 price trajectory with €138/tCO_2 by 2050			

4. Results and Discussion

4.1. Epistemic Uncertainty

4.1.1. The Technological and Socio-Economic Layer

We first report results for the iron and steel sector, being at the very core of the macroeconomic system intervention. In general, all results presented should be understood as possible ranges of effects. Note that we raise no claim of completeness of possible scenarios, but give first structured insights into uncertainties within the framework as we have defined it here. Further note that all results are given relative to a respective baseline scenario, which includes the very same assumptions regarding climate policy as the low-carbon scenarios, but with the new iron and steel technologies not activated. Figure 2 shows how regional market prices for iron and steel change, for the main scenario, relative to the baseline development (see section 3 for details on the scenario assumptions). The top row in Figure 2 gives results for the high technology cost specification, the bottom row for the low technology cost specification; the difference between top and bottom row thus represents the technological uncertainty. In addition we address the socio-economic uncertainty layer by carrying out the same analysis for two additional SSPs (SSP3 and SSP5, in addition to SSP2).

With a high cost specification, prices are higher in all regions, ranging between +8.4% (Austria in 2036) and +0.6% (Greece[6] in 2050) with peaks in 2036[7] and declining thereafter, but remaining higher until 2050. Prices are higher due to higher production costs, both because of additional capital costs due to investment requirements, which have to be repaid, and because of higher operating costs (as presented in Table 2). The inverted U-shaped price development reflects the additional burden of financing the new facilities.[8] With a low cost specification, the CO_2-price more than compensates the production cost disadvantage of the process-emission-free technology, which leads to lower iron and steel prices in all regions, ranging between -5.6% (Austria in 2050) and -0.7% (Greece in 2050), as compared to the baseline scenarios.[9]

Concerning socio-economic uncertainty, we see that the results are robust as the direction and (in most cases) also the magnitude of effects does not vary significantly across SSPs. However, in some regions we see relatively large differences when comparing SSP3 to SSP2 or SSP5. This is because in SSP3 the GDP growth rates in EU regions are lowest due to higher depreciation rates. Thus, capital prices are higher and as the new technology is more capital intensive, price effects are pushed upwards (as compared to SSP2 and SSP5). In other words, when introducing a capital intensive technology in a world with high capital prices, its effects are stronger (to the positive in terms of price effects) than in a world with lower capital prices.

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[6] Note that in Greece the effect emerges only indirectly via international trade, since in Greece itself there are no BF-BOF steelmaking facilities to be replaced.

[7] Peaks emerge in 2036 since this is the point in time when additional capital costs (annuity payments) for financing new facilities begin to decrease.

[8] Note that in the reference case there would be 100% conventional steel output at that point in time, with a still rising CO2-price, which would further increase production costs of the (baseline) BF-BOF technology, whereas production costs for the process-emission-free technology would start to fall in 2036. Hence, the relative cost-disadvantage of the process-emission-free technology decreases from 2036 onwards and thus the prices of the reference technology and the process-emission-free alternative would converge, which leads to an inverted U-shaped effect.

[9] Regarding regional differences, Austria seems to be the most sensitive region. This is because the share of the BF-BOF steelmaking technology is highest in Austria (>90% of steel is produced along this route), whereas the shares in EEU, NEU and WEU lie at 65% and in SEU only at 30% (see Figure A2 in the Appendix for details).

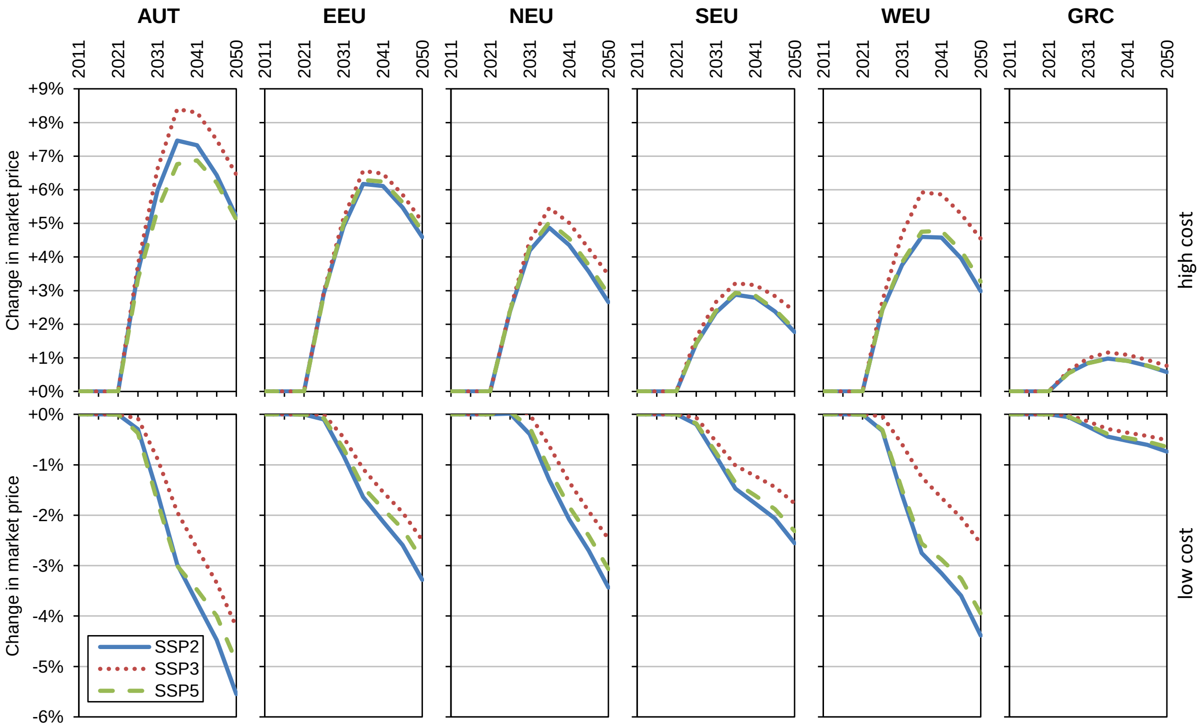

Figure 2 Change of iron and steel market prices, relative to the baseline scenario with SSP variations on the socio-economic uncertainty layer (assuming reluctant climate policy and full capacity utilization).

The changes in relative prices translate into iron and steel output effects, which are given in Figure 3, aggregated on an EU level. With a high technology cost specification, output is lower relative to the baseline (between -6% and -10% in 2050), whereas with a low technology cost specification, output is higher (between +7% and +9% in 2050). Again, concerning socio-economic uncertainty our results are robust in terms of direction and magnitude, with stronger effects under SSP3 (driven by the stronger price effect).For detailed regional output effects and explanations see Figure A3 in the Appendix.

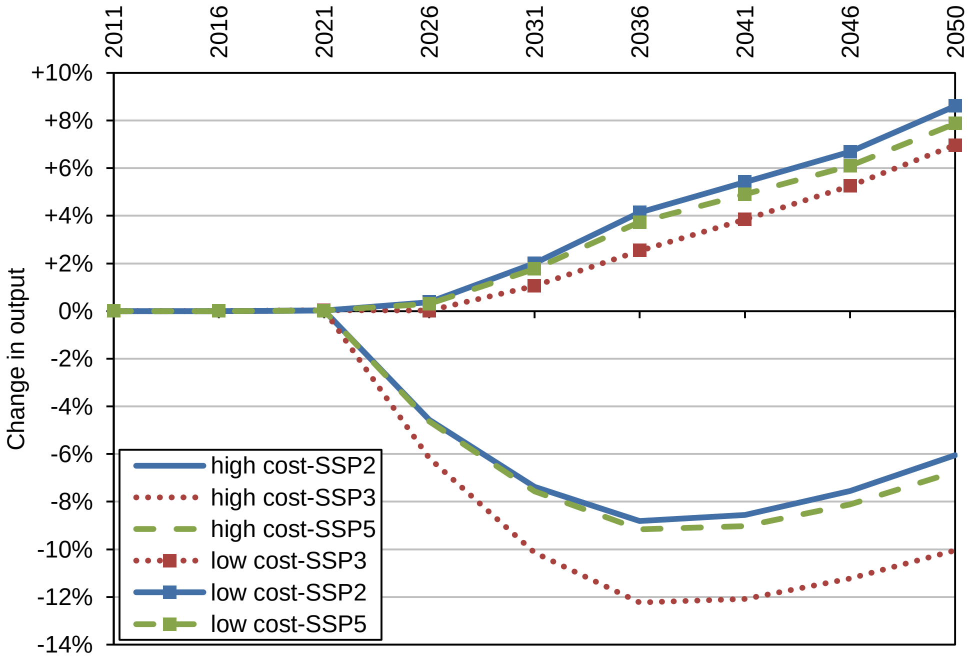

Figure 3 Change of EU-wide iron and steel output, relative to the baseline scenario with SSP variations on the socio-economic uncertainty layer (assuming reluctant climate policy and full capacity utilization).

Due to interlinkages across economic sectors and final demand agents, the effects from the iron and steel sector also have effects on the rest of the economy and eventually on GDP and welfare. EU-wide GDP effects are shown in Figure 4, again for the main scenario with variations of SSPs. With a high technology cost specification, more inputs are necessary to produce one unit of steel, leading to a loss of competitiveness (as compared to the conventional technology in the baseline) and thus a lower GDP. Even after the investment phase (beyond 2036), production costs (and prices) are still higher and thus the economy does not recover by 2050. EU-wide GDP is below the baseline level by up to -1.4% (in 2050). In the low technology cost case we only see short term negative effects, since during the investment phase the economy shifts to a more capital-intensive structure, which temporarily increases unemployment, lowering income and thus consumption (more than offsetting the additional investments). Long term effects are positive, though, since after the investment phase process-emission-free steel becomes increasingly advantageous compared to the conventional technology (the CO_2 price continues to rise). This leads to higher GDP by up to +0.5% in 2050. The region-specific GDP effects and explanations are given in Figure A4 in the Appendix.

Regarding socio-economic uncertainty, we see that results are robust in terms of direction and magnitude. For both the high and low technology cost specifications, the regional GDP implications are robust to SSP variation but less severe under SSP3. This applies in particular to the relative change in GDP in WEU, which is primarily due to comparably low multi-factor productivity growth (see Figure A1 in the Appendix).

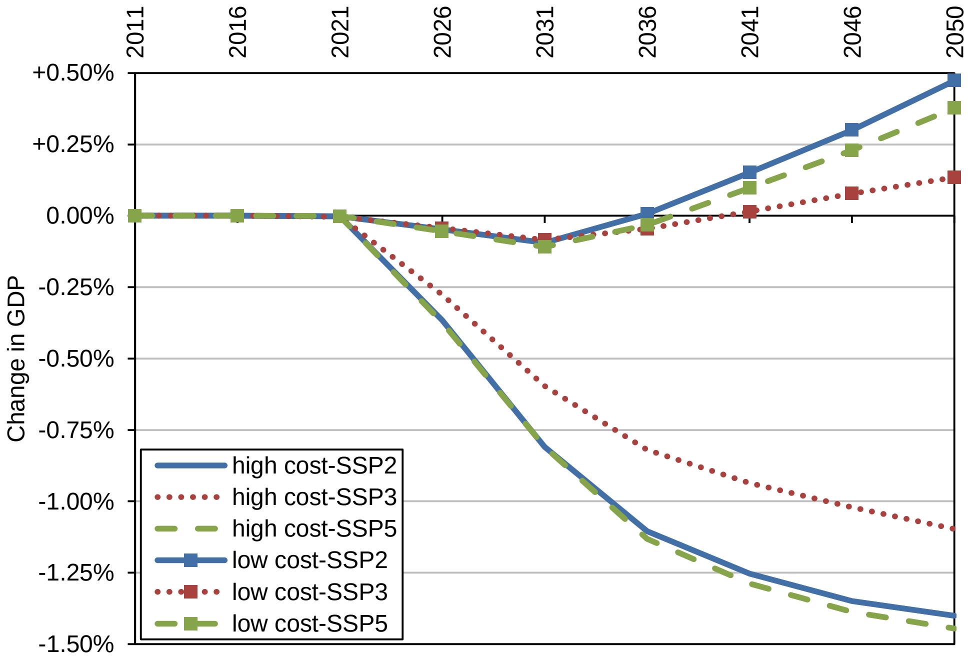

Figure 4 Change of EU-wide GDP, relative to the baseline scenario with SSP variations on the socio-economic uncertainty layer (assuming reluctant climate policy and full capacity utilization).

What is not captured in GDP is the shift of income use from consumption to investments (for the new facilities of the new technology, water-electrolysis plant and integrated DRI-EAF or PDSP). Since we assume full capacity utilization, consumption must be reduced to allow for covering additional investment out of the same output level. This reduction of consumption is reflected in a lower welfare[10] level. The effect is, however, more severe than the GDP effect, since GDP also includes the positive effect of higher investments. In general, the welfare effects follow a very similar pattern as the GDP effects, with lower welfare levels of up to -2.5% in the high cost case (in EEU in 2050) and higher welfare levels of up to +0.9% in the low cost case (in WEU in 2050; see Figure A5 in the Appendix for details).

Switching from the conventional technology to one of the two carbon-free alternatives is accompanied by changes on the labor market and employment effects. In principle, the new steelmaking technology is characterized by a lower labor intensity, which might lead to lower employment, however overall macroeconomic performance may outweigh this effect. In our analysis we distinguish between skilled and unskilled labor. In the high technology cost case, the macro-economy is negatively affected, with a lower demand for steel and the strong interdependency with other sectors translating into higher regional unemployment rates (as compared to the baseline). In

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[10] Measured by means of Hicks'ian Equivalent Variation, which describes the change in consumption possibilities, or the willingness to pay (accept) for a price rise (fall) not to occur.

addition, the lower labor intensity of the new technology increases unemployment, for both skilled and unskilled labor (see Figure A6 and Figure A7 in the Appendix for detailed regional effects). By 2050, unemployment rates increase by up to +2%-points as compared to the baseline. In contrast, long-term unemployment rates tend to be lower in the low technology cost specification, because of stronger economic performance overall. However, in the short term, unemployment rates are still higher due to the shift to a more capital intensive economic structure during the investment phase.

4.1.2. The Climate Policy Layer

Having explored the technological and socio-economic uncertainty layer, we investigate the climate policy layer and its uncertainties. Again, we run the main scenario but now under different policy worlds. In addition to the “globally reluctant” world we introduce a “globally ambitious” and an “EU ambitious” world (see section 3 for details). Note that climate policy is implemented as an exogenous CO_2 tax that is active in both the baseline scenarios and in the respective transition scenarios. Figure 5 illustrates the effects on EU-wide GDP, with the transition happening within the three different policy worlds. With a high technology cost specification, the highest GDP losses emerge in the policy world with lowest support, i.e. the “globally reluctant” world. In the “EU ambitious” world, the transition is less costly, since there is more policy support for the process-emission free technology with a lower production cost disadvantage. We see that GDP losses can be reduced relatively strongly (by up to 0.5%-points in 2050), when introducing a more ambitious climate policy in the EU. Interestingly, GDP losses are rather insensitive to non-EU policy. In some regions the GDP loss becomes even stronger when switching to a “globally ambitious” policy (see Figure A8 in the Appendix for details).[11]

With a low technology cost specification, climate policy helps to foster the positive GDP effect. Compared to the “globally reluctant” world, ambitious EU policy can increase GDP gains by +0.5%-points (in 2050) with slightly higher benefits in the “globally ambitious” world. In general, we see that the “policy world” uncertainty substantially influences the magnitude of the GDP effect; however, the sign of the effect is robust. The same patterns as observed for GDP apply to welfare effects, which are shown in Figure A9 in the Appendix.

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[11] This can be explained via lower EU exports to non-EU regions, since in a world where non-EU regions’ economies are also confronted with higher CO_2 taxes (“globally ambitious”), import demand of non-EU regions is lower.

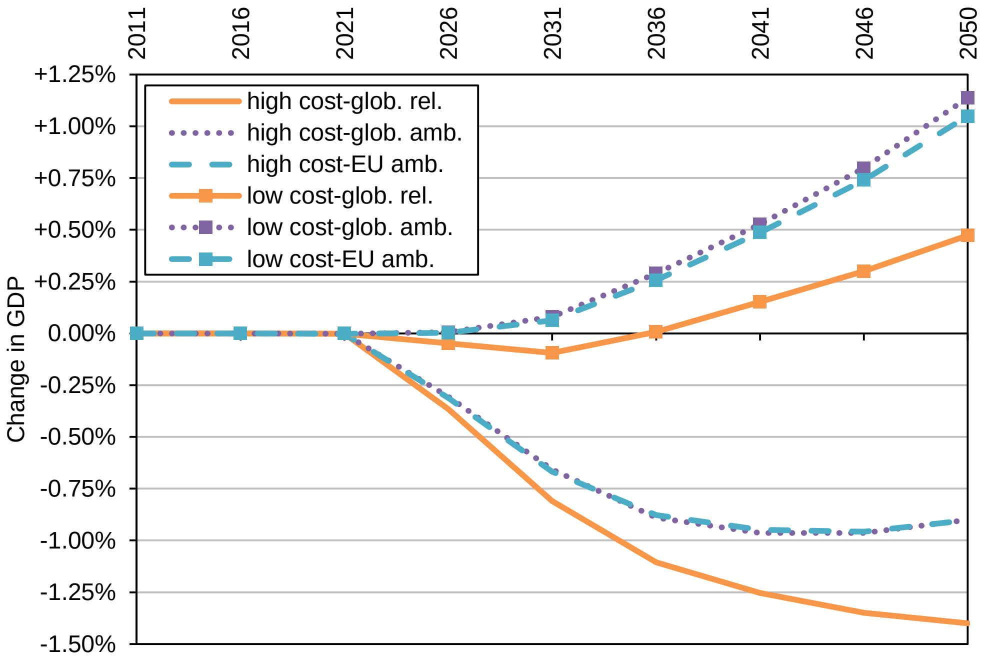

Figure 5 Change of EU-wide GDP, relative to the baseline scenario in different policy-worlds, assuming SSP2 and full capacity utilization (globally reluctant: €46/tCO$_2$ by 2050; globally ambitious: €138/tCO$_2$ by 2050; EU ambitious: €138/tCO$_2$ in EU-ETS only and €46/tCO$_2$ in the rest of the world; high cost: high technology cost specification; low cost: low technology cost specification).

4.2. Paradigmatic and Translational Uncertainty

4.2.1. The Macroeconomic Layer

We now address paradigmatic uncertainty and translational uncertainty (with the latter emerging as a consequence of the former). All results shown thus far are generated by a general equilibrium model (WEGDYN), assuming *full capacity utilization* (or constrained resources in production). Additionally, we now deploy a post-Keynesian econometric model (E3ME) that assumes a macroeconomic *output gap* (no resource constraint in production). Again, we investigate the main scenario (SSP2, globally reluctant climate policy) for the low and the high cost specifications of the new steel technology.

Regarding price effects (Figure 6), we see that with a high cost specification, effects mostly coincide in terms of direction, magnitude and development over time. Interestingly, the price effects are distributed more uniformly across regions when deploying E3ME.[12] This effect originates from stronger market integration across regions in E3ME (than in WEGDYN), since there is homogeneity assumed for domestically produced goods and imported goods. However, with a low cost

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[12] This effect originates from stronger market integration across regions in E3ME (than in WEGDYN), since there is homogeneity assumed for domestically produced goods and imported goods.

specification the price effects show different signs and developments over time, with constantly declining prices under the full capacity assumption (starting right after the beginning of the transition), and a rise-and-fall development under the output gap assumption, with a decline in prices only after the investment phase has ended. Nevertheless, price developments after the investment phase has ended are very similar (parallel downward trend) between the *full capacity utilization* and the *output gap* cases. To understand the macroeconomic uncertainty we need to understand how price changes emerge under the two different macroeconomic approaches. As stated in section 4.1.1, under the full capacity utilization assumption price changes are explained by changes in relative unit costs between the baseline technology and the process-emission-free iron and steel technology. The relative unit costs change over time, as they are accompanied by an exogenously given CO_2 price and endogenous price effects for inputs such as coke, production factors (capital, labor) and electricity. When assuming an output gap, any additional demand increases the price level, since there is no compensating effect via demand reductions elsewhere in the economy. In contrast, in the case of full capacity utilization, in which the economy's production resources are constrained, additional demand in one place of the economy does not increase price levels (at least not strongly), since this additional demand has to be balanced out by reductions elsewhere. This is why even with the low cost specification prices are rising when assuming an output gap; though not as strong as with the high cost specification.

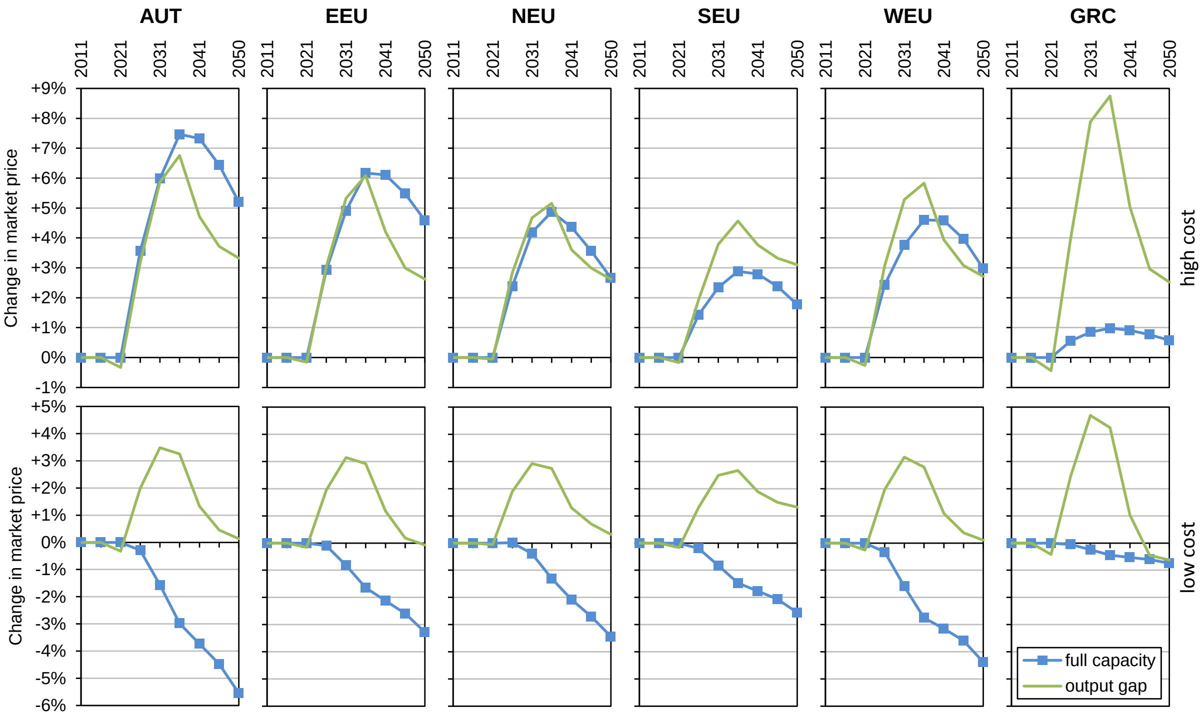

Figure 6 Change of regional iron and steel market prices, relative to the baseline scenario assuming SSP2, globally reluctant climate policy and variations on the macroeconomic uncertainty layer ("full capacity utilization" or "output gap" assumption).

In the post-Keynesian model, demand does not respond strongly to price changes and consequently output of the iron and steel sector also does not change substantially (see Figure A10 for details).This holds true for both the high and the low cost specification. Iron and steel output quantities change between ±0.5% during the investment phase (stimulus from expanding economy-wide investment). After the investment phase (starting in 2036) effects are very small, with slight variations across regions, due to competition effects on the international iron and steel market. As explained in section 4.1.1, under the assumption of full capacity utilization output reacts stronger and in different directions, depending on regional characteristics and the assumed cost specification (see Figure A3). Thus, large uncertainties are connected to the degree of factor utilization (*full capacity utilization* versus *output gap assumption*).

At the aggregate level (Figure 7) and under the output gap-assumption, EU-wide GDP is higher by up to +0.25% during the transition phase and remains nearly unchanged thereafter (for both technology cost cases), while the long-term supply-side-oriented approach of assuming full capacity utilization indicates for the low cost case a lower GDP during the transition by up to -0.1%, with potential GDP gains after the transition has been completed (+0.5% in 2050). In the high cost case, GDP effects are negative, with a lower GDP at EU level by -1.4% (in 2050). Hence, uncertainties are again large with regard to the degree of factor utilization (see Figure A11-Figure A13 for details on regional GDP and welfare effects).

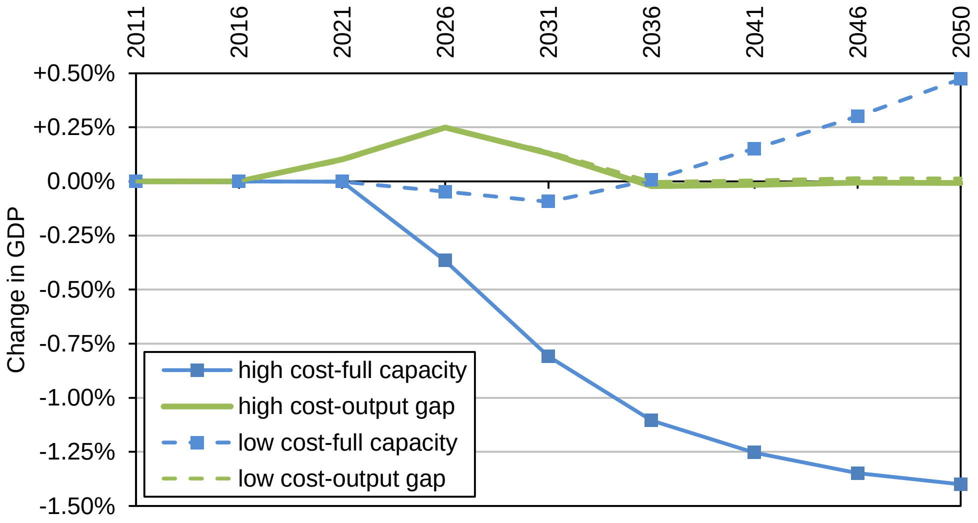

Figure 7 Change of EU-wide GDP, relative to the baseline scenario assuming SSP2, globally reluctant climate policy and variations on the macroeconomic uncertainty layer (“full capacity utilization” or “output gap” assumption).

4.3. Discussion

Our results concerning uncertainty are summarized in **Error! Reference source not found.** (top row: high technology cost; bottom row: low technology cost specification). We show how results for the indicator of EU-wide GDP and welfare deviate from the main scenario (i.e. SSP2, globally reluctant climate policy and full capacity utilization, indicated as vertical dashed line), when varying assumptions on the different uncertainty layers (socio-economic, climate policy and macro-economic). In addition, we show the variation of regional effects (within the main scenario), coming from differences in regional characteristics. The uncertainty spreads are given for (i) the end year of the analysis (2050) indicated as vertical black dashes (i.e. the long-run effect) and (ii) the range of effects across the time period in which production of the new technologies is already running (2036-2050), depicting possible short-run effects along the way until 2050, indicated by cross marks (labeled "short-run range extension").

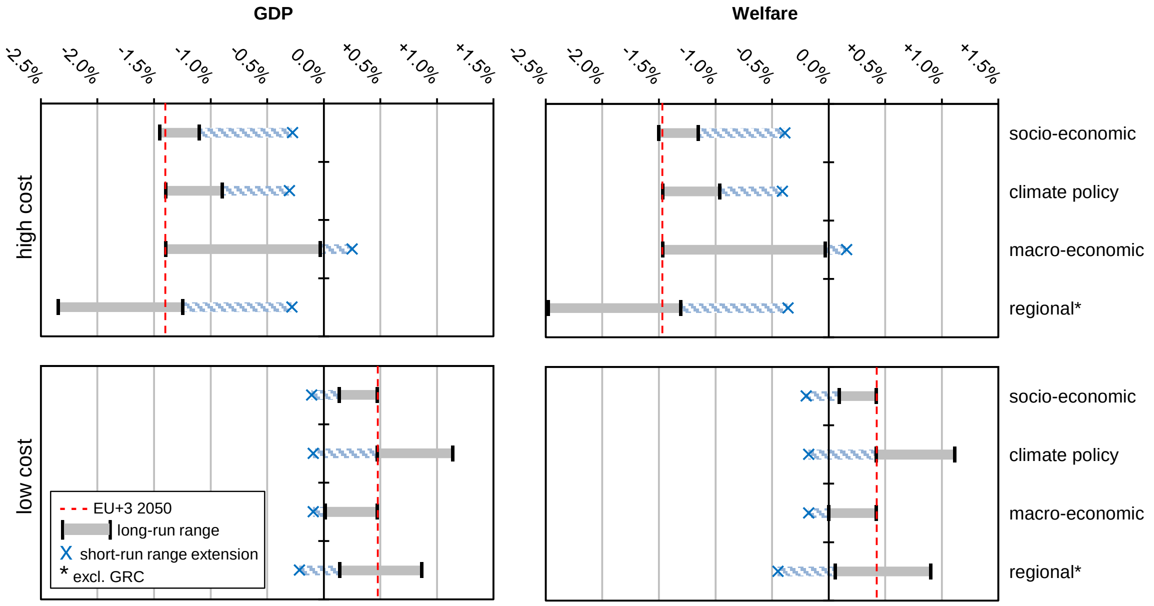

Figure 8 Uncertainty ranges of EU-wide GDP and welfare change, relative to baseline scenario, across main scenario results (main scenario result level indicated by dashed line). Upper panels: high technology cost specification; lower panels: low technology cost specification.

We find that for the high cost technology specification, short-run effects are less severe, than in the long-run (in 2050). A significant result is that there is a very large uncertainty range from the macro-economic uncertainty layer with results ranging from -1.4% to close to zero. The relatively strong negative impact results from the full capacity utilization assumption, whereas the less severe (close to zero) impact results from the output gap assumption. Note that in the short-run we even observe a temporary positive effect, when assuming an output gap. Another finding is, that there is a relatively broad regional spread, given the diversity of economic structures and factor endowments across Europe, with negative GDP effects up to a GDP lower by -2.3% (Eastern Europe), whereas the "lucky loser" is confronted with only -1.3% (Northern Europe). The uncertainty from both the socio-economic and climate policy layer is smaller.

For the low technology cost specification, we find that the short-run effects might be negative (and that short-run unemployment could increase), however, long-run effects are positive throughout, but again with larger uncertainties on the macroeconomic layer, with effects close to zero when assuming an output gap. For this technology specification there are also larger uncertainties at the climate policy layer (as the carbon price can trigger a stronger relative competitive advantage over the conventional technology), with a globally ambitious climate change policy being the best case. Again, there is a relatively broad regional range of macroeconomic impacts.

5. Conclusions

In the literature, various attempts have been made to address uncertainty within macroeconomic frameworks. However most studies only cover one of the three types of uncertainty as they are characterized by the IPCC (Kunreuther et al., 2014), most often addressing *epistemic* uncertainty, but not *paradigmatic* and *translational* uncertainty. For the case of the European iron and steel industry transition towards process-emission-free production, we carry out a systematic analysis of the potential economy-wide effects, addressing all of the three types of uncertainty. Our analysis clearly shows that uncertainties are large, however, they need to be interpreted with care to draw conclusions.

For technological uncertainty, we see that macro-economic implications can be either positive in case of the introduction of a low cost technology or negative in case of a high cost alternative, which would imply a rather large uncertainty. However, we need to be aware that the choice of production technology is made by business executives. From such a perspective it might be too risky to go for a technology which is still in its infancy, although it is characterized by low costs and might trigger macroeconomic gains (in both GDP and welfare). If there is a window of opportunity that “forces” businesses to make a decision in favor of a low-carbon technology, they may opt for the more mature, but costlier, technology, and society would have to accept macro-losses. We conclude that a discussion on how policy can help to reduce such losses and possibly induce a mix of technologies to diversify risk seems to be needed.

Regarding socio-economic uncertainty, we make use of different SSPs, which describe different socio-economic background developments in which the transition takes place. Here we find that effects are relatively robust, however, socio-economic uncertainties also concern regional differences. While we have explored them elsewhere (Mayer et al., 2017), they are likely to interact with the uncertainties explored here. We find that the macro-economic effects are co-determined relatively strong by regional characteristics, such as capital and labor intensities (i.e. how much of value added is created by capital and/or labor), foreign trade patterns (the degree to which regions rely on imports) and the regional and inter-sectoral dependency on iron and steel itself (both on the demand and supply side). In addition, over the course of economic development, different regions show different trajectories, most prominently regarding growth of the labor force and capital stock as well as the development of relative prices, which co-determine the regional effects. To isolate or decompose the most important regional drivers of uncertainty, as we have indicated here, is an important, new and promising avenue also for further future research. Nevertheless we can conclude that low carbon transition pathways should be region specific and that transferability of regional case studies to other regions seems to be limited.

Uncertainty originating from climate policy layer seems to be smaller than from other layers, since here we observe a clear signal concerning the direction of results. Not surprisingly, we find that in a world with a more stringent climate policy the potential losses from a transition are smaller, and potential gains are stronger. Interestingly, we find that in the case of a low carbon transition of the iron and steel sector, GDP and welfare effects are rather insensitive to non-EU policy.

Next to epistemic uncertainty, we also address paradigmatic and translational uncertainty by deploying two fundamentally different modeling approaches. First, the general equilibrium approach emphasizes potential supply side constraints and a rather long-term perspective, while, second, the post-Keynesian demand-side oriented approach presupposes that additional demand can be met and that the supply side will adjust, which thus fits best in a situation of sufficient idle capacity (i.e. under-utilization of production capacity, or an output gap). We find that the initial parameterization, and more so the underlying theoretical assumption of whether the macroeconomic state is described better by the general equilibrium or post-Keynesian approach, crucially determines not only the magnitude, but also the direction of change in (macro-)economic indicators. In a general equilibrium setting, higher long term GDP (and welfare) only materializes when the new technology has a cost advantage over the traditional one (also considering carbon pricing), meaning that productivity can be increased. This advantage fully materializes after the physical investment phase has been completed. However, when using a post-Keynesian approach, any additional (investment) demand raises output and GDP. In the transition analyzed here, the additional investment demand for new facilities is a significant demand component. Thus, applying a post-Keynesian model we find that output (both across the economy and in the steel sector) as well as GDP rise during the investment phase, and going back or close to baseline levels thereafter, without any strong long term effects, irrespective of changes in production cost (dis-)advantages. From these findings we conclude as follows. First, we emphasize that the short and long run effects might be very different, with potential negative effects in the transition phase, but long-run and sustainable macroeconomic benefits. Second we conclude that from a policy-makers perspective the model choice for policy analysis, and the implicit assumptions of the macroeconomic state (full capacity utilization or output gap), are highly relevant and should be made with great care. We find that the choice of the used model might pre-determine the results of the policy to be analyzed. This means that the research community as a whole should be more transparent, in order to inform policy makers about the underlying assumptions. Also results should be presented in the right context. We also suggest a more entangled cooperation between different macroeconomic modeling groups who use different approaches; such general equilibrium and post-Keynesian modelers.

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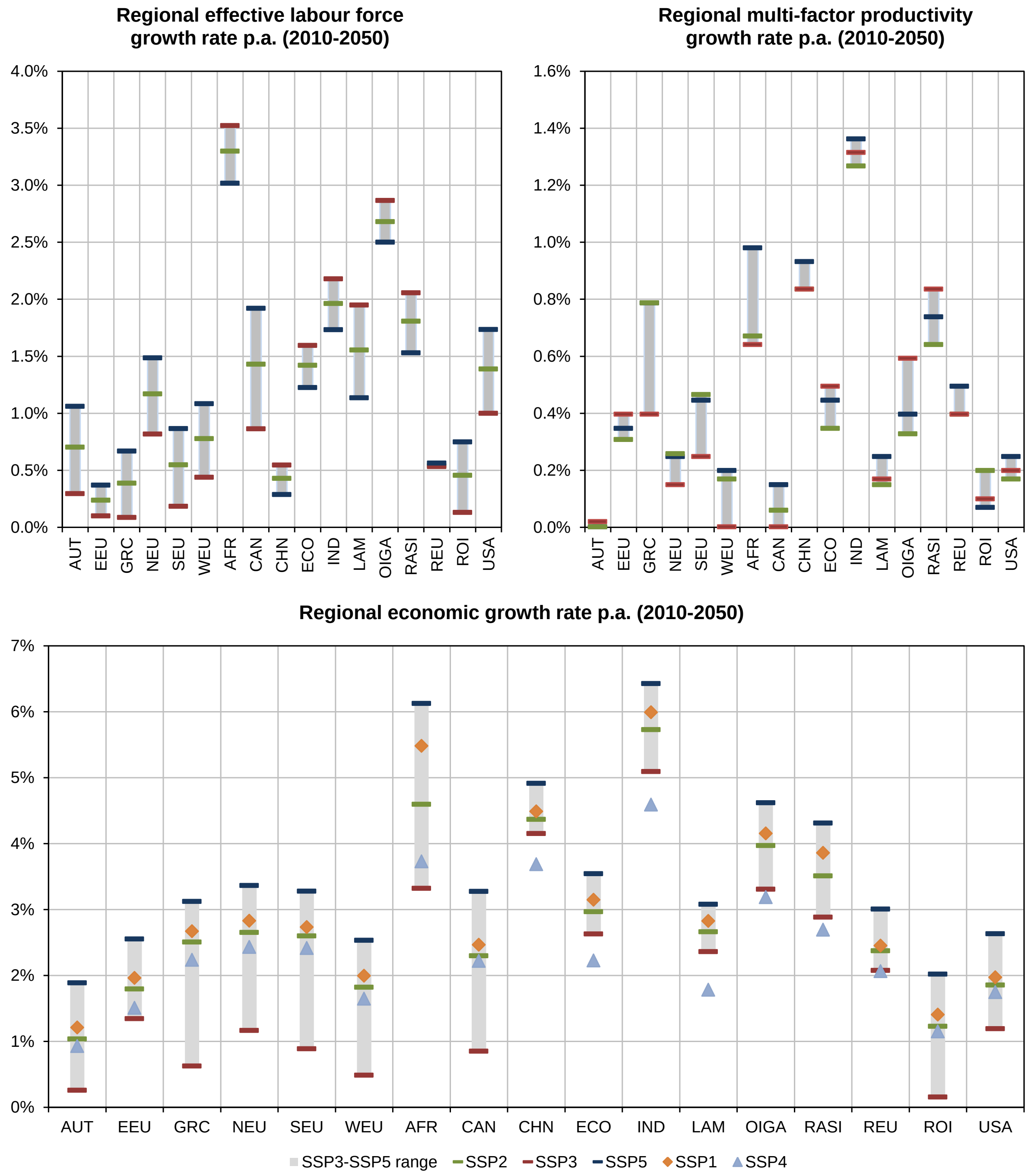
Appendix



Regional effective labour force growth rate p.a. (2010-2050)

Regional multi-factor productivity growth rate p.a. (2010-2050)

Regional economic growth rate p.a. (2010-2050)

Figure A1 GDP growth assumptions across model regions and SSPs (based on IIASA, 2017)

Table A1 Regional long term capital depreciation rates (deltaL); calculated from Penn World Table data (Feenstra et al., 2015) using annual depreciation rates delta, capital stocks KS in the period of 1990-2011 and the equation shown below the table.

region	deltaL	region	deltaL
AUT	0.0450	ECO	0.0422
EEU	0.0453	IND	0.0528
GRC	0.0294	LAM	0.0407
NEU	0.0429	OIGA	0.0481
SEU	0.0388	RASI	0.0561
WEU	0.0407	REU	0.0509
AFR	0.0463	ROI	0.0489
CAN	0.0404	USA	0.0490
CHN	0.0506		

$$deltaL = \frac{\sum_{t=1990}^{2011}(delta_t * KS_t)}{\sum_{t=1990}^{2011} KS_t}$$

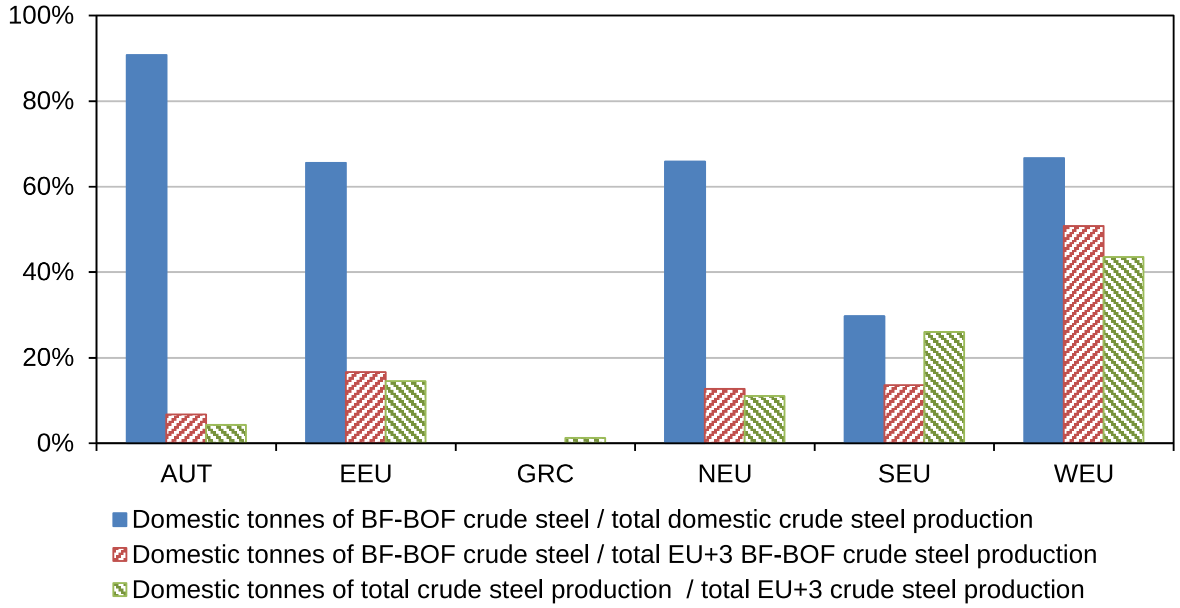


Figure A2 BF-BOF crude steel production 2011 in EU+3 countries (i.e. EU28+ Norway, Iceland and Liechtenstein) based on (WSA, 2012).

Table A2 Sector aggregates of the WEGDYN model

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 (Iron and Steel)
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 A3 Regional aggregates of the WEGDYN model

Model code	Aggregate name	Aggregated countries
AUT	Austria	Austria
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	Greece, Croatia, Cyprus, Spain, Italy, Malta, Portugal
WEU	Western Europe	Belgium, Germany, France, Liechtenstein, Iceland, Luxembourg, Netherlands
CHN	China	China
IND	India	India
CAN	Canada	Canada
USA	USA	USA
REU	Rest of Europe	Albania, Switzerland, Bosnia-Herzegovina, Makedonia, Serbia, Moldavia
ROI	Rest of industrialised 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

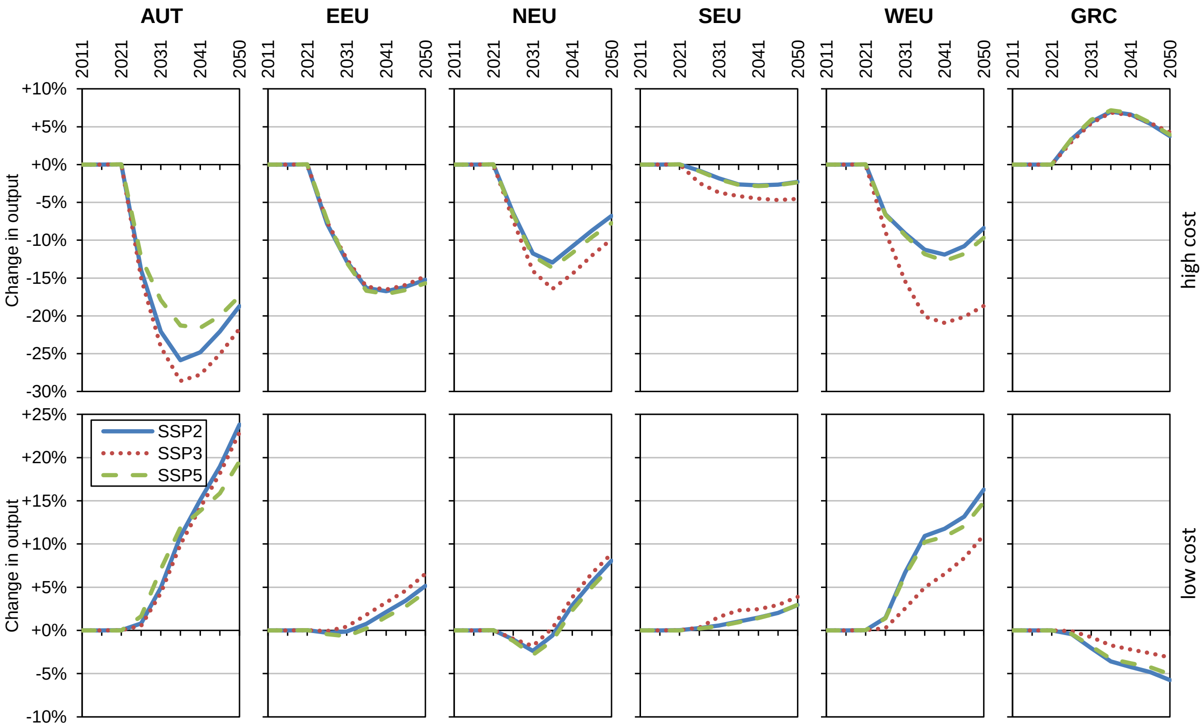


Figure A3 Regional changes of iron and steel output, relative to the baseline scenario with SSP variations on the socio-economic uncertainty layer (assuming reluctant climate policy and full capacity utilization).

Figure A3 provides regional output effects. With a high cost specification, output is lower relative to the baseline, with the strongest price effects leading to the strongest output effects. Output is lower by up to -29% (Austria). Note that there is no replacement of steelmaking processes in Greece, which leads to a competitive advantage in the high cost case and thus higher output (up to +7%). With a low cost specification the opposite is the case, with higher output levels by up to +24% (Austria), but lower output in Greece (-6%). Again, concerning the socio-economic uncertainty, our results are robust in terms of direction and for most regions also in terms of magnitude, with exceptions for SSP3 (for the same reason as explained for the price effects).

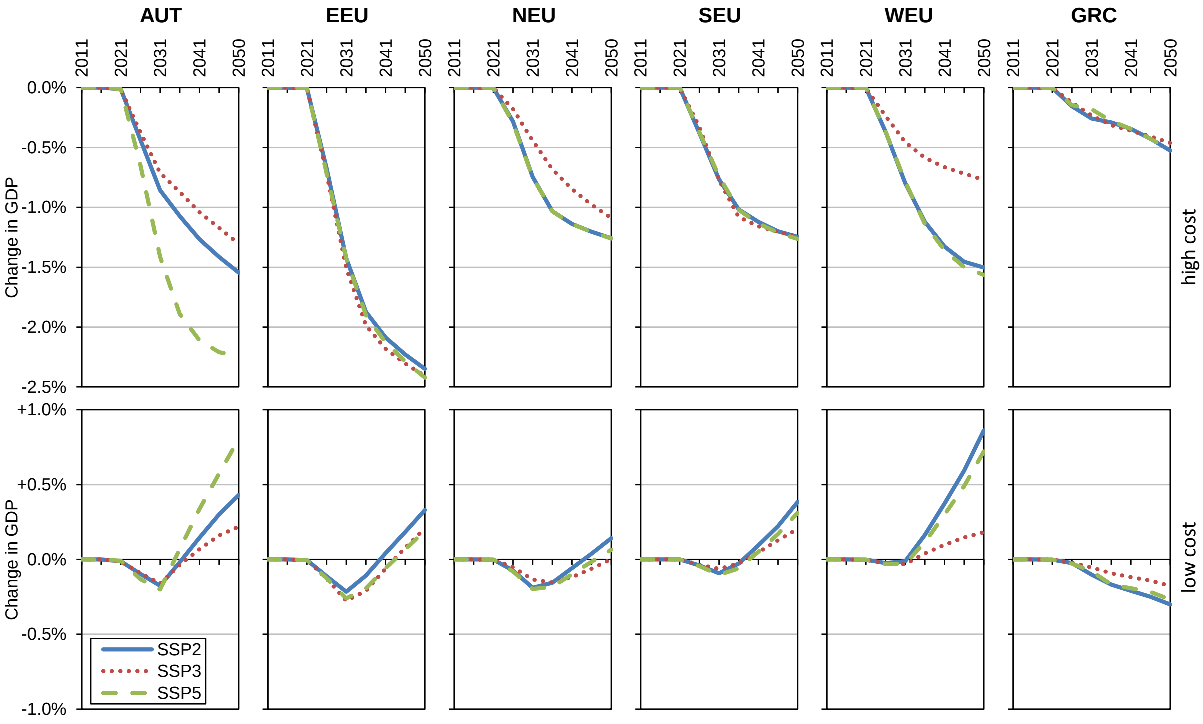


Figure A4 Change of regional GDP, relative to the baseline scenario with SSP variations on the socio-economic uncertainty layer (assuming reluctant climate policy and full capacity utilization).

The regional differences (as given in Figure A4) can be traced back to the share of BF-BOF technology in a region's steel production (highest in AUT, followed by WEU, NEU and EEU), but when looking at GDP we also need to account for the iron and steel sector's contribution to regional output, which is comparably high in EEU (about 2%)[13], which is precisely the region with the strongest negative GDP effect in the high cost specification. However, for a low cost technology switch we can see that the positive GDP effects are strongest in WEU (with medium iron and steel output share). Thus, the specific regional implications depend not only on the prevalent share of BF-BOF to be phased out but on various factors including *inter alia* responsiveness (i.e. sensitivity) of intermediate and final demand in foreign and domestic markets.[14] Regarding socio-economic uncertainty, we see that results are robust in terms of direction and magnitude for most regions. Exceptions are AUT and WEU, with relatively large differences in magnitude across SSPs. The greater variation in AUT and WEU can be explained by the different regional composition of growth factors under different SSPs (multi-factor productivity, effective labor force growth and capital endowment) contributing to economic growth measured by GDP. In NEU the sign of the effects in 2050 becomes unclear in the low cost case, however, the trend points to positive GDP implications in the long-term, regardless of

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[13] Regional output share of the iron and steel sector: AUT: 1.5%; GRC: 0.9%; EEU: 2.0%; NEU: 0.9%; SEU: 1.3%; WEU: 1.3% (Aguiar et al., 2016).

[14] To trace back every single regional composition effect is out of scope of this paper but should be scrutinized in more depth in future work.

the socio-economic background assumption. Summarizing, for both high and low cost specifications the regional GDP implications are robust regarding socio-economic uncertainty but less strong under SSP3. This applies particularly for the relative change in GDP in WEU, which is primarily due to comparably low multi-factor productivity growth (cf. Figure A1 in the Appendix).

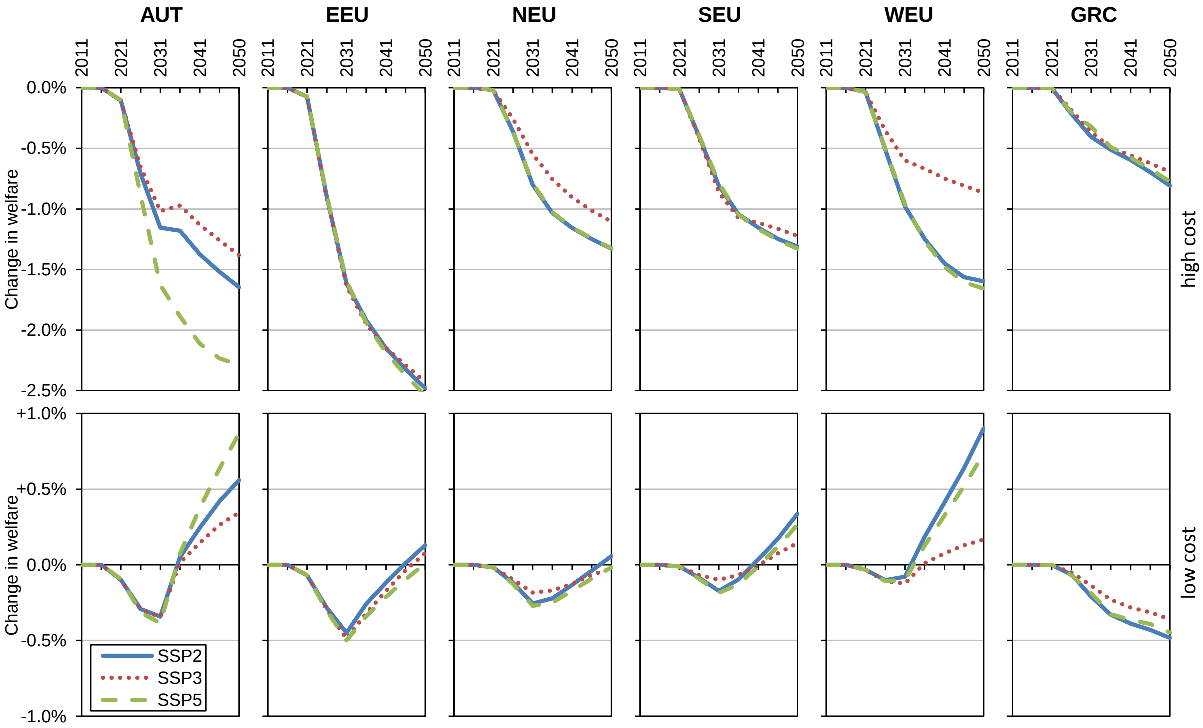

Figure A5 Change of regional welfare (Hicksian Equivalent Variation), relative to the baseline scenario with SSP variations on the socio-economic uncertainty layer (assuming reluctant climate policy and fully capacity utilization).

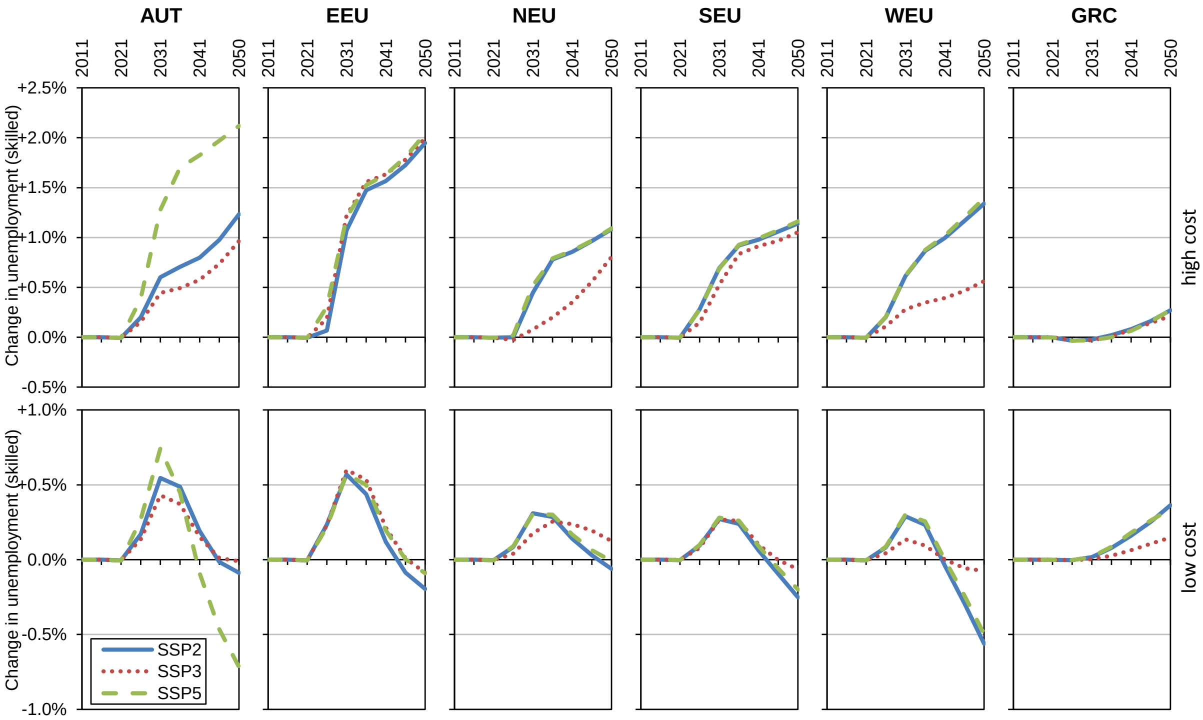

Figure A6 Change of unemployment (%-points) of the skilled labor force, relative to the baseline scenario with SSP variations on the socio-economic uncertainty layer (assuming reluctant climate policy and full capacity utilization).

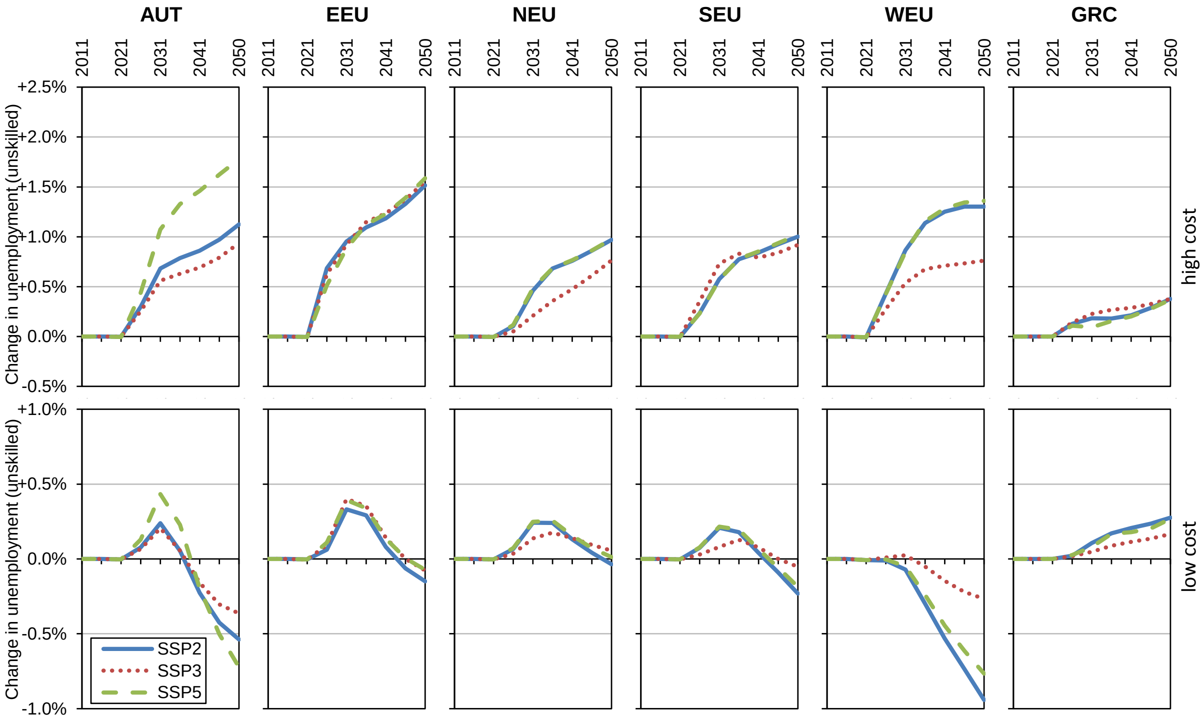

Figure A7 Change of unemployment (%-points) of the unskilled labor force, relative to the baseline scenario with SSP variations on the socio-economic uncertainty layer (assuming reluctant climate policy and fully capacity utilization).

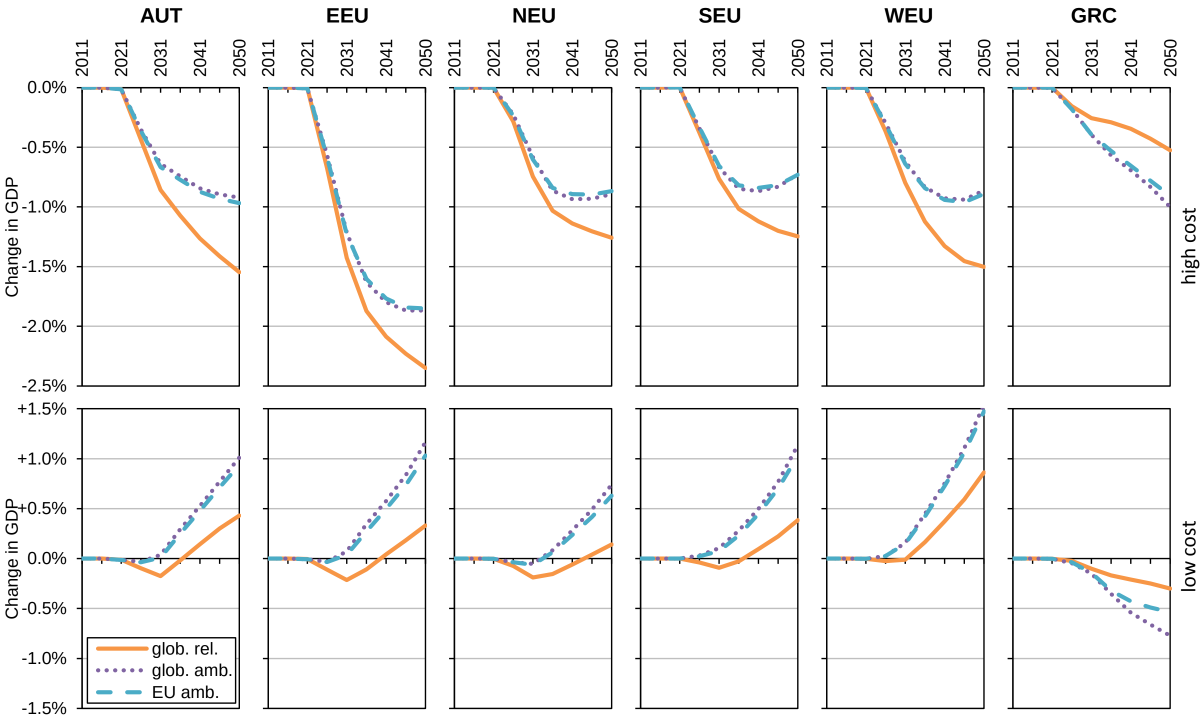

Figure A8 Change of regional GDP, relative to the baseline scenario in different policy-worlds, assuming SSP2 and full capacity utilization (globally reluctant: €46/tCO$_2$ by 2050; globally ambitious: €138/tCO$_2$ by 2050; EU ambitious: €138/tCO$_2$ in EU-ETS only and €46/tCO$_2$ in the rest of the world).

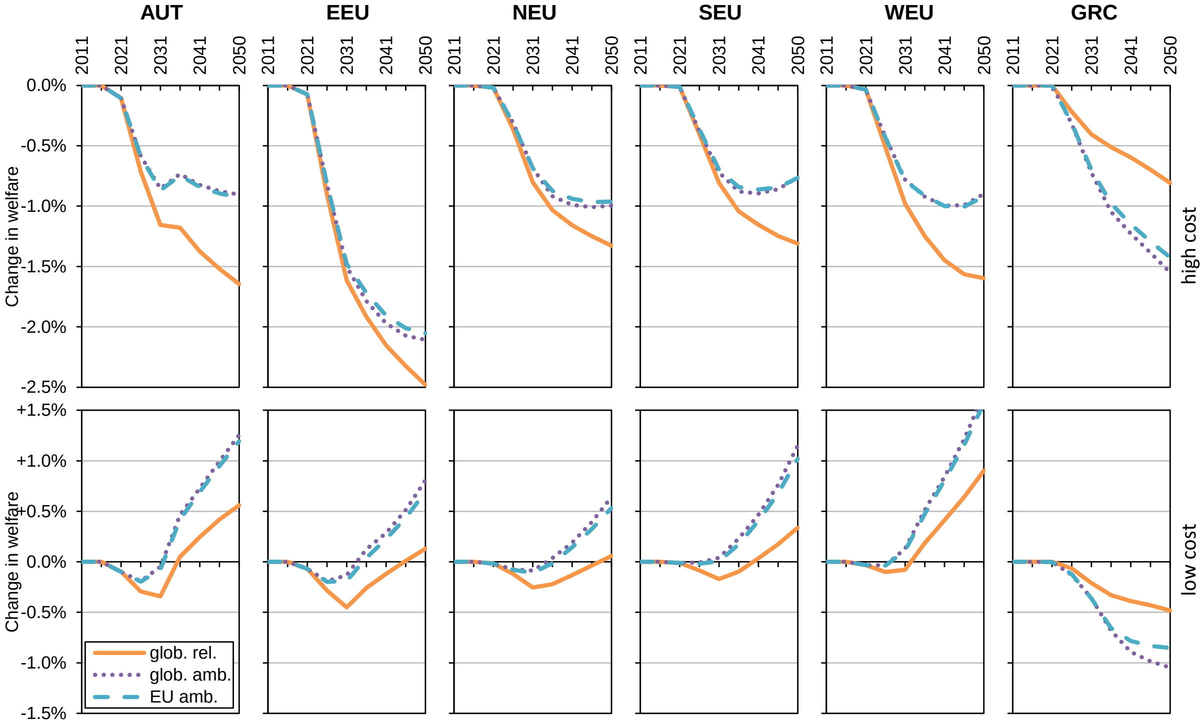

Figure A9 Change of regional welfare effects, relative to the baseline scenario in different policy-worlds, assuming SSP2 and full capacity utilization (globally reluctant: €46/tCO$_2$ by 2050; globally ambitious: €138/tCO$_2$ by 2050; EU ambitious: €138/tCO$_2$ in EU-ETS only and €46/tCO$_2$ in the rest of the world).

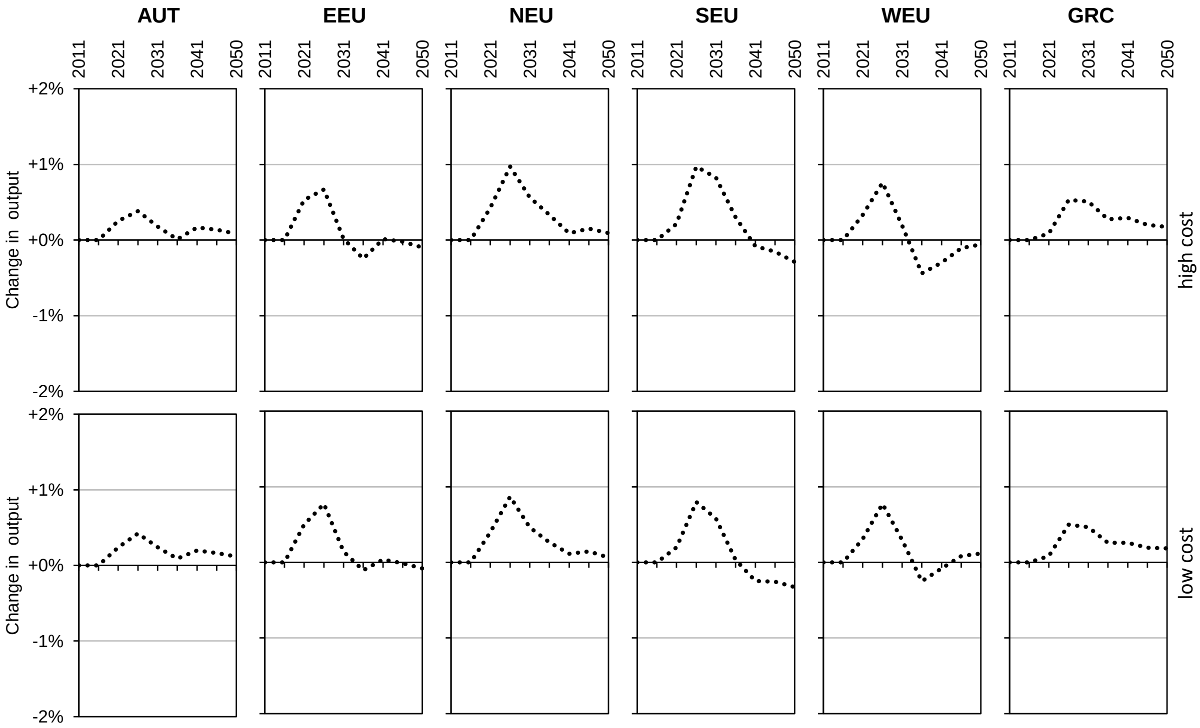

Figure A10 Change of regional iron and steel output effects, assuming SSP2, globally reluctant climate policy and output gap (E3ME model)

Figure A10 shows the regional output effects of the iron and steel sector when assuming an output gap (E3ME model), with slight negative effects after the investment phase emerging in EEU, SEU and WEU and slight positive effects in those regions with a competitive advantage (AUT and NEU). For comparison, when assuming full capacity utilization (WEGDYN model) we observe lower output levels of up to -25% (yet in the transition phase itself, with less severe impacts after transition has been completed).

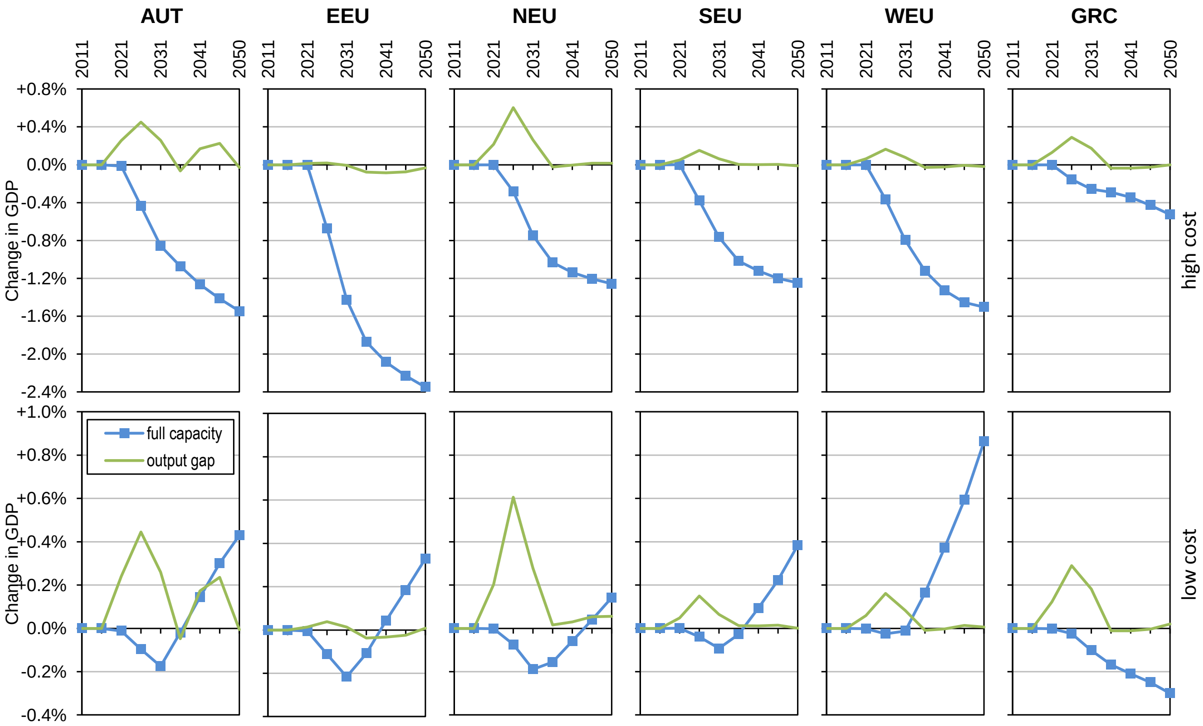

Figure A11 Change of regional GDP, relative to the baseline scenario assuming SSP2, globally reluctant climate policy and variations on the macroeconomic uncertainty layer (“full capacity utilization” or “output gap” assumption).

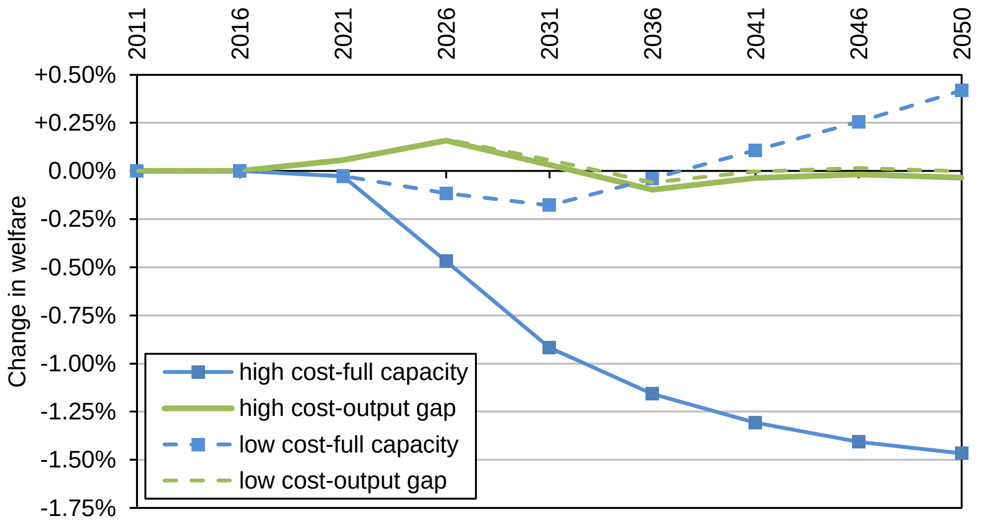

Figure A12 Change of EU-wide welfare (for E3ME: change in consumption quantities), relative to the baseline scenario assuming SSP2, globally reluctant climate policy and variations on the macroeconomic uncertainty layer (“full capacity utilization” or “output gap” assumption).

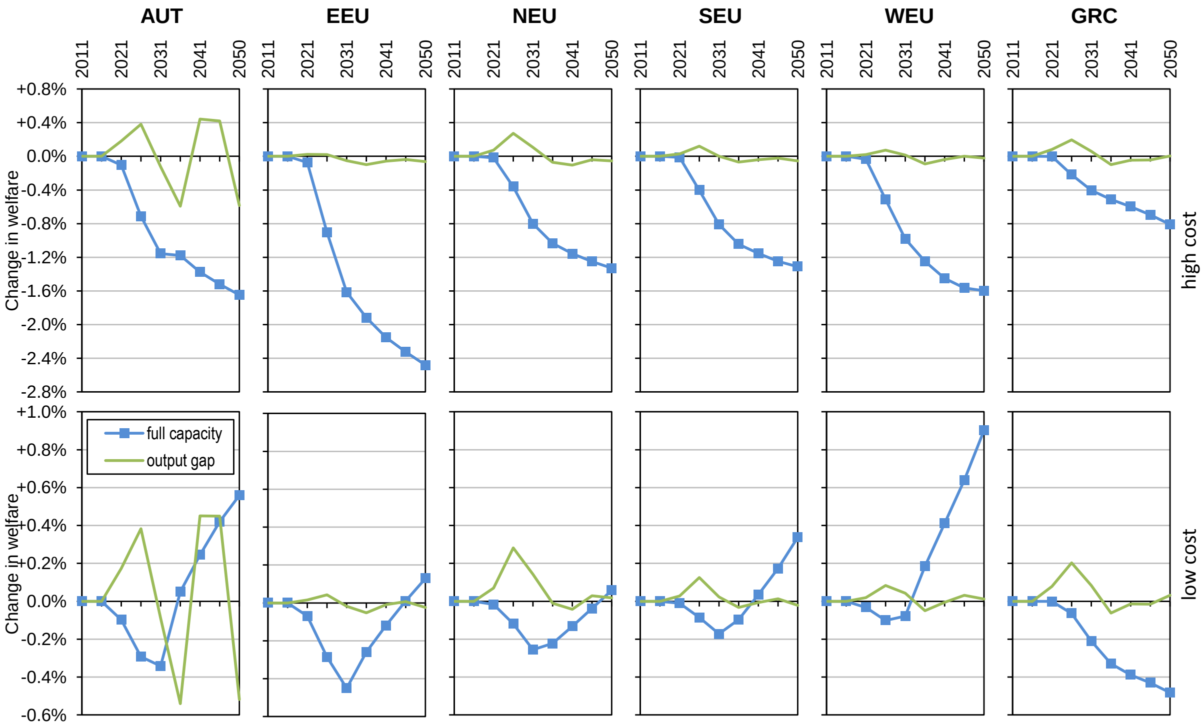

Figure A13 Change of regional welfare (for E3ME: change in consumption quantities), relative to the baseline scenario assuming SSP2, globally reluctant climate policy and variations on the macroeconomic uncertainty layer (“full capacity utilization” or “output gap” assumption).