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Uncertainties in macroeconomic assessments of low-carbon transition pathways - The case of the European iron and steel industry

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ABSTRACT

The climate targets agreed in Paris 2015 render deep decarbonization of energy- and emission-intensive industries crucial. Policy makers are interested in the macroeconomic consequences of such decarbonization pathways and often rely on integrated modelling studies. However, the underlying modelling assumptions and uncertainties 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 influence results. We show that effects strongly depend on technology choice, prevailing macroeconomic states as well as regional characteristics. The underlying socio-economic development and the climate policy trajectory seem to play a less important role. Particularly, we find that the choice of model, i.e. which macroeconomic theory strand it arises from, influences the sign and magnitude of macroeconomic effects and thus should be well understood in terms of appropriate interpretations by both modelers and policy makers. We emphasize that model assumptions should be transparent, results sought as to be robust across a range of possible contexts, and presented together with the conditions under which they are valid. To that end, co-design and co-production in research would support its relevance and applicability.

1. Introduction

By mid-century, the net balance of annual greenhouse gas (GHG) emissions needs to be at least neutral to meet the climate targets as defined in the Paris Agreement. This demands fundamental changes in the socio-economic systems (Rockström et al., 2017), which might trigger a multitude of economy-wide effects that are in synergy or conflict with other societal objectives (e.g. full employment). Due to the complexity of the socio-economic system, these effects are surrounded by a broad spectrum of uncertainties, which deserves attention (Aldred, 2012; Roelich and Giesekam, 2019).

In 2015, for UNFCCC Annex I countries, the highest share of GHG emissions related to the combustion of fossil fuels (81%) (UNFCCC, 2017). A further, non-negligible, portion was comprised of industrial process emissions (7%).[1] Thus, to achieve the goals as set out in the Paris Agreement, industrial process emissions also need to be reduced (if demands on negative emissions should not be excessive). Considering that all sectors where process emissions occur are substantially trade exposed and that process emissions often account for the dominant share of emissions of these sectors, the required process emission reduction implies a significant potential macroeconomic risk. Nevertheless, compared to the analysis of combustion-based emissions, only a narrow strand of literature focuses on the macroeconomic implications of measures to tackle industrial process emissions (examples are Bednar-Friedl et al., 2012; Pang et al., 2014; Schinko et al., 2014). In our analysis, we contribute to this crucial strand of the literature and focus on the economy-wide effects of the low-carbon transition of the European iron and steel sector. As the steel sector is deeply interwoven in modern economies and expected to play a key role in the low-carbon transition as supplier of high-tech materials, many factors might co-determine how and in which direction the economy-wide effects materialize. Thus, the iron and steel sector serves as an excellent case for the analysis of risks and uncertainties as unintended outcomes might be severe and manifold. In this article we build upon the analysis of Mayer

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[1] The remaining shares refer to Agriculture (8%), Waste (3%) and other activities.

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et al. (2019) who indicate the presence of large uncertainties, which we here explore in more depth.

We introduce and operationalize different layers of uncertainty (for technology, socio-economics, policy, and macroeconomics), each of which represents incomplete knowledge of different aspects of the problem at hand. Special emphasis is placed on the macroeconomic layer, where we compare the results of two different macroeconomic modelling approaches. Specifically, we run a computable general equilibrium (CGE) model (in spirit "neo-classical") and a Post Keynesian macro-econometric (PKME) model in their standard-setups. Thereby we reveal methodological uncertainty, but also uncertainty at the science-policy interface, since the commissioning of modelling studies happens routinely and potentially without much reflection on each modelling team's attribution to a specific school of thought. This in turn might co-determine results and policy recommendations.

The core goals of this paper are: first to pinpoint those layers which drive uncertainties concerning the magnitude and direction of economy-wide effects of low-carbon transitions; and second to relate these uncertainties to each other. To the authors' best knowledge, a systematic and comprehensive analysis of uncertainties, as it is carried out here, has not been published so far.

The remainder of the paper is structured as follows. In Section 2 we comprehensively review the literature and clarify our contribution. In Section 3 we develop the uncertainty framework, its layers and describe the methods and assumptions to operationalize them. In Section 4 we present results and discuss them. In Section 5 we draw conclusions.

2. Concepts of uncertainty in extant macroeconomic research

The literature offers many definitions of uncertainty. One used prominently was given by Knight (1921), who emphasizes that uncertainty is an *immeasurable* lack of knowledge, whereas risk is measurable via probability with known possible outcomes. In different schools of economic thinking, however, uncertainty is interpreted and treated differently, e.g. in Keynesian economics there is an emphasis on immeasurable uncertainty. In *A Treatise on Probability* Keynes distinguishes between the "weight" and the "probability" of an argument (Keynes, 1921), with the former being described as "*the degree of completeness of the information*" (Runde, 1990, p. 276). Sixteen years later[2] he *explicitly* framed "uncertainty" in his *General Theory* as matters for which "*there is no scientific basis on which to form any calculable probability whatever. We simply do not know.*" (Keynes, 1937, p. 214). For Keynes uncertainty is an essential cause for "hoarding money" (thus for liquidity), leading to reluctant investment, spare production capacities and involuntary unemployment (Lucarelli, 2010). Influential Post Keynesian economists such as Shackle (1943; cit. in Zappia, 2014), or later Davidson (1991) followed this thinking and thus Keynesian uncertainty is still very salient for Post Keynesian economists. A more recent interpretation of this causality is that "fundamental uncertainty" makes it impossible for agents to use all available resources fully (Mercure et al., 2019), leading to idle available resources. Another early statement on uncertainty in (Ecological) economics was given by Georgescu-Roegen (1954, p. 524), referring to Knight and Keynes: "*In the case of risk, but not in the case of uncertainty, we can define the probability of the outcome.*" Neoclassical economics, on the other hand, treats probabilistic risk and uncertainty synonymously; expectations are at the center, which are based on past data and respective probabilities or on subjective perceptions on probabilities. From a mainstream perspective the demand for liquidity is thus irrational (Davidson, 1991; Machina, 1987) and money is neutral.

The importance of the different treatment of uncertainty in different economic schools is emphasized by Mercure et al. (2019, p. 1023): "*The theoretical difference between the schools has at its heart a difference in the treatment of risk and uncertainty*" and Davidson (1991, p. 141) concludes that "*The analyst must* (…) *choose which system is more relevant for analyzing the economic problem under study.*" Hence, uncertainty plays different roles in different economic schools and co-determines how respective models work, but there is no agreed handling of uncertainty in economics.

So far we have touched upon how uncertainty is treated *within* economics,[3] however, uncertainty also plays an important role at the science-policy interface. This is emphasized by the IPCC (Kunreuther et al., 2014, p. 155), who 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.*" They further differentiate three different types of uncertainty. 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, on methods for scientifically investigating them, and on how to combine knowledge from disparate research traditions.*" Third, translational uncertainty "*results from scientific results that are incomplete or conflicting so that they can be invoked to support divergent policy positions.*" (ibid., p. 178).

For the operationalization of uncertainty in empirical economic research, the IPCCs typology might be too blurry, though. For example, the choice between a Neoclassical or Post Keynesian macroeconomic model would be subject to uncertainty on two issues: how to characterize phenomena (epistemic uncertainty) *and* the absence of agreement on how to investigate a problem (paradigmatic uncertainty). Moreover, in the literature epistemic uncertainty is typically contrasted with (irreducible) aleatoric uncertainty or variability (see e.g. Basu, 2017; Bjarnadottir et al., 2019; Morales-Torres et al., 2019; Walker et al., 2003), with epistemic uncertainty resulting from not enough knowledge to properly describe a system (parameters but also functional relationships), whereas aleatoric uncertainty results from randomness. Using this typology, macroeconomic model uncertainty is clearly epistemic for those models which are currently predominantly used (deterministic models), but might be also aleatoric (or chaotic) when other approaches (such as system dynamics) are chosen.

For managing uncertainty in model-based decision support Walker et al. (2003) suggest a harmonized framework. They define uncertainty as "*any deviation from the unachievable ideal of completely deterministic knowledge of the relevant system*" (ibid., p. 5). The authors emphasize that uncertainty should be regarded along three dimensions: location (system boundary, model parameters and variables, functional relationships), level (spectrum known to unknown) and nature (epistemic versus variability). Refsgaard et al. (2007) further extend this framework and suggest suitable methodologies for addressing different types of uncertainty within the various dimensions.

Another – in our view very helpful – typology for uncertainty for applied policy-related science is given by Reilly and Willenbockel (2010), who refer to the seminal work by Funtowicz and Ravetz (1990), and differentiate between technical, methodological and epistemological uncertainty. Technical uncertainty refers to data quality for model calibration and the assumption for the drivers of change, methodological uncertainty refers to the structure, functional forms and behavioral equations of the model, and epistemological uncertainty refers to changes in human behavior and values, technological surprises and so called high impact-high uncertainty events, but also to deeper uncertainty such as randomness and surprises. Funtowicz and Ravetz (1990, p. 38) state that "*the more complex aspects of methodological*

[2] Although it is questionable whether Keynes followed his early theory of probability from 1921 when writing his *General Theory*, which was published in 1936 (O'Connell, 1996).

[3] Since climate policy assessment is currently strongly based on Neoclassical computable general equilibrium models, with Post Keynesian econometric input-output models gaining traction, the focus in this paper is on these two schools of thought.

uncertainty, and epistemological uncertainty as well, are outside the boundaries of any calculi.", thus going even beyond aleatoric uncertainty or variability, implicitly referring to immeasurable uncertainty in the Knightian sense.

For managing uncertainty, there are several approaches. Measurable uncertainty is usually addressed via probabilistic methodologies such as Monte Carlo simulations. More challenging is the management of immeasurable uncertainty. For that, a powerful approach is the creation of "alternative futures" (Dror, 1970) or scenario analysis (Refsgaard et al., 2007; Reilly and Willenbockel, 2010). Also Gowdy and Erickson (2005) suggest that scenario analysis with technical descriptions of particular economies should be used to address uncertainty (a "structural approach"; Duchin, 1998 cit. in Gowdy and Erickson, 2005), and propose the application of the precautionary principle. Methodological uncertainty and uncertainty about functional relationships or behavior (epistemic/epistemological) can be tackled via multi-model comparisons.[4]

We here aim to push the boundary of uncertainty appraisal in empirical macroeconomic policy-related research by going into deeper dimensions of uncertainty as it is usually done and to demonstrate that there are also major uncertainties at the science-policy interface. Our approach is motivated by the existing empirical literature on low-carbon transitions, where uncertainty appraisal is mostly done via scenario analysis, e.g. Fujimori et al. (2014) combine scenario assumptions on mitigation efforts and energy demand. An example for Monte Carlo simulations is given by Abler et al. (1999), who investigate economic and sectoral policies impacting environmental indicators, or by Babonneau et al. (2012) and Wang and Chen (2006) focusing on climate policies. An example of multi-model comparison is given by the Energy Modelling Forum 29 (Böhringer et al., 2012), however all of the models used are general equilibrium models, which all share the same basic functional mechanism.[5] The same is true for an analysis by Guivarch et al. (2016), who test for uncertainty across different socio-economic developments.

To summarize, and using the typology of Funtowicz and Ravetz (1990), current approaches most often do not go beyond technical uncertainty. Yet, for a fully-fledged assessment, it is essential to include methodological, and ideally epistemological, uncertainty. In the definition framework of Walker et al. (2003) this means to not only capture the location dimension of uncertainty, but also including the nature dimension. This ultimately leads to discussions on fundamental (in our case macroeconomic) questions, such as whether the economy is supply- or demand-driven, and which model to choose in which situation. This discussion is not new. For example already Dutt (1984) pointed out that the policy implications on income distribution are very different when assuming either a "supply-driven" or a "demand-driven" model. Yet, this dimension of uncertainty has so far not been carried over to the field of climate change economics as modelling groups of different schools, such as Neoclassical and Post Keynesian, mostly work in parallel strands, rather than together. Notable exceptions, and thus attempts for such an integrated analysis are offered by Edenhofer et al. (2010), Jansen and Klaassen (2000), Kober et al. (2016) or Meyer and Ahlert (2019), who all implicitly address this type of uncertainty (as each of them deploys different macroeconomic model types). However, the mentioned studies do not explicitly embed their findings in a broader framework of uncertainties – and most importantly, do not offer a comparison across different types. Only recently Mercure et al. (2019) conceptually discuss the differences between general equilibrium models and non-equilibrium models and the implications for (climate) policy; however, they only mention preliminary results of a modelling exercise in which two model of different type have been enhanced regarding innovation and finance, with convergence of models as a result. Our research contributes to this fundamental discussion on ecological macroeconomics (Fontana and Sawyer, 2016; Rezai and Stagl, 2016).

[4] At least if different theories and corresponding models for these relationships or behaviors are available.

[5] There are some models which allow for out of equilibrium conditions on certain markets (e.g. the labor market), but the main behavioral assumptions of optimization under budget/resource constraints are still the same.

3. Uncertainty layers, methods and scenarios

In this section we lay out our methodological framework. Our general approach is to combine different "uncertainty layers" to create different worlds in which a switch from a baseline technology (i.e. process emission-intensive steel production) to a process emission-free alternative takes place (see Fig. 1). The technology switch itself generates (i) the *technological uncertainty* layer, where a low and a high-cost technology specification span the uncertainty range on costs. The second layer (ii) captures *socio-economic uncertainty*, with variations across shared socio-economic pathways (SSPs). Third (iii), the *climate policy uncertainty* varies the stringency and geographic scope of climate policy. Fourth (iv), for the *macroeconomic uncertainty* layer we apply different macroeconomic model types, thereby changing the assumption of the prevailing macroeconomic state and also capturing uncertainty at the science-policy interface. The specific assumptions of the four layers are explained in Sections 3.1-to 3.4. To connect our methodology to the various typologies of uncertainty as discussed in Section 2, Table 1 assigns the layers to different types of uncertainty and briefly explains how these uncertainties are implemented in our modelling framework. Note, that in Table 1 we also include "other layers", as we do not want to claim completeness and because we treat translational uncertainty qualitatively when discussing our results. Relating our approach to the framework of Refsgaard et al. (2007), the quantitative part of our analysis combines multiple model simulations ("*having different conceptual models based on different* (…) *interpretations*"; ibid., p. 1550) and scenario analysis ("*deal explicitly with different assumptions about the future*"; ibid., p. 1551).

3.1. Technological uncertainty layer

There exist several technologies to produce process emission-free iron and steel, opening up the first uncertainty layer. We specify two alternative technologies, replacing the current CO_2-emission-intensive blast-furnace basic oxygen furnace route (BF-BOF). First, hydrogen-based direct reduced iron, which is fed into an electric arc furnace (DRI-H-EAF). This technology is mature and already in use, yet not based on hydrogen (H), but natural gas (CH_4). Second, plasma-direct-steel-production (PDSP); a single-step production process, with iron ore as the only relevant raw material input. PDSP is still in the experimental phase, but seems promising with respect to unit costs, flexibility of scale, steel quality and GHG emissions (Sabat and Murphy, 2017).

By analyzing present estimates of production cost range of a mature technology and one which is still in its infancy, we cover a broad range of uncertainty. The respective operation cost structures are given in Table A1. To broaden the cost range we also assume different industry specific electricity prices, leading to two techno-economic specifications: *High-cost* (i.e. DRI-H-EAF with electricity costs of 0.05 EUR/kWh) or *low-cost* (i.e. PDSP with 0.03 EUR/kWh). Thus, these two specifications presumably represent the extreme ends of the cost spectrum (at least according to the current knowledge) capturing as much of the uncertainty regarding unit costs as possible. Note, that the low-cost specification has still higher unit costs than the conventional technology (BF-BOF), thus representing the low-cost *alternative* specification. Also note, that during the investment phase, additional capital expenditures (annuities for new facilities) increase the unit cost of the new technologies (on top of the already higher operating costs). For the upscaling of the PDSP technology, further research and development (R &D) is required; how much is uncertain, though. We thus follow a

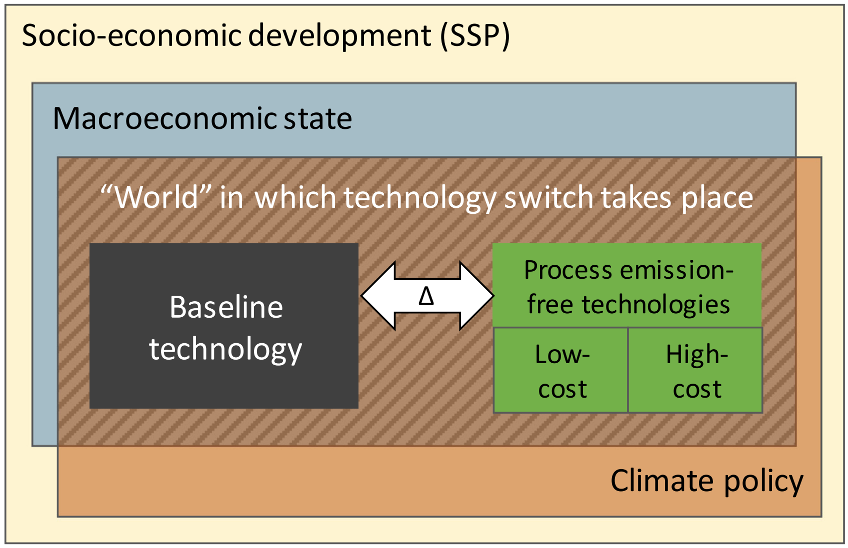

Fig. 1. Uncertainty framework and different layers of uncertainty, which in combination create the world in which the technology switch to a process emission-free iron and steel technology takes place.

pragmatic approach and assume that these R&D investments are financed publicly, but crowding out other R&D investment elsewhere, i.e. without an impact on the absolute level of economy-wide investment. For technological and cost details see the Appendix.

In our analysis the deployment of the new technologies is deterministic, i.e. exogenous, which we interpret as a zero-emission standard. The industry thus cannot simply decide to pay the carbon price and keep the conventional technology.

3.2. Socio-economic uncertainty layer

To capture socio-economic uncertainties, we deploy different SSPs, which are the standard scenarios in the climate change research community. SSP2 (O'Neill et al., 2017, 2014) is a "Middle of the road" socio-economic background development, with moderate climate change mitigation and adaptation challenges. We deploy additionally SSP3 and SSP5, which span the uncertainty range of regional economic growth rates for EU regions (see Fig. A2). The narrative of SSP3 is characterized by regional rivalry, which unfolds in slow economic growth and slow technological change, whereas SSP5 is characterized by strong growth and excessive (fossil) energy use. Compared to SSP2, the SSPs 3 and 5 imply higher challenges for mitigation (which we model by lower multi-factor productivity; see Fig. A2). SSP3 also implies higher challenges for adaptation due to low adaptation capacities (low income), whereas SSP5 is characterized by low adaptation challenges. To capture these differences, we mimic high/low adaptation challenges by increasing/decreasing capital depreciation (by ± 25%, relative to SSP2). This should serve as a representation of higher or lower vulnerability to climate change and thus differences in capital stock accumulation.[6] The long-term capital depreciation rates we use are given in Table A2.

3.3. Climate policy uncertainty layer

For the climate policy layer, we specify three different climate-policy settings. First, *reluctant policy* reflects a modest global CO_2 price, reaching 46 EUR_{2011}/tCO_2 globally by 2050 (based on IEA (2016); see Fig. 2). Second, *ambitious policy* reflects a more stringent policy by tripling the reluctant CO_2 price trajectory, so it reaches 138 EUR_{2011}/tCO_2 globally by 2050. This is in line with the Interagency Working Group on Social Cost of Carbon (IWGSCC, 2015)[7] and the 450 ppm scenario by the International Energy Agency (IEA, 2016).[8] The *ambitious policy* world thus may reflect an upper bound of politically feasible CO_2 pricing. Third, we set up an *EU-ambitious* case in which the EU (within its emission trading scheme, ETS) implements an *ambitious* policy but the rest of the world remaining *reluctant*.

3.4. Macroeconomic uncertainty layer

3.4.1. Macroeconomic models: full capacity utilization vs. available resources

At the macroeconomic uncertainty layer we use two macroeconomic model types, being based upon different underlying macroeconomic theories. One model is a computable general equilibrium (CGE) model, which describes the economy in a state of *full capacity utilization*. The basic idea behind CGE models is that all markets are in equilibrium (i.e. supply = demand) and this "general equilibrium" can be disturbed by an intervention (e.g. by an enforced switch to a new technology), triggering relative price changes as well as demand (quantity) adjustments until a new general equilibrium emerges. From the difference between new and old equilibrium we draw conclusions on how the economy reacts to the intervention. In recursive dynamic CGE models (which are predominantly used), such annual equilibria are extrapolated into the future via the connection of investment and capital accumulation over time. Hence, the investment activity in one year, determines the capital availability of the next year. The adjustment process that leads to the new equilibrium happens smoothly and instantaneously and is driven by assumptions on the behavior of economic agents. Producers are assumed to maximize profits and consumers to maximize utility out of consumption, subject to prices, factor and income availability as well as flexibility in substitutability across factors and goods.[9] As optimal behavior is assumed, all available production factors are fully used (factor prices adjust until this is the case). This process reflects the long-term optimality perspective of CGE

[6] We assume that the physical climate change scenario is the same across socio-economic developments, however we do not implement a specific temperature trajectory with respective economic damages.

[7] Social Costs of Carbon of USD_{2011} 212/tCO_2 in 2050 (95th percentile)

[8] Reaching USD_{2011} 140/tCO_2 in 2040.

[9] In quantitative modelling this flexibility is typically specified via elasticities of substitution; a feature that sets CGE models apart from Input-Output or basically also econometric models, which assume fixed material production structures.

Table 1
Overview of the uncertainty layers used in the analysis, respective type of uncertainty that is addressed and model implementation.

Uncertainty layer	Typology and respective type of uncertainty captured[a]			Model implementation via
	Knight (1921), Keynes (1921, 1937)	IPCC, Kunreuther et al. (2014)	Funtowicz and Ravetz (1990)	
Technology	No: some costs estimates of technologies are available	Epistemic	Technical	Two different iron and steel production technologies
Socio-economic	No: plausible corridors for socio-economic development until 2050 are given	Epistemic	Technical	Three different shared socio-economic pathways (SSPs)
Climate policy	Yes: How climate policy might evolve is uncertain[b]	Epistemic	Epistemological	Three different climate policy worlds (stringency and geographic scope)
Macroeconomic state	Yes: We do not know, how macroeconomic states will look like in the future	Epistemic/paradigmatic	Methodological/ epistemological	Two different macroeconomic models, with main differences being in assumptions about degree of capacity utilization and the speed of adjustment
Other layers		Translational		Not directly captured in the here applied models, but using two different macroeconomic models opens up the discussion on the quantification of translational uncertainty at the science-policy interface (cf. Section 4.4).

[a] Yes/no for Knight/Keynes describes whether our layers capture Knightian/Keynesian uncertainty or not.
[b] See e.g. sudden change due to presidency of Donald Trump in the USA.

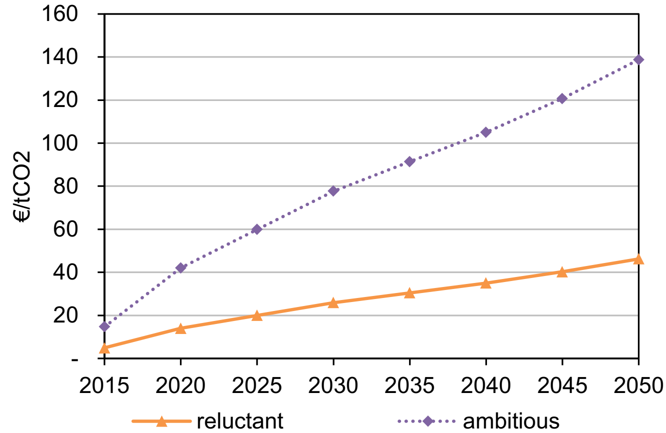

Fig. 2. Different CO_2 price trajectories [EUR_{2011}/tCO_2].

models, implying that cost changes fully pass through to final demand. The main characteristics of CGE models are thus that relative price[10] changes drive the system towards a new equilibrium and that factor supply constrains economic activity; i.e. there are no idle capacities, the economy runs at (optimal) *full capacity utilization* and growth is driven by factor supply changes (the model is "supply-driven").

In addition, we deploy a Post Keynesian macro-econometric (PKME) model that allows for economies not working at *full capacity utilization* and for rigidities in adjustment processes. In such models, economic growth is "demand-led", meaning that demand changes drive the growth of output in the model. There is no concept of the economy being in a general, or full-employment, equilibrium. Industries are not assumed to behave optimally, but the model simulates behavior as derived from past observation (using econometric estimation). Thus, typically technological coefficients are fixed and no input substitution in production takes place. In case of additional demand stimulus, *available resources* can be activated, which would increase economic output and income. In contrast to CGE models, PKME models are motivated by both short-run and long-run perspectives and thus explicitly capture the transition between the past and the future (non-equilibrium states), whereas CGE models compare depictions of the economy that are in equilibrium, before and after a system intervention takes place (long-run perspective). This also means that in PKME there may be full-cost pass-through to final demand only in the long run.

To summarize, general differences between CGE and PKME are reflected by different assumptions on the degree of capacity utilization (full in CGE versus idle/unknown in PKME) as well as the way in which economic behavior is treated (optimization in CGE versus based on historical behavior in PKME). Further, CGE models are supply-driven, assuming full employment, whereas PKME models are demand-driven, constrained by full employment and policies preventing excessive inflation. These two model classes show the extreme ends of the spectrum. An example for a "hybrid" New Keynesian model, in which optimization and econometric input-output modelling is combined is given by Sommer and Kratena (2017).

3.4.2. The WEGDYN model

For the case of average long-term *full capacity utilization* we deploy the Wegener Center Dynamic CGE model WEGDYN (Mayer et al., 2018), which is a global multi-sector, multi-country, recursive dynamic CGE model. WEGDYN is based on the GTAP9 database (Aguiar et al., 2016). The model solves for static equilibria in five-year steps,

[10] These relative prices include wage, interest and exchange rates, but there are also CGE models which fix certain prices, or assume their one-direction rigidity, such as downward rigidity of the real wage rate to model minimum wages and unemployment.

connected through endogenous capital stock accumulation, exogenous labor force (population) growth and multi-factor productivity growth. Activities of production and consumption involve the emission of carbon dioxide (CO_2) originating from the combustion of fossil fuels and/or from industrial processes. For this analysis, WEGDYN is set up with 15 economic sectors (Table A3). For the iron and steel sector we differentiate between three sub-sectors representing: (i) a conventional and process emission-intensive technology (BF-BOF), (ii) a new process emission-free technology (as discussed in Section 3.1) and (iii) the casting, rolling and finishing of crude steel. The former two sub-sectors supply crude steel, which is combined with output of the third sub-sector to provide a final iron and steel market supply. WEGDYN divides the world into 16 regions (Table A4), with a focus on the EU.[11] On the labor market, classical unemployment is implemented via a minimum wage; hence this market is not in equilibrium. Foreign trade is implemented via bilateral trade flows on a sectoral basis, where domestically produced goods are imperfect substitutes for foreign goods (Armington, 1969). Changes in trade patterns are triggered by relative prices changes. Price formation is thus a function of unit cost changes, endogenous relative price effects on the domestic markets as well as import price effects. Please see Appendix A2 for additional information. For the full model documentation see Mayer et al. (2018).

3.4.3. The E3ME model

For the case of a Post Keynesian macroeconomic treatment of the economy, we use the global Energy-Environment-Economy Macro Econometric model E3ME (for application see Barker et al., 2012). E3ME is a PKME model in which functional relationships are determined by parameter estimations for 28 sets of short and long-term econometric equations at regional and sectoral level, using historical data since 1970. However, the input-output coefficients are fixed for each year (on exogenous technological trends), except those for the energy inputs, which are derived from an energy module allowing for substitution when relative prices change. As opposed to CGE models, E3ME includes economies of scale. E3ME allows for frictions and time lags, with investment and employment being determined by each industry in each country, depending on expected outputs, and the prices and wage costs per unit of output in relation to the output prices. Most components of total demands and the divisions between outputs and imports are affected by relative prices at disaggregated level.

Proxies for the utilization of capacity for each industry in the projections are given by the ratio of output (solved from demand) to expected or "normal" output (from autoregressive equations on past output), although this converges to unity in the long run. In E3ME money supply is endogenous, hence there are spare capacities on the capital market and thus there is no full crowding out of investments (Pollitt and Mercure, 2018). The second key spare capacity is in the labor market. The available labor force depends on participation rate equations using exogenous population forecasts. The proxies for capacity utilization are especially important for the short-run responses: a higher ratio leads to more inflationary pressure, all else being equal. The main supply-side constraint is the availability of labor (labor participation rate is endogenous). Production levels exceeding expected levels lead to higher prices and higher rates of import substitution.

There is an extensive dynamic treatment of prices, wages and costs and the effect of changes in relative prices on the real economy in E3ME. The full equation for price formation in E3ME includes unit costs, import prices (capturing international competition effects), technology indices, and the ratio of actual to expected output. The degree to which exogenous cost changes are passed through to prices is driven by the level of competition in the sector, determined by the parameter for unit costs in the econometric equation. In the long run, the assumption of 'Invariance of Tax Incidence' is imposed on the estimated equations, so that all price and unit-cost changes in total supplies (i.e. including imports) are passed on to final demand. Barker and Gardiner (1996) provide a full description of the estimated employment, wage and price equations in an earlier EU-only version of E3ME. Please see Appendix A3 for additional information. For the full model documentation see Cambridge Econometrics (2019).

3.4.4. Similarities between WEGDYN and E3ME

Despite the fundamental differences, WEGDYN and E3ME also have similarities, namely, the high level of sector disaggregation and sector interconnectedness via an input-output framework, that makes both approaches capable of examining varying sectoral impacts, both directly and indirectly (through changes in demand from other sectors and changes in disposable incomes). These economy-wide – as opposed to partial – approaches recognize implications for sectors that are not directly targeted by a particular intervention in the economic system, such as a GHG emission mitigation measure. Also, both models capture foreign trade via bilateral trade and international competition, which influences price formation on domestic markets. Model specific differences are presented with the discussion of our results.

3.5. Scenario definitions and comparisons

To address the first three uncertainty layers (technology, socio-economic, climate policy) we make use of scenario analysis. Fig. 3 extends Fig. 2 and shows how the variations on the different layers are combined into scenarios. In each of the dashed boxes, the technology switch to either a high-cost or a low-cost alternative takes place and is compared to the baseline. This difference is indicated by a delta sign (Δ), which is however different in each box, as the switch happens under different circumstances, capturing the uncertainties. In the results, we thus compare differences in differences. As a starting point, we construct a main scenario (MAIN), which is described as follows. For the socio-economic layer we assume SSP2, for the climate policy layer we assume a *globally reluctant* climate policy and for the macroeconomic layer we assume *full capacity utilization* (by using WEGDYN). We then deviate from MAIN according to the arrows in Fig. 3. The quantitative analysis aims at tackling technical and epistemic/epistemological uncertainties regarding technologies, policies and the socio-economic future. The deployment of fundamentally different macroeconomic models, WEGDYN (*full capacity utilization*) and E3ME (with idle *available resources*), allows us to reveal epistemic/paradigmatic (Kunreuther et al., 2014) or epistemological/methodological uncertainty (Funtowicz and Ravetz, 1990). At this point we need to stress, that our quantitative analysis does not directly capture translational uncertainty, however, as we use different macroeconomic models in their standard setups we make a first step towards reducing translational uncertainty at the science-policy interface.

4. Results and discussion

4.1. Technological and socio-economic uncertainty

We first report results for the iron and steel sector itself, being at the very core of the system intervention. All results are given relative to a respective baseline, in which the new iron and steel technologies are not activated and all other aspects remain equal. Note, that we initially assume *full capacity utilization* (i.e. we use the WEGDYN model).

Fig. 4 shows effects on regional market prices for iron and steel. The top/bottom row gives results for the high/low-cost technology specification. The difference between top and bottom row thus represents the technological uncertainty. In addition, we depict the socio-economic

[11] Actually, EU + 3 (EU28 plus Norway, Lichtenstein and Iceland). Austria (AUT) and Greece (GRC) are modeled as individual 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 Fig. A1).

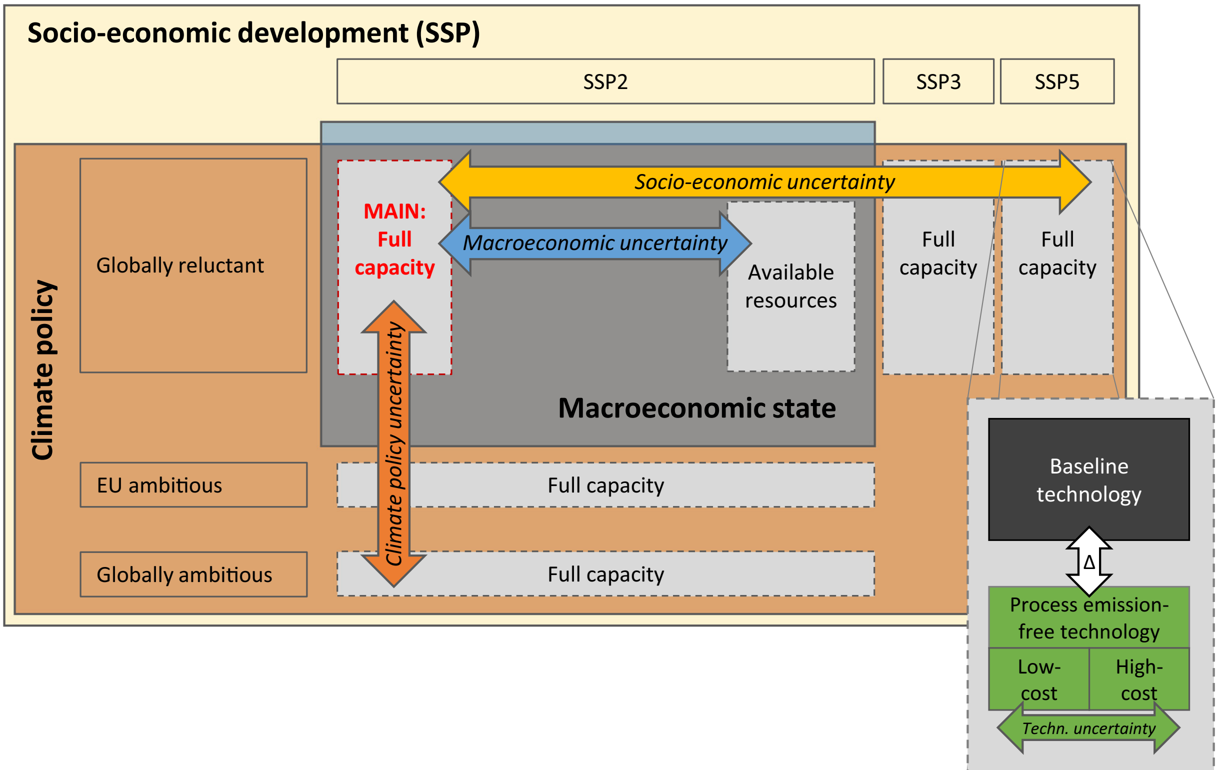

Fig. 3. Uncertainty space, emerging from the combinations of different uncertainty layers (Technological, Socio-Economic, Climate Policy, Macroeconomic state).

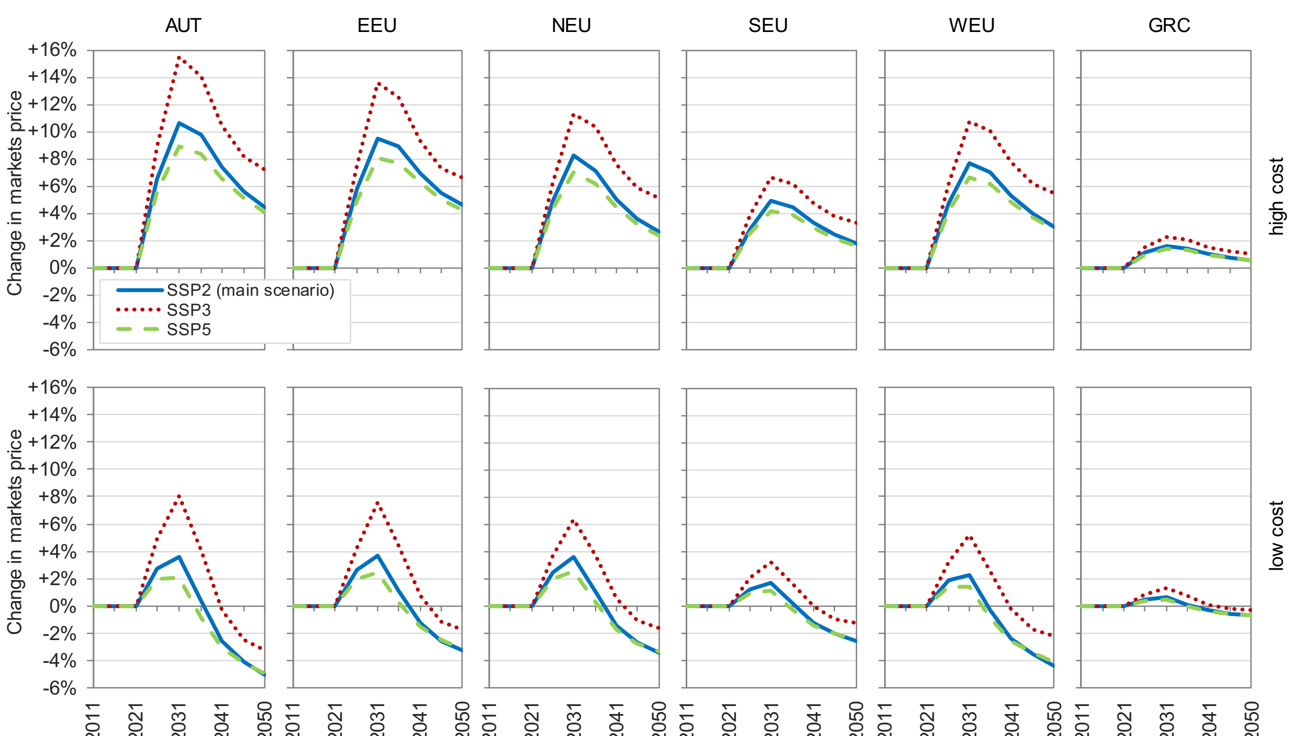

Fig. 4. Change of iron and steel market prices, relative to the baseline with SSP variations on the socio-economic uncertainty layer (assuming reluctant climate policy and full capacity utilization [WEGDYN]).

uncertainty layer by simulating the technology switch within two alternative SSPs (SSP3 and SSP5, in addition to SSP2).

With a high-cost specification, prices are above baseline levels in all regions, with peaks ranging between +15% (Austria in 2031) and +2% (Greece[12] in 2031) and declining thereafter, but remaining above the baseline until 2050. Prices are higher due to higher production (unit) costs, both because of additional capital costs due to investment requirements (annuities for financing new facilities), and because of higher operating costs (Table A1).[13] With a low-cost specification, the CO_2 price more than compensates the production (unit) cost disadvantage of the process emission-free technology in the long-term, which leads to lower iron and steel prices in all regions in 2050, ranging between −5% (Austria in 2050) and −1% (Greece in 2050). In the short-term, however, also the low-cost specification leads temporarily to higher prices, especially due to capital investment costs.

Regarding regional differences, Austria seems to be the most sensitive region. This is because the share of the BF-BOF steelmaking in the iron and steel industry is highest in Austria (> 90% of steel is produced along this route), whereas the shares in EEU (Eastern EU), NEU (Northern EU) and WEU (Western EU) lie at 65% and in SEU (Southern EU) only at 30% (see Fig. A1 for details).

Concerning socio-economic uncertainty, results are robust as the direction of effects does not vary across SSPs. However, in some regions we see relatively large differences when comparing SSP3 to SSP2 or SSP5. This is because in SSP3 depreciation rates are higher (see Section 3.2). 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. The opposite effect is the case for SSP5, where depreciation rates are below the SSP2 rate.

The changes in relative prices translate into output effects, which are shown in Fig. 5a, aggregated to EU level. In 2050, with a high-cost technology specification, output is lower relative to the baseline (between −6% and −13%), whereas with a low-cost technology specification, output is higher (between +4% and +8%). Again, concerning socio-economic uncertainty our results are robust in terms of direction and magnitude, with stronger effects under SSP3. For detailed regional output effects see Fig. A15.

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 Fig. 5b, again for the main scenario with variations of SSPs. For the low-cost case we observe a lower GDP during the transition by up to −0.8%, with potential long run GDP gains (+0.25% in 2050). This can be explained as follows. In the first periods of the transition the higher unit-costs translate into lower productivity of the iron and steel sector, which lowers GDP (compared to the baseline). However, the unit cost disadvantage (w.r.t. baseline) disappears and flips into an advantage, due to the rising CO_2 price, hence productivity increases. Thus, the GDP effect turns positive, but not immediately, as it needs some time to return to baseline levels via faster capital accumulation (which is getting faster as soon as unit costs are below the baseline level). With a high-cost technology specification unit costs also increase, leading to a loss of productivity and thus a lower GDP (−1.6% by 2050). Even after the investment phase (beyond 2031), production costs (and prices) are still higher and thus GDP does not return to the baseline by 2050, but remains at a lower level (−1.5%). See Fig. A16 for region-specific effects.

Regarding socio-economic uncertainty, the results are robust in terms of direction and magnitude for the high-cost specification. For the low-cost technology specifications, however, the GDP effects vary in their long-term (2050) effects across SSPs, with slight negative effects under SSP3 and slight positive effects under SSP2 and SSP5. This is because under SSP3 capital prices are higher, which leaves the newly introduced – more capital-intensive – technology with a stronger cost-disadvantage compared to the baseline technology.

What is not captured in GDP is the shift from consumption to savings/investments for new production facilities. Since we assume *full capacity utilization* in the main scenario, consumption is reduced to offset the additional investment. This reduction of consumption is reflected in a lower welfare[14] level. The effect is similar, however, more severe than the GDP effect, since GDP also includes the positive effect of higher investments. We observe lower welfare levels of up to −3% in the high-cost case (in EEU in 2050) and higher welfare levels of up to +0.5% in the low-cost case (in WEU in 2050; see Fig. A17 for details).

For employment, the effect depends on the sign of the change in labor intensity in combination with the overall productivity (unit cost) change of the new technology. In our analysis, the new steelmaking technologies are characterized by lower labor intensities, which in isolation leads to decreased employment due to lower labor demand. In addition, negative productivity effects (in terms of higher unit costs) adds to this effect, paired and amplified with indirect effects to other sectors due to a strong dependency on steel (see Figs. A18 and A19 for regional effects). By 2050, unemployment rates are thus higher by up to +2.5%-points (as compared to the baseline), when assuming the high-cost technology specification. For the low-cost technology specification, unemployment rates also tend to be above baseline levels, however the effects are less severe and unemployment tends to return to baseline levels – or even below – in the long-run as overall productivity and growth catch up.

4.2. Climate policy uncertainty

We now investigate the climate policy layer. Again, we compare to the main scenario, but now for different policy worlds, implemented as different exogenous CO_2 prices (in both the baseline and in the technology-switch scenarios). Fig. 5c illustrates EU-wide GDP effects. With a high-cost technology specification, the highest GDP losses emerge in the policy world with lowest support for clean technologies, 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 smaller production cost disadvantage. We see that GDP losses are weaker (by up to 0.5%-points in 2050), when the transition takes place in a world with a more ambitious climate policy in the EU. EU-wide GDP losses are rather insensitive to non-EU policy (see Fig. A20 for regional details).[15] With a low-cost technology specification, climate policy helps to foster the positive GDP effect. Compared to the "globally reluctant" world, ambitious EU policy can increase GDP gains by +1%-point (in 2050) with slightly higher benefits in the "globally ambitious" world. In general, we see that the

[12] 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.

[13] Note that in the baseline there would be 100% conventional steel output over the full time horizon, however with a still rising CO_2 price, which would 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 baseline technology and the process emission-free alternative would converge, which leads to an inverted U-shaped effect.

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

[15] This can be explained via the model closure for foreign trade: In the standard setup, we assume a flexible exchange rate and fixed foreign savings (current account balance). Thus, regional trade patterns can change but not the absolute level of net exports.

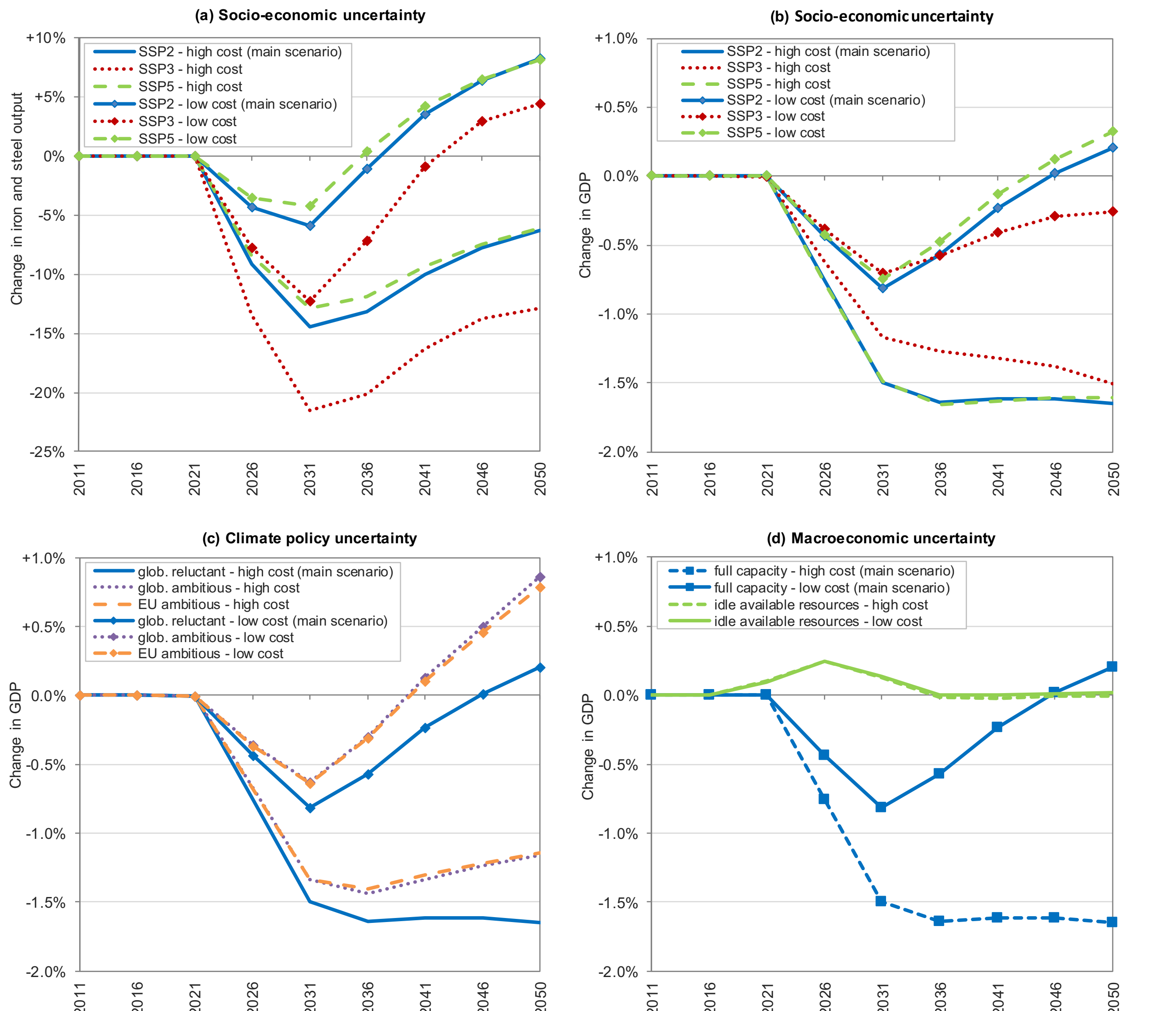

Fig. 5. (a) Change of EU-wide iron and steel output, relative to the baseline with SSP variations on the socio-economic uncertainty layer (assuming reluctant climate policy and full capacity utilization [WEGDYN]). (b) Change of EU-wide GDP, relative to the baseline with SSP variations on the socio-economic uncertainty layer (assuming reluctant climate policy and full capacity utilization [WEGDYN]). (c) Change of EU-wide GDP, relative to the baseline in different policy-worlds, assuming SSP2 and full capacity utilization [WEGDYN] (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). (d) Change of EU-wide GDP, relative to the baseline assuming SSP2, globally reluctant climate policy and variations on the macroeconomic uncertainty layer ("full capacity utilization" [WEGDYN] or "available resources" [E3ME] assumption). Note that (a) is scaled differently.

uncertainty from the climate policy layer 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 (see Fig. A21).

4.3. Macroeconomic uncertainty

We next address macroeconomic uncertainty. All results shown thus far are generated by WEGDYN, a CGE model that assumes the optimal macroeconomic state of *full capacity utilization* (or constrained resources in production). Additionally, we here deploy E3ME, a PKME model that assumes idle *available resources*. Again, we investigate the main scenario (i.e. SSP2, globally reluctant climate policy, *full capacity*) and now compare results to those obtained from E3ME (SSP2, globally reluctant climate policy, idle *available resources*).

To understand the differences in macroeconomic effects between WEGDYN and E3ME, we need to understand for each model how the technology cost changes translate into price changes and how these further pass through the economic system. As explained in Section 4.1, in WEGDYN changes in unit costs are treated as changes in sectoral productivity. Higher/lower unit costs, means that more/less inputs are needed to create one unit of output. This change in productivity immediately translates into relative price changes (which perfectly and immediately pass through the economic system) and GDP changes.

In E3ME the key factor for price setting is also unit costs, however an important difference with WEGDYN is that economic structures are more rigid. Intermediate production structures (excluding energy inputs) have fixed input coefficients. This means that sectors, which need steel in their production as an input, cannot substitute steel by other inputs.[16] Put differently, iron and steel inputs to other industries depend on their outputs and do not respond directly to price changes.

[16] Which is to a limited extent the case in WEGDYN. This is implemented via nested constant elasticity of substitution functions in the production function of producers. Elasticities of substitution across non-energy intermediate inputs range between zero and 0.6 (based on Okagawa and Ban (2008)).

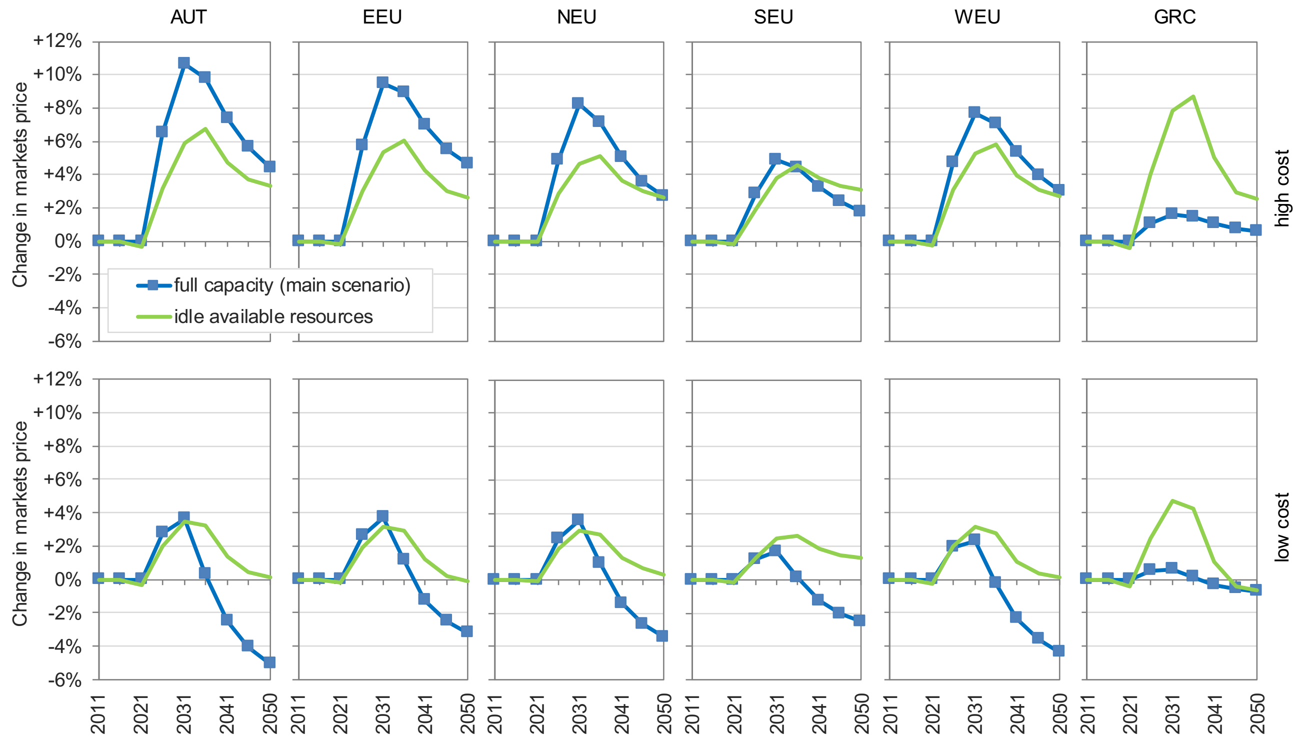

Fig. 6. Change of regional iron and steel market prices, relative to the baseline assuming SSP2, globally reluctant climate policy and variations on the macroeconomic uncertainty layer ("full capacity utilization" [WEGDYN] or "available resources" [E3ME]).

Thus, in E3ME, pass-through of higher costs along the supply chain is not necessarily the case. In addition, higher costs are also compensated via lower profits. Hence, overall indirect effects are limited. Ultimately, the direct and (very limited) indirect cost changes arrive through the supply chain at final demand in the form of higher consumer prices, where substitution between final consumption categories is possible.[17]

Looking at the price effects, we see that with a high-cost specification (Fig. 6, top), effects mostly coincide in terms of direction, magnitude and development over time. We see somewhat stronger effects when assuming *full capacity utilization*, due to higher capital demand, capital scarcity and the resulting feedbacks on capital markets (higher capital prices/rents), whereas there are spare capacities (*available resources*) in the alternative model. With a low-cost specification (Fig. 6, bottom), the price effects also largely coincide, but only until 2031. In general, after this point in time additional capital costs for investment repayments (annuities) start to fall again, accompanied with the increasing carbon price. With a *full capacity utilization* assumption, unit costs – and thus prices – are ultimately lower than in the baseline by then and thus prices are also lower. When assuming *available resources* (which reflects non-optimal states and rigidities), though, prices do not react immediately and less strong, and prices do not fall below the baseline levels by 2050. Initially, the price increase is primarily driven by increases in steel production costs. After the investment period (when CAPEX costs are repaid), prices do decrease again, but slower as compared to the *full capacity* assumption, due to rigidities. The extent of the price increase partly depends on the competitive import price, in which case profits will be lower; in any case, profits are the residual. We also observe that the price effects are distributed more uniformly across regions. This effect originates from stronger market integrations across regions in E3ME[18] than in the WEDGYN model, even though the main mechanisms for price formation are similar. Note, that in E3ME Greece acts largely as a price taker in the European market and thus the price for steel in Greece is very sensitive to technology changes in the rest of the EU.

In the Post Keynesian model, it is only final demand (consumption) that can react to price changes, as there are fixed input coefficients in production. As cost pass-through from production output (e.g. raw material) to consumption goods is limited, demand does not respond strongly to price changes of iron and steel. Also, full cost pass-through to final demand only happens in the long term ('Invariance of Tax Incidence'-assumption, see Section 3.4.3). The impact of the price increases is to reduce real incomes, rather than the demand for iron and steel. Consequently output does not change substantially. Changes of output range between ± 0.5%, which are driven by the investment stimulus (dominating the limited demand reduction from higher prices). After the investment phase (starting in 2036) effects are very small, with slight variations across regions, due to competition effects from varying import price levels. Under the assumption of *full capacity utilization* output reacts immediately, more strongly and in different directions, depending on regional characteristics and the assumed cost specification (see Section 4.1, and Figs. A15 and A22 for regional details on output).

At the aggregate level (Fig. 5d) and under the *available resources* 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). This clearly indicates that the GDP dynamics are dominated by the short-run effects, i.e. investment requirements in the iron and steel sector. This is because capital accumulation and capital productivity does not change via the changing unit costs and prices, as the economy is not at *full capacity* in the baseline and compensates potential productivity losses by activating *available resources*. In

[17] As parameter settings as well as elasticities of substitution play an important role in both models, we provide more details in Appendices A2 and A3. For WEGDYN the interested reader can also find all the nested production and consumption functions.

[18] In E3ME there is more homogeneity between domestically produced goods and imported goods within the EU, than in WEGDYN, where there is stronger product differentiation according to Armington (1969).

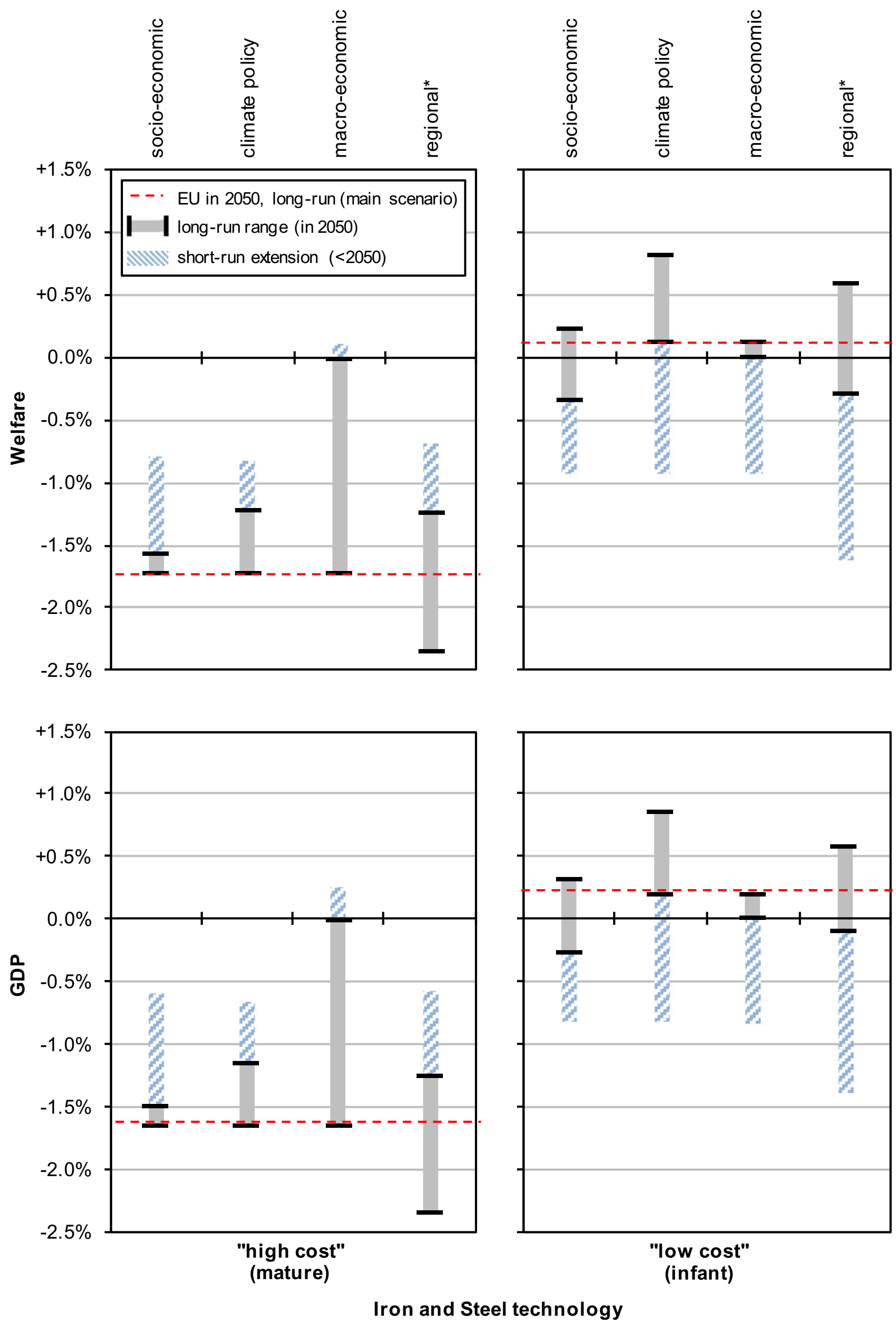

Fig. 7. Uncertainty ranges of EU-wide GDP and welfare change, relative to baseline, across scenario and model results (main scenario result levels are indicated by red dashed line). Left/right columns give high/low technology cost specification. (* = Excluding Greece, as no technology switch is implemented in this region.) (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

contrast, under the *full capacity utilization* assumption it is long-run productivity that dominates GDP effects. Thus, we observe that uncertainties are large with regard to the macroeconomic state (see Figs. A24 and A25 regional GDP and welfare effects).

4.4. Discussion

Our results are condensed in Fig. 7. The solid bars (grey) show the range of long-run effects, i.e. effects *in* 2050, and how these effects might change, when changing assumptions on different uncertainty layers. As a point of reference we indicate the results from the main scenario as a horizontal dashed line (red, i.e. SSP2, globally reluctant climate policy and *full capacity utilization* [WEGDYN]). In addition to the long-run effect we also show short-run effects: The hatched bars (blue) extend the bars of the long-term effects (grey), thereby indicating the total range of effects when also taking into account all the years < 2050; i.e. across time.[19] Hence, the short-run bars simply extend the uncertainty ranges that are given from the long-run perspective to visualize that effects might be stronger or weaker along the way until 2050 than *in* 2050. Moreover, we show the variation of regional effects (within the main scenario), originating from differences in

[19] Only taking into account years in which production of the new technologies is already running (starting in 2036).

regional characteristics (indicated by the columns labelled "regional"). Finally, the difference between left and right plots shows the technological uncertainty (high versus low-cost technology specification).

Starting the discussion at the technological uncertainty we find that for the high-cost technology specification in the short-run effects are less severe than in the long-run (i.e. by 2050). By contrast, with a low-cost technology specification long-run effects turn out to be beneficial, but at the cost of higher negative impacts in the short-term. Note, that our analysis assumes a strict technology standards, which private steel companies have to comply with. The choice of a production technology that meets this standard is, however, made by business executives (but is unknown) and depends upon various factors besides (expected) technology costs. From such a perspective, it might be too risky for firms to choose a technology which is still in its infancy, although it is expected to be the low-cost alternative in the long-run, with potential sectoral and macroeconomic gains. If there is a general policy that incentivizes low-carbon technology adoptions, managers may still opt for the less risky and more mature, but in the long-term costlier technology, and society would have to accept more significant macro-losses.

Regarding socio-economic uncertainty, we find that the effects are relatively robust; however, socio-economic uncertainties also concern regional differences, such as capital and labor intensities, the degree to which regions rely on steel imports, or the regional and inter-sectoral dependency on iron and steel itself. We find that the macroeconomic effects are co-determined relatively strongly by such regional characteristics. In addition, over the course of economic development, different regions might show different trajectories regarding e.g. growth of the labor force and capital stock as well as the development of relative prices, which co-determine the regional effects. We thus find that there is a relatively broad regional spread. For the high-cost specification we observe GDP losses of up to of −2.3% (Eastern EU), whereas the "lucky loser" is confronted with only −1.3% (Northern EU). To isolate the most important regional drivers of uncertainty, as we have indicated here, is an important, new and promising avenue for future research.

Uncertainty originating from the climate policy layer seems to be smaller than from other layers, as we observe a clear signal in 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 larger. Interestingly, the low-cost technology specification shows larger uncertainties at the climate policy layer, since the carbon price can trigger a stronger relative competitive advantage over the conventional technology. Thus, a globally ambitious climate policy becomes the least detrimental for GDP and welfare. We also show that EU-wide GDP and welfare effects are rather insensitive to non-EU policy, however this result is driven by the standard model setup itself (foreign trade closure of flexible exchange rate and fixed current account balance). We thus identify foreign trade sensitivity as another source of uncertainty, which should be addressed in future research.

A significant result is that there is a considerable uncertainty range from the macroeconomic layer. For the high-cost technology specification EU-wide GDP effects range from −1.6% to close to zero. The possible negative impact results from the *full capacity utilization* assumption, whereas the less severe impact (close to zero) results from assuming (idle) *available resources*. For the latter case, we even observe a temporary positive effect in the short-run, due to the investment stimulus. For the low-cost technology specification, we find that the short-run effects for the *full capacity* case might be negative; however, long-run effects are positive throughout. Again, there are large uncertainties on the macroeconomic layer, with effects close to zero when assuming *available resources*.

Other potential sources of uncertainty are climate change impacts for the economy as a whole and for the iron and steel sector itself. As soon as the steel sector switches from coke-based production to renewable hydrogen-based production, the risks of being adversely affected by climate policy might be lower. However, existing impact studies (e.g. Solaun and Cerdá (2019) offer a comprehensive review) indicate increasing risk from physical climate change impacts, potentially affecting also renewable electricity (hydrogen) generation. Hence, new technologies might be competitive, but nevertheless business executives might be reluctant to switch due to a deteriorating uncertainty/risk profile in the value chain. An integrated assessment of climate change impacts and climate mitigation therefore becomes essential.

Regarding macroeconomic uncertainty we explained the fundamental differences in concepts and methodology between the two applied macroeconomic models (neoclassical CGE models and PKME) in Section 3.4.1.[20] Many of the differences that are relevant here (assumptions on rationality, optimality, money neutrality, labor market dynamics) are reflected in the assumption between *full capacity utilization* and *available resources*. However, in addition to these general differences there are also model-specific differences between WEGDYN (the CGE used here) and E3ME (the PKME used here). These differences are determined by the modelers rather than by the theoretical underpinnings of the models and might influence differences in results. We argue that model-specific differences add to the translational uncertainty at the science-policy interface and need attention when discussing our results. We have grouped these differences into three sets.

First, there are differences for the labor market. Both models assume market imperfection in the labor market; WEGDYN in the sense of classical unemployment, set by a minimum wage that is bound to the consumer price index of the baseline scenario. E3ME includes unemployment (voluntary or otherwise) as defined in official data as a regional/country variable in the model. The unemployment rate affects consumers' expenditure and investment in dwellings by region and wage rates by industry and region. Second, there are differences regarding the relationship between savings and investment. In WEGDYN savings drive investments, according to a constant savings rate. New investments (compared to those in the baseline) are assumed to crowd out consumption. In E3ME, new investments are assumed to be funded by banks creating new debt, without any crowding out.[21] Third, there are differences regarding foreign trade. WEGDYN assumes a fixed current account balance (foreign savings) with flexibility in exchange rate and trade patterns. In E3ME, exchange rates are exogenous. Current account balance of payments deficits or surpluses are assumed to be matched by capital account flows. These differences require a more in-depth and systematic comparison to further disentangle uncertainties at the macroeconomic layer, i.e. fundamental macroeconomic differences and model-specific differences, which should help in reducing translational uncertainty.

To summarize, here we show that methodological uncertainties as well as uncertainties at the science-policy interface are large and give first quantified estimates on aggregate. Hence, we do not claim completeness in our analysis, but give first structured insights into uncertainties from running different models in their standard setups. This approach should raise awareness that results might strongly depend on which modelling groups are hired for policy analysis (as typically modelling groups use their models in the standard setup). However, results should be compared carefully, as we cannot claim a ceteris paribus assumption. Still, we demonstrate the importance of carefully choosing models.

[20] The interested reader will find further information and good summaries of each school in the *Exploring Economics* website https://www.exploring-economics.org/en/.

[21] Note that this difference actually relates to the full capacity utilization versus available resources distinction. In WEGDYN capital is scarce, as the economy runs at full capacity, whereas in E3ME money is created by banks, with new finance only limited by the banks' aversion to risk.

5. Conclusions

In the literature, various attempts have been made to address uncertainty within macroeconomic frameworks, however, studies typically do not go beyond technical uncertainty, and therefore do not address methodological and epistemological uncertainty. For the example of the European iron and steel industry's transition towards process emission-free production, we explicitly capture for the first time all of these types of uncertainty by carrying out a systematic analysis of the potential sectoral and economy-wide effects. Additionally, uncertainties at the science-policy interface, such as translational uncertainty, are usually ignored, which we discuss as well in this contribution. We show that uncertainties are large, however, they are different in their meaning and should thus be interpreted with care.

For the range of technological uncertainty, we find for our example that macroeconomic implications can be either positive or negative, depending on the relative technology costs. This implies quite a significant uncertainty, which however can be managed by business executives. We conclude that a discussion is needed on how policy can help to reduce such risks (potential macroeconomic losses) and possibly induce a mix of technologies to diversify risk. Possible instruments might be production standards, subsidies or public investments into research and development. Further, from the relatively large regional spreads in results we conclude that low-carbon transition pathways should be region-specific and that the transferability of regional case studies to other regions seems to be quite limited. From the analysis of macroeconomic uncertainty we conclude that the long-run GDP effects might be between zero and moderately negative for a high-cost technology specification, or between slightly positive and zero for a low-cost technology specification.

Concerning policy, we clearly see that a CO_2 price is needed to support the transition, best if increased over time (in real terms). Furthermore, we conclude that R&D is needed to support a rapid development of low-cost technologies. If policy makers incentivize sectors to use a currently already mature carbon-free technology (e.g. by new standards), this might result in (moderate) negative GDP effects.

We draw further policy conclusions, specifically from the comparison of the two applied macroeconomic models (CGE and PKME). First, we emphasize that the short- and long-run effects might be very different, with potential negative effects in the transition phase, but with long-run and sustainable macroeconomic benefits. Inter-generational equity issues should thus be accounted for.

Second, we conclude that from a policy-makers' perspective the model choice for policy analysis, and the implicit assumptions of the macroeconomic state, are highly relevant and should be made with great care. We demonstrate that the choice of the model influences the signs and magnitudes of the macroeconomic impacts. Due to this translational uncertainty may occur ("*results that are incomplete or conflicting so that they can be invoked to support divergent policy positions*"; Kunreuther et al. (2014, p. 178)) and policy recommendations might differ strongly. We see the danger that results could be consciously (mis)used to push policy agendas. This implies that the research community as a whole should be fully transparent, in order to inform policy makers about the underlying assumptions. Co-design and co-production can help to foster better communication concerning model choice and setup. Additionally, the results should be presented in the right context, i.e. together with the conditions under which they are valid. Thus, regarding policy recommendations we need to state (as so often) that "it depends"; in this case strongly on the state of the economy (i.e. whether resources are available, which is the case during a recession, or if the economy runs at full capacity, which is the case during an economic boom). (Climate) policy makers should thus include economic cycles into their timing and decisions.

Third, we suggest to increase funding for closer cooperation between different macroeconomic modelling groups that use different approaches; such as the one explored in the research reported in this article, general equilibrium and Post Keynesian modelers. A critical and constructive collaboration across groups might trigger (highly needed) model validation studies as well as the development of new models. Also, it should be tested whether uncertainties between models with similar theoretical foundations are smaller than across models with seemingly quite different assumptions. We thus conclude that in the commissioning of modelling studies uncertainty should get more important, e.g. by calling for multi-model comparisons across different schools of thought. This could also help to foster cooperation between modelling camps.

Finally, we emphasize that potential negative macroeconomic effects of our analysis are moderate. In our "worst-case" scenario EU-wide absolute GDP/welfare is lower by < 2% in 2050, compared to the Baseline, which is equivalent to reducing the annual GDP growth rate by 0.05%-points. This might be an acceptable "price" for helping to solve a major crisis. One could also interpret the negative welfare effect as a kind of "forced savings" behavior, necessary to enable a green transition (cf. Kemp-Benedict, 2018), or, as mandatory insurance against possible catastrophic climate change (Weitzman, 2009).

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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