Carbon price variations in 2°C scenarios explored

Céline Guivarch[a], Joeri Rogelj[b]

a. CIRED, Ecole des Ponts ParisTech, Nogent-sur-Marne, France. guivarch@centre-cired.fr
b. ENE, International Institute for Applied Systems Analysis (IIASA), Laxenburg, Austria. rogelj@iiasa.ac.at

2017, January 13

AIM AND SCOPE

Clarify the variations in carbon prices found in mitigation scenarios that limit global mean surface temperature increase to below 2°C relative to preindustrial levels.

CONTEXT

Integrated assessment models[1] (IAM) are dominant tools for the development of long-term emissions scenarios in line with climate objectives. There is a large variety of IAMs and, together with variations in socioeconomic and technological assumptions, this variety results in important differences in model behavior. For the achievement of low emissions scenarios, models typically assume or produce an implicit shadow price for carbon or represent policy instruments, including carbon pricing. This briefing aims at exploring and understanding the variation in these carbon price estimates for stringent climate change mitigation scenarios.

The focus of this exercise will be on scenarios that limit global mean temperature surface increase (henceforth, warming) to below 2°C relative to preindustrial levels with a greater than 66% probability. This choice is driven by data availability for this particular temperature objective, and does not represent an official or scientific interpretation of the Paris Agreement long-term temperature goal. The assumption is that the qualitative insights would also to a large degree apply to scenarios that limit warming to below 2°C with higher probabilities or to 1.5°C.

[1] Note that the IAMs concerned in this briefing are all "process-based" IAMs, as opposed to a different class of highly aggregated IAMs that apply a benefit-cost framework to climate change mitigation analysis. Benefit-cost models are used to estimate optimal mitigation efforts balancing the costs of mitigation with the benefits in terms of avoided climate change damages. They are also used to quantify the social cost of carbon, i.e. the present social value of damages from an additional ton of carbon released in the atmosphere. Example of benefit-cost models include DICE (Nordhaus, 2013) and PAGE (Hope and Hope, 2013). In contrast, process-based models are used to analyze transformation pathways to achieve a pre-determined level of mitigation effort such as 2°C climate stabilization, in a cost-effectiveness framework.

KEY MESSAGES

- **Scenarios that limit warming to below 2°C with a greater than 66% probability imply carbon prices increasing throughout the 21st century.**
    - o The latest quantifications of such carbon price trajectories show a wide range of results, with short-term prices varying from 15 to 360 USD_{2005}/tCO_2e in 2030, 45 to 1000 USD_{2005}/tCO_2e in 2050 and 140 to 8300 USD_{2005}/tCO_2e in 2100.
    - o In the models used to make these estimations, these 'carbon' prices are applied to all anthropogenic greenhouse gas emissions. They are therefore expressed in USD per metric ton of carbon-dioxide equivalent emissions (USD/tCO_2e).
- **The wide range of results can be explained by socioeconomic factors, whose evolutions are uncertain but can at times also be influenced by policy decisions, and by differences in modeling frameworks.**
    - o Differences between the modeling frameworks used in this exercise to quantify carbon prices are responsible for a large share of the carbon price variations.
- **Optimization frameworks, in which agents have perfect foresight of future technological and socioeconomic developments, tend to have exponentially increasing carbon price trajectories with relatively lower carbon prices in the short term and higher prices in the longer term compared to other frameworks. For instance, recursive dynamic frameworks with limited foresight tend to have opposite trends with higher carbon prices in the short term and lower carbon prices in the long term.**
    - o In optimization frameworks, investment and technology decisions that involve long-lived capital integrate the knowledge of future prices, leading to lower carbon prices in the short term. In recursive dynamic frameworks emissions reductions in the short term are only based on knowledge of current prices and costs, and this results in carbon prices being higher. These insights have important policy implications: near-term carbon prices have to be assessed in context of the credibility of their implied long-term carbon price signal.
- **Differences in model structure can have strong implications for the flexibility of models to respond to climate mitigation signals. Consequently, the carbon price required to achieve stringent mitigation targets in different models varies strongly.**
    - o One model in our set, characterized as a "low response" model, implies carbon prices which are consistently up to a factor 4 to 10 higher than "medium response" or "high response" models.
- **The future evolutions in socioeconomic factors also determine the level of carbon prices. These evolutions are uncertain, and partly independent of climate change policies. They were systematically explored in the scientific literature with Shared Socioeconomic Pathways (SSPs) and Shared Policy Assumptions (SPAs).**
    - o Socioeconomic pathways that concur to low challenges to mitigation (with *shifts toward a more sustainable path, emphasizing more inclusive development that respects perceived environmental boundaries and where consumption is oriented toward low material growth and lower resource and energy intensity*) robustly imply lower carbon prices, whereas socioeconomic pathways characterized by high challenges to mitigation (where *the push for economic and social development is coupled with the exploitation of abundant fossil fuel resources and the adoption of*

resource and energy intensive lifestyles around the world) consistently require higher carbon prices.

- **Climate policy implementation which delays global action and accession to stringent policy leads to higher overall carbon prices.**
    - Lower carbon prices at the global level in the short term are more than compensated by higher carbon prices in the medium and long term.
- **The inability to control land-use emissions (with limited pricing of land-use emissions for instance) can imply the need for higher carbon prices which are required to foster faster decarbonization of the energy sector so that stringent mitigation targets can still be reached.**
- **In conclusion, this means that there is no single carbon price trajectory or corridor consistent with the 2°C target. Such a trajectory depends on socioeconomic evolutions that are not determined by climate policies only. It also depends on how mitigation policies are implemented in the near term and further over time.**

1. Overview of data sources

The SSP database aims at the documentation of quantitative projections of the so-called Shared Socioeconomic Pathways (SSPs) and related Integrated Assessment scenarios (for an overview see Riahi et al, 2016). The SSPs are part of a new framework that the climate change research community has adopted to facilitate the integrated analysis of future climate change impacts, vulnerabilities, adaptation, and mitigation. Information about the scenario process and the SSP framework can be found in Moss et al. (2010), as well as O'Neil et al. (2014) and Kriegler et al. (2014). The framework is built around a matrix that combines climate forcing on one axis and socioeconomic conditions on the other (van Vuuren et al., 2014). Together, these two axes describe situations in which mitigation, adaptation and residual climate damage can be evaluated.

The SSP quantifications build upon the collaborative effort between the IAV and IAM community, which have met in a series of meetings and identified a limited set of five SSP storylines/narratives (O'Neill et al, 2012). The narratives describe the main characteristics of the SSP future development pathways, which differ in terms of challenges to mitigation and challenges to adaptation (Table 1). They served as the starting point for the identification of internally consistent assumptions for the quantification of SSP elements. A range of different modeling tools were used to develop quantifications of these storylines, including factors like population, economic development, land use and energy use.

		Challenges to mitigation	Challenges to adaptation
SSP1	Sustainability – Taking the Green Road	Low	Low
SSP2	Middle of the Road	Medium	Medium
SSP3	Regional Rivalry – A Rocky Road	High	High
SSP4	Inequality – A Road Divided	Low	High
SSP5	Fossil-fueled Development – Taking the Highway	High	Low

Table 1: The five SSPs. An extended description of the five SSPs narratives can be found in O'Neill et al. (2016).

For each SSP, a single storyline-specific population and urbanization scenario, developed by the International Institute for Applied Systems Analysis (IIASA) and the National Center for Atmospheric Research (NCAR), is provided. For GDP, three alternative interpretations of the SSPs by the teams from the Organization for Economic Co-operation and Development (OECD), the International Institute for Applied Systems Analysis (IIASA) and the Potsdam Institute for Climate Impact Research (PIK) have been developed.

The socioeconomic information of the SSPs has been used as input for the development of the IAM scenarios. In addition to these core indicators, each IAM also needs to make additional socioeconomic assumptions for their scenarios to be in line with a particular SSP. For example, IAMs need to interpret the SSP storylines in light of energy intensity improvements, the development and cost of certain classes of technologies like fossil fuels, renewables or nuclear, or food demand and diet preferences, amongst many other aspects (for example, see Fricko et al, 2016).

The IAM data set includes both reference (baseline) and mitigation scenarios. In the quantitative elaboration of the mitigation scenarios, three of the four RCPs forcing targets were used if applicable (6.0, 4.5, 2.6 W/m2). The fourth forcing level (8.5 W/m2) is only reached in the absence of climate change mitigation in one specific SSP. A total of six IAM teams from FEEM, IIASA, PBL, NIES, PIK and PNNL participated so far in the SSP scenarios development process. Each SSP has been implemented by multiple IAM models (Table 2). There are thus alternative interpretations from different IAM models for each of the SSPs.

	Equilibrium type	Modeling approach	Classification from diagnostics (Kriegler et al., 2015)
AIM-CGE	General equilibrium	Recursive dynamic	Medium response
GCAM	Partial equilibrium	Recursive dynamic	High response
IMAGE	Partial equilibrium	Recursive dynamic	High response
MESSAGE-GLOBOIM	General equilibrium	Intertemporal optimization	High response
REMIND-MagPIE	General equilibrium	Intertemporal optimization	High response
WITCH-GLOBIOM	General equilibrium	Intertemporal optimization	Low response

Table 2: Models (IAMs) involved in the development of SSPs quantifications, and their main characteristics.

This briefing will focus on RCP2.6 scenarios available in the SSP database (Table 3). RCP2.6 scenarios limit warming to below 2°C with a greater than 66% probability (IPCC, 2014). This temperature objective is taken as a proxy for 2°C but represents neither an official nor a scientifically conclusive interpretation of the Paris Agreement climate goals (Schleussner et al., 2016). The RCP2.6 scenarios are reached by implementing mitigation policies in the SSP scenarios. These policies may differ greatly across the SSPs, and need to be consistent with the overall characteristic of the different narratives. Based on concepts from Kriegler et al. (2014), so-called shared climate policy assumptions (SPAs) for the implementation of mitigation policies in the SSP scenarios were developed Table 4). The SPAs describe in a generic way the most important characteristics of future mitigation policies, consistent with the overall SSP narrative as well as the SSP baseline scenario developments. More specifically, the mitigation SPAs describe critical issues for mitigation, such as the level of international cooperation (particularly in the short to medium term) and the stringency of the mitigation effort over time. The mitigation SPAs also define the coverage of different economic sectors, and particularly the land-use sector, which traditionally has been a challenging sector for mitigation in many countries.

	SSP1 Sustainability	SSP2 Middle-of-the-road	SSP3 Regional Rivalry	SSP4 Inequality	SSP5 Fossil-fueled development
AIM-CGE	X	X		X	X
GCAM	X	X		**X**	X
IMAGE	**X**	X			
MESSAGE-GLOBIOM	X	**X**			
REMIND-MagPIE	X	X			**X**
WITCH-GLOBIOM	X	X		X	

Table 3: RCP2.6 scenarios availability in the SSP database. Marker implementations for each respective SSP are indicated in bold.

Near-term policy stringency and timing of regional participation	Coverage of land use emissions
SSP1, SSP4 Early accession with global collaboration as of 2020	***SSP1, SSP5*** Effective coverage (at the level of emissions control in the energy and industrial sectors)
SSP2, SSP5 Some delays in establishing global action with regions transitioning to global cooperation between 2020-2040	***SSP2, SSP4*** Intermediately effective coverage (limited REDD*, but effective coverage of agricultural emissions)
SSP3 Late accession – higher income regions join global regime between 2020-2040, while lower income regions follow between 2030-2050	***SSP3*** Very limited coverage (implementation failures and high transaction costs)

*REDD: Reducing Emissions from Deforestation and forest Degradation

Table 4: Summary of Shared Policy Assumptions (SPAs) assumed for climate change mitigation in each of the SSPs. In each of the SPAs a period with moderate and regionally fragmented action until 2020 is assumed, but mitigation policies develop differently thereafter. Reproduced from Riahi et al. (2016).

The quantifications of the SSPs (reported in the accompanying online database (https://tntcat.iiasa.ac.at/SspDb/, Riahi et al. (2016)) are the dataset of choice for a structural exploration of carbon prices to limit warming to various levels. The SSP dataset provides information from the most up-to-date Integrated Assessment Models (IAMs), for multiple radiative forcing targets ranging from unmitigated baselines to very stringent mitigation scenarios. Moreover, the SSP framework allows to explore socioeconomic uncertainties in a structured way across models. Figure 1 shows that the RCP2.6 scenarios from the SSP database are consistent with the low end of the full range of emissions scenarios available in the IPCC AR5 Scenario Database[2]. The lowest scenario category assessed in the IPCC AR5 was consistent with limiting warming to below 2°C with a *likely* (>66%) probability. More stringent scenarios, in line with limiting warming further to 1.5°C, have also been published in the literature (Rogelj et al., 2015), but the underlying scenarios were not contributed in time to the IPCC AR5 Scenario Database. Currently, the IAM community is using the SSP framework to explore scenarios that would limit global total anthropogenic radiative forcing to 1.9 W/m^2 in 2100. These scenarios could be consistent with limiting warming to less than 1.5°C in 2100 with greater than 50% probability.

[2] hosted at the International Institute for Applied Systems Analysis (IIASA) and available at: https://tntcat.iiasa.ac.at/AR5DB/

2. MAIN RESULTS

The carbon prices in RCP2.6 scenarios in the SSP database cover a wide range of trajectories. All trajectories are increasing over time, to high levels by mid-century and in most cases very high levels by the end of century (Figure 1). Carbon prices range from 15 to 360 USD_{2005}/tCO_2e in 2030, 45 to 1000 USD_{2005}/tCO_2e in 2050 and 140 to 8300 USD_{2005}/tCO_2e in 2100. Because this 'carbon' price is applied to all anthropogenic greenhouse gas emissions in IAMs, it is expressed in units of USD per metric ton of carbon-dioxide-equivalent emissions[3] (USD/tCO_2e).

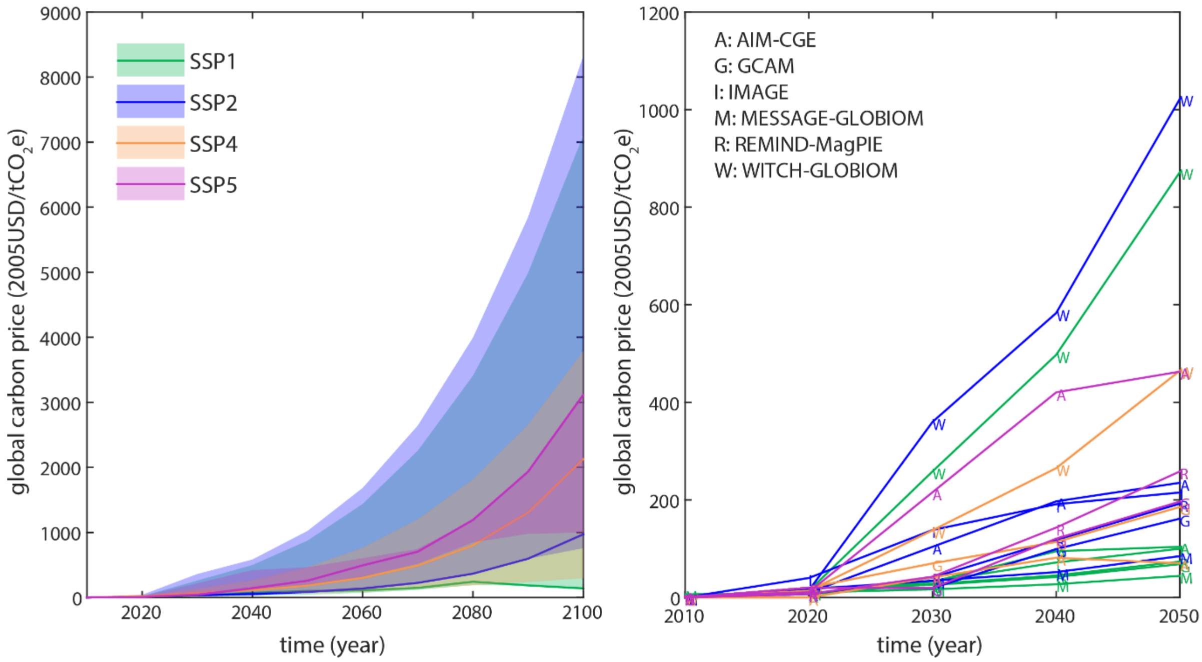

Figure 1*: Carbon price trajectories from RCP2.6 scenarios limiting warming during the 21st century to below 2°C with a likely (greater than 66%) probability. The left panel shows carbon price trajectories over the entire century per SSP. Shaded areas show the range per SSP and solid lines indicate the carbon price trajectory for the marker implementation of each SSP (Riahi et al., 2016). All scenarios listed in Table 3 are shown.*

The wide range of carbon prices can be explained by both structural modeling differences and varying socioeconomic conditions. An analysis of the relative contribution of SSP and model differences to the overall variation in carbon prices[4] shows that the largest part of the variation (90%) is due to inter-model differences (p-value <<0.01). Socioeconomic variations as represented by the SSPs account for about 10% of the variation across our set of RCP2.6 scenarios (p-value of 0.06). This relatively small contribution of SSPs to the overall variation in this set is because those scenarios that are deemed infeasible during their development cannot be included in the analysis. In particular, no model was able to model an RCP2.6 scenario under SSP3 socioeconomic assumptions. This information was not included in this analysis of the variance. In the two following sections we explore how the choice of modeling framework and assumed SSP can influence carbon price levels and trajectories.

[3] Carbon-dioxide equivalence is in this exercise calculated with 100-year global warming potentials from the IPCC Fourth Assessment Report.

[4] A two-way ANOVA was carried out exploring the influence of SSP and model variation on the overall variation of carbon prices in RCP2.6 scenarios.

Modeling frameworks determine the shapes and levels of carbon prices trajectories

Differences in modeling approaches across various frameworks lead to differences in the shapes of carbon price trajectories (Figure 2). On the one hand, intertemporal optimization modeling approaches lead to exponentially increasing carbon price trends. On the other hand, recursive dynamic approaches show higher prices in the short term, which then increase more slowly and thus result in lower levels in the long term. This can be explained by different representation of future price anticipations. In optimization frameworks, economic agents have perfect foresight of future technological and socioeconomic development. Investment and technology decisions that involve long-lived capital thus integrate the knowledge of future prices. This leads to emissions already being reduced in the short term (while current prices are still low) under the anticipation of significantly higher carbon prices in the medium to long term. Contrary to this approach, recursive dynamic frameworks have myopic anticipations of future prices, such that emissions reductions in the short term are only based on current prices, knowledge and expectations. This results in higher required carbon prices.[5]

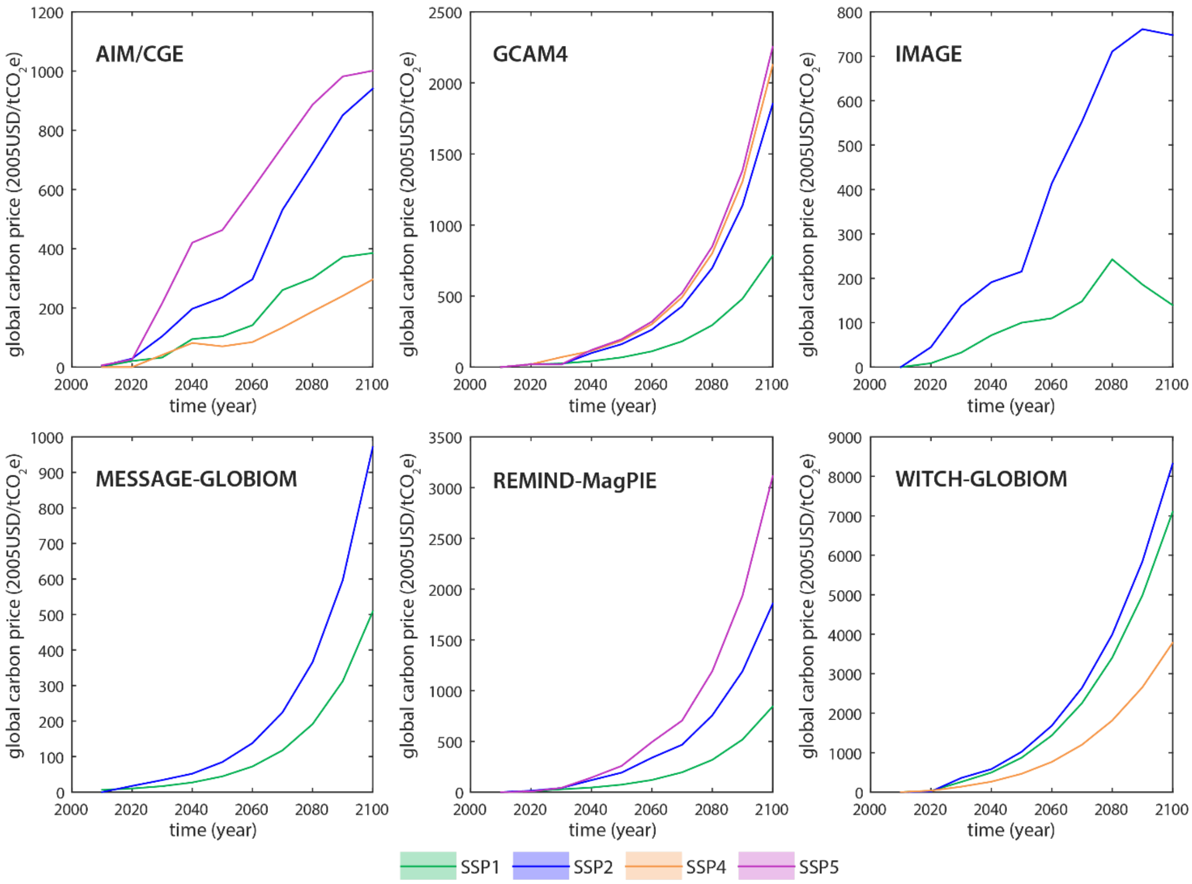

Figure 2*: Carbon price trajectories over the 21st century for RCP2.6 scenarios. Each panel shows the trajectories for one specific model. The trajectory colors indicate the assumed SSP. See footnote 5 for additional information on the carbon price trajectories of the GCAM model.*

[5] The GCAM model is an atypical exception here. Although it is categorized as a recursive dynamic framework, it still exhibits exponentially increasing carbon prices. This is because, for the scenario implementation of the SSP study, the GCAM framework was driven with exogenous assumptions of exponentially increasing carbon prices. This approach aims at minimizing discounted overall costs over the entire century for the GCAM model.

Besides the shape of carbon price trajectories over time, also their magnitude depends on the structure and assumptions of the modeling framework with which they are estimated. Models can be classified according to how responsive they are to a carbon price signal, and are typically categorized in models with a low, medium or high response[6] (Kriegler et al., 2015). We expect this responsiveness to also be reflected in carbon prices when models attempt to achieve one specific climate forcing target (RCP2.6). Indeed, one expects low response models to yield high required carbon prices, and vice versa. In our set, WITCH shows particularly high carbon prices compared to the other models. Of the participating modeling frameworks, WITCH is the only model that is categorized as a low-response model, whereas the other participating models are either high-response (GCAM, IMAGE, MESSAGE, REMIND) or medium-response (AIM-CGE).

For all modeling frameworks, the carbon prices trajectories are ordered in the following order: SSP4<SSP1<SSP2<SSP5, except for GCAM where carbon prices in SSP4 scenario are above SSP2 and close to SSP5 levels. This brings us to the exploration of carbon price variations across socioeconomic scenarios, in following section.

Socioeconomic conditions and policy implementation determine carbon prices levels

To explore how socioeconomic conditions and assumption about policy implementation influence carbon prices, we first focus on the "middle-of-the-road" SSP2 socioeconomic scenario. This scenario represents a continuation of historical dynamics, yet is more than a simple extrapolation of current trends (Fricko et al., 2016). The quantifications of SSP2 with the 6 IAMs available in the SSP database result in carbon price ranges from 20 to 360 USD_{2005}/tCO_2e in 2030, 85 to 1000 USD_{2005}/tCO_2e in 2050 and 750 to 8300 USD_{2005}/tCO_2e in 2100 (Figure 3, left panel). The net present value (NPV) of the global carbon price across models (calculated with a 5% discount rate over the 2020-2100 period) shows a slightly smaller spread than carbon prices in single years (Figure 1Figure 3, middle versus left panel). For the NPV of carbon prices, 5 models out of 6 gather around 20 USD_{2005}/tCO_2e. This is because models that tend to have higher prices in the short term (AIM-CGE, IMAGE) have lower prices in the long-term, and vice versa. The WITCH model remains an outlier with a significantly higher NPV of carbon prices than the other models. This reflects the structural characteristics of the WITCH model which is categorized as a 'low-response' model (see discussion above).

Changing the socioeconomic assumptions underlying the scenarios results in a relative shift in carbon prices. For instance, a clear trend is visible when moving between SSP1, SSP2, and SSP5 (see Figure 3, right panel). There is a robust reduction in carbon prices when shifting from SSP2 to SSP1 scenarios. This is not surprising because the SSP1 narrative dictates that SSP1 represents a world which evolves under a green-growth paradigm with low challenges to mitigation. The reduction in carbon prices is close to a 50% reduction in 2050 for most models. The bracketing models here are WITCH (close to 15% reduction) and IMAGE (close to 80% reduction).

On the opposite side, there is a robust increase in carbon prices when moving from SSP2 to SSP5 scenarios. This is consistent with the SSP5 narrative, which dictates a socioeconomic development with

[6] The classification of models is done with diagnostics indicators that characterize the model's behavior in response to defined carbon price trajectories. A low response model corresponds to (i) a low relative abatement index (i.e. an index which characterizes the emission reductions in a carbon tax scenario relative to the baseline), (ii) a high CoEI indicator (carbon intensity over energy intensity, that captures the proportionality of carbon and energy intensity reductions in response to carbon prices) and (iii) a low transformation index (which characterizes the change in structure of the energy mix due to the imposed carbon prices).

high challenges to mitigation. Carbon price increases range from approximately 10% to 70% in 2050, although only 3 out of 6 models have explored this particular socioeconomic world (see Table 3).

When moving from SSP2 to SSP4 the change in carbon price is not unidirectional. For one model (GCAM) the carbon price is a little higher in SSP4 than in SSP2, whereas for two models (WITCH and AIM-CGE) the carbon price in SSP4 is roughly 50% lower than in SSP2. Intuitively, one might expect lower carbon prices in SSP4 (which is described as a world with low mitigation challenges) compared to SSP2 (a world with medium mitigation challenges). Several factors, and their interaction, contribute to this intuition not always being correct for the stringent RCP2.6 scenarios.

For a start, elements of the SPAs associated with SSP2 and SSP4 differ in two ways. SPA4 is characterized by early accession to stringent policy with global collaboration as of 2020, whereas SPA2 sees some delays in establishing global action. Second, SPA4 is characterized by limited pricing of land-use emissions, whereas SPA2 has land-use emissions priced at the level of carbon prices in the energy sector (unless this leads to afforestation). From the first difference, one would expect lower carbon prices in the short term in SSP2, relative to SSP4, but higher in the medium to long term to compensate for delays in the emissions reductions. But from the second difference, one would expect higher carbon prices in SSP4 to compensate for the inability to control land-use emissions (lower priced or unpriced land-use emissions). Whichever effect dominates depends on the modeling teams' interpretation of the SPAs as well as on the representation of the land-use sector in the models. In GCAM (which has a detailed representation of the land-use sector), the latter effect dominates for stringent mitigation targets. In the GCAM framework, SSP4 world is one where it is easy to mitigate, but only up to a certain point. As the radiative forcing target declines, the price of carbon begins to rise significantly due to the limited ability to reduce land-related GHG emissions in low income regions (Calvin et al., 2016). Finally, in addition to the policy assumptions, also other socioeconomic assumptions embedded in the SSPs, like the availability of particular technologies or the acceptance of carbon capture and storage (CCS) and its link to the land-use sector through availability of biomass energy for negative emissions, can further influence the difference between various implementations. For instance, in WITCH and AIM implementations of the SSPs, higher acceptance of carbon capture and storage in SSP4 relative to SSP1 is an important factor explaining lower carbon prices in SSP4 compared to SSP1 levels.

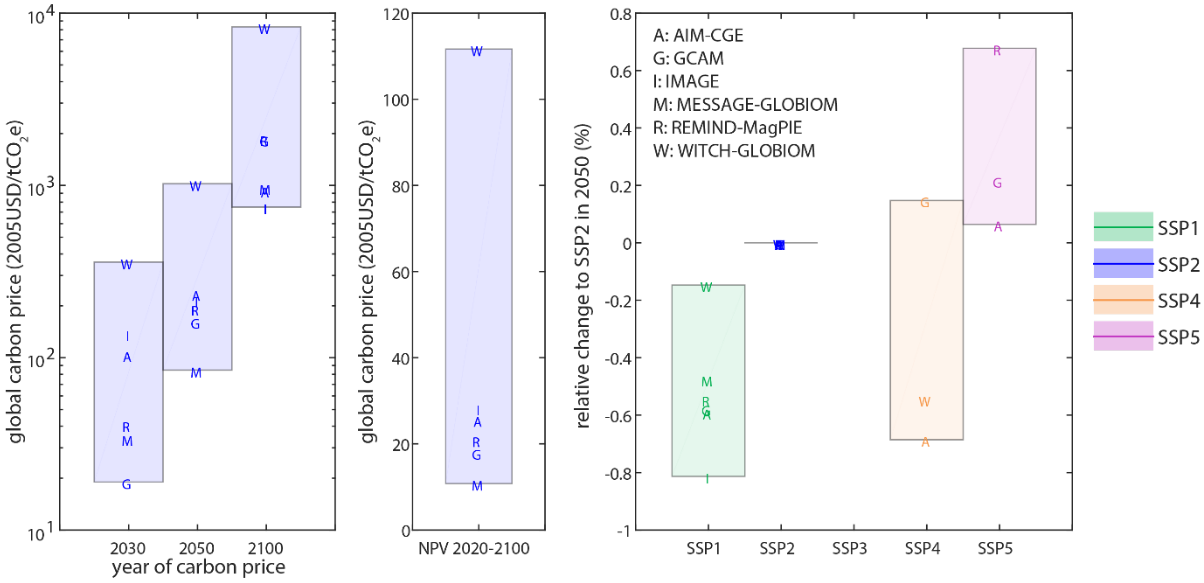

Figure 3*: Carbon price ranges for RCP2.6 scenarios. Carbon price ranges for the years 2030, 2050, and 2100 for RCP2.6 scenarios modelled under SSP2 socioeconomic assumptions (left panel). Net present value (NPV) of the carbon prices in RCP2.6 scenarios modelled under SSP2 socioeconomic assumptions (middle panel; 5% discount rate over 2020-2100 period). Relative change of year-2050 carbon prices under varying SSP assumptions.*

3. DISCUSSION

Comparison with IPCC AR5 WGIII carbon price ranges

Figure 4 compares the carbon prices from this study to the ranges reported in the chapter on assessing transformation pathways (Clarke et al., 2014) of the Working Group III (WGIII) Contribution to the Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC). The price trajectories from this study cover approximately the same ranges as the IPCC AR5 430-480 ppm CO_2eq category. This category was assessed to corresponds to a *likely* (i.e. >66% probability) to limit warming to below 2°C during the 21st century (Table SPM.1 in IPCC Synthesis Report 2014). With only a few scenarios, the SSP RCP2.6 carbon price range covers the full range 430-480 ppm CO_2eq scenarios of the IPCC AR5 Scenario Database. In the short term (2020 and 2030), our range of global carbon prices is slightly shifted to the lower bound, whereas it is shifted to the higher bound in the long term (2100). This is particularly true for the range of middle-of-the-road SSP2 and fossil-fuel intensive SSP5 scenarios, which assumes delay in global mitigation action to varying degrees. A delay in global mitigation action implies lower global prices in the short-term, and has to be compensated by more mitigation efforts in the long term. These stronger mitigation efforts are reflected by higher global prices by the middle and end of the century.

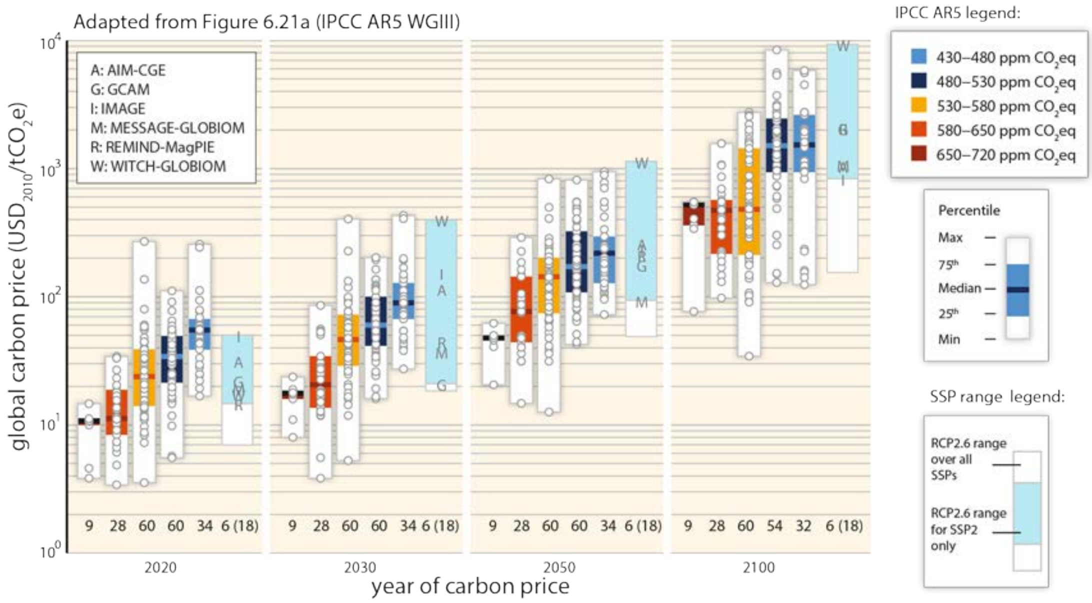

Figure 4: Comparison of carbon price ranges with IPCC AR5 Scenario Database values. SSP-based carbon price ranges span almost the entire range of scenarios included in the IPCC AR5 Scenario Database. Characters shown on top of the light blue SSP range represent the SSP2 value for each model, respectively. Figure adapted from Figure 6.21 from Clarke et al. (2014).

Carbon prices increase for increased 1.5°C ambition

This briefing does not explore carbon prices necessary for increasing ambition so that warming is further limited to below 1.5°C. An initial study (Rogelj et al., 2015) analyzed differential mitigation costs for 1.5°C and 2°C scenarios. That study estimated the anticipated carbon price increase to move from a scenario that limits warming to below 2°C relative to pre-industrial levels with precisely 66% probability to a scenarios that returns warming to below 1.5°C in 2100 with precisely 50% (after temporarily exceeding that limit for a few decades during the 21st century). The study found that, all other aspects kept the same, carbon prices in 1.5°C scenarios are up to about 2 to 3 times higher than in the 2°C scenarios as defined above. Note that until now only scenarios with a 50% probability of limiting warming to 1.5°C have been explored, in contrast to 2°C scenarios which most often have been assumed to have a *likely* (>66%) probability of success. Finally, currently all 1.5°C scenarios assume that global mean temperature rise temporarily exceeds the 1.5°C limit for a certain time until being again reduced to below it by the end of the century.

Carbon prices and mitigation policy instruments

Carbon prices quantified in the scenarios explored in this briefing do not necessarily represent actual carbon taxes. In optimization frameworks, carbon prices reflect the 'shadow prices' of the constraint which was imposed on emissions. These shadow prices do not mean, however, that the pathways resulting from the model runs should necessarily be implemented through a tax on carbon. In recursive dynamics frameworks, carbon prices represent actual policy instruments, carbon taxes or equivalent cap-and-trade systems in essence. However, policy instruments that give an explicit or implicit price to carbon are not limited to carbon taxes or emissions trading systems. They also include technological regulations, renewables mandates, subsidies, feed-in tariffs or auctions, inter alia.

There are considerable debates about which policy instrument, or which policy instrument mix, should be used to meet a desired mitigation goal. The efficiency argument is often used in favor of carbon taxes or emissions trading systems. However, some authors have shown that in second best situations carbon taxes do not always guarantee efficiency (e.g. Goulder et al., 2016). Other considerations, such as distributional equity, the ability to address uncertainties, and political feasibility, can also give arguments in favor of other policy instruments than taxes (see, for example, Goulder and Parry, 2008 for a review).

Furthermore, carbon prices interact with other mitigation policy instruments and with other policies in the context of multiple policy objectives. For example, policy instruments for renewable energy interact with carbon pricing, and may have countervailing effects (Böhringer and Rosendahl, 2010; Fischer and Preonas, 2010). Also, carbon pricing interacts with transport infrastructure policy or with urban policies, in a way such that policies restricting the deployment of high-carbon transport infrastructure can lower the cost of mitigation (Waisman et al., 2013; Ó Broin and Guivarch, 2017).

Uniform carbon prices vs. differentiated prices across sectors and/or countries

Carbon prices quantified in the scenarios explored in this briefing correspond to uniform carbon prices across sectors and countries, with two exceptions. In some socioeconomic pathways (SSP2 and SSP5), mitigation policy assumptions impose delays in establishing global action. Carbon prices are in this case differentiated between countries until 2040 with lower prices in lower income countries. Also, in some scenarios (SSP4 and SSP2) land-use sector emissions are not subject to carbon pricing, whereas the rest of the economy is.

There are strong arguments in favor of globally uniform carbon pricing (e.g. Weitzman, 2015, Cramton et al., 2015), or for a 'linkage'[7] of national policies to give the flexibility to reduce emissions where it is the cheapest (Bodansky et al., 2015). The economic textbook recommendation is indeed that uniform pricing results in overall, global efficiency of mitigation actions. However, it has been shown that the same global uniform carbon prices lead to high mitigation costs in emerging and developing countries (Clarke et al., 2014), giving rise to equity concerns. The economic textbook result states that efficiency and equity are separable, and that equity issues can be solved with international transfers. However, transfers may be politically difficult or potentially infeasible at the scale required, and when transfers are limited or capped, uniform pricing does not guarantee efficiency (Sandmo, 2007). Furthermore, in cases where the production of a public good is implied (as is the case with climate change mitigation), theoretical work shows that efficiency and equity are not separable and that a uniform carbon price is neither necessary nor sufficient to ensure efficiency (Chichilnisky and Heal, 2000; Sheeran, 2006).

Similarly, the efficiency argument is often used to recommend uniform carbon pricing across sectors. However, other considerations, including distributional issues, the presence of other externalities, or differential inertia between sectors, may support the rationale to differentiate prices or other mitigation policy instruments across sections (e.g. Vogt-Schilb et al., 2013).

[7] By linkage, we mean the formal recognition by a mitigation program in one jurisdiction of emission reductions undertaken in another jurisdiction for the purposes of complying with the first jurisdiction's requirements.

References

Bodansky, D. M., S.A. Hoedl, G.E. Metcalf, and R.N. Stavins. 2016. « Facilitating linkage of climate policies through the Paris outcome ». *Climate Policy* 16 (8): 956-72.

Böhringer, C., and K.E. Rosendahl. 2010. « Green promotes the dirtiest: on the interaction between black and green quotas in energy markets ». *Journal of Regulatory Economics* 37 (3): 316-25.

Calvin, K., B. Bond-Lamberty, L. Clarke, J. Edmonds, J. Eom, C. Hartin, S. Kim, et al. 2017. « The SSP4: A world of deepening inequality ». *Global Environmental Change* (in press).

Chichilnisky, G., and G.M. Heal. 2000. *Environmental markets. Equity and Efficiency*. Columbia University Press. New York.

Clarke L., K. Jiang, K. Akimoto, M. Babiker, G. Blanford, K. Fisher-Vanden, J.-C. Hourcade, V. Krey, E. Kriegler, A. Löschel, D. McCollum, S. Paltsev, S. Rose, P. R. Shukla, M. Tavoni, B. C. C. van der Zwaan, and D.P. van Vuuren, 2014: Assessing Transformation Pathways. In: Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel and J.C. Minx (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Cramton, P., A. Ockenfels, and S. Stoft. 2015. « An International Carbon-Price Commitment Promotes Cooperation ». *Economics of Energy & Environmental Policy* 4 (2).

Fischer, C., and L. Preonas. 2010. « Combining Policies for Renewable Energy: Is the Whole Less Than the Sum of Its Parts? » *International Review of Environmental and Resource Economics* 4: 51-92.

Fricko, O., P. Havlik, J. Rogelj, Z. Klimont, M. Gusti, N. Johnson, P. Kolp, et al. 2017. « The marker quantification of the Shared Socioeconomic Pathway 2: A middle-of-the-road scenario for the 21st century ». *Global Environmental Change* (in press).

Goulder, L.H., and I.W.H. Parry. 2008. « Instrument choice in environmental policy ». *Review of Environmental Economics and Policy* 2 (2): 152-74.

Goulder, L.H., M.A.C. Hafstead, and R.C. Williams. 2016. « General Equilibrium Impacts of a Federal Clean Energy Standard ». *American Economic Journal: Economic Policy* 8 (2): 186-218.

Hope, C. and M. Hope. 2013. « The social cost of CO2 in a low-growth world ». *Nature Climate Change* 3(8): 722-724.

IPCC (2014). Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Core Writing Team, R. K. Pachauri and L. A. Meyer. Geneva, Switzerland, IPCC: 1-151.

Kriegler, E., J. Edmonds, S.Hallegatte, K.L. Ebi, T. Kram, K. Riahi, H. Winkler, and D. P. van Vuuren. 2014. « A New Scenario Framework for Climate Change Research: The Concept of Shared Climate Policy Assumptions ». *Climatic Change* 122 (3): 401-14.

Kriegler, E., N. Petermann, V. Krey, V.J. Schwanitz, G. Luderer, S. Ashina, V.Bosetti, et al. 2015. « Diagnostic indicators for integrated assessment models of climate policy ». *Technological Forecasting and Social Change* 90, Part A: 45-61.

Moss, R. H., J. A. Edmonds, K. A. Hibbard, M. R. Manning, S. K. Rose, D. P. van Vuuren, T. R. Carter, S. Emori, M. Kainuma, and T. Kram. 2010. « The next generation of scenarios for climate change research and assessment ». *Nature* 463 (7282): 747-56.

Nordhaus, W. D. 2013. « The climate casino: Risk, uncertainty, and economics for a warming world ». New Haven, CT, Yale University Press.

Ó Broin, E., and C. Guivarch. 2017. « Transport infrastructure costs in low-carbon pathways ». *Transportation Research Part D: Transport and Environment* (in press).

O'Neill, B.C., T.R. Carter, K.L. Ebi, J. Edmonds, S. Hallegatte, E. Kemp-Benedict, E. Kriegler, L. Mearns, R. Moss, K. Riahi, B. van Ruijven, D. van Vuuren. 2012. « Meeting Report of the Workshop on The Nature and Use of New Socioeconomic Pathways for Climate Change Research », National Center for Atmospheric Research (NCAR), Boulder, CO November 2-4, 2011.

O'Neill, B.C., E. Kriegler, K. Riahi, K.L. Ebi, S. Hallegatte, T.R. Carter, R. Mathur, and D.P. van Vuuren. 2014. « A New Scenario Framework for Climate Change Research: The Concept of Shared Socioeconomic Pathways ». *Climatic Change* 122 (3): 387-400.

O'Neill, B. C., E. Kriegler, K.L. Ebi, E. Kemp-Benedict, K. Riahi, D.S. Rothman, B. J. van Ruijven, et al. 2016. « The roads ahead: Narratives for shared socioeconomic pathways describing world futures in the 21st century ». *Global Environmental Change* (in press).

Riahi, K., D. P. van Vuuren, E. Kriegler, J. Edmonds, B.C. O'Neill, S. Fujimori, N. Bauer, et al. 2017. « The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: An overview ». *Global Environmental Change* (in press).

Rogelj, J., G. Luderer, R.C. Pietzcker, E. Kriegler, M. Schaeffer, V. Krey, and K. Riahi. 2015. « Energy System Transformations for Limiting End-of-Century Warming to below 1.5 °C ». *Nature Climate Change* 5 (6): 519-27.

Sandmo, A. 2007. « Global Public Economics: Public Goods and Externalities ». *Économie publique/Public economics*, n° 18-19. http://economiepublique.revues.org/4282?file=1.

Schleussner, C.-F., J. Rogelj, M. Schaeffer, T. Lissner, R. Licker, E. M. Fischer, R. Knutti, A. Levermann, K. Frieler, and W. Hare. 2016. « Science and policy characteristics of the Paris Agreement temperature goal ». *Nature Climate Change* 6 (9), 827-835.

Sheeran, K.A. 2006. « Who Should Abate Carbon Emissions? A Note ». *Environmental and Resource Economics* 35 (2): 89-98.

van Vuuren, D.P., E. Kriegler, B.C. O'Neill, K.L. Ebi, K. Riahi, T.R. Carter, J. Edmonds, et al. 2014. « A New Scenario Framework for Climate Change Research: Scenario Matrix Architecture ». *Climatic Change* 122 (3): 373-86.

Vogt-Schilb, A., G. Meunier, and S. Hallegatte. 2013. « Should marginal abatement costs differ across sectors? The effect of low-carbon capital accumulation ». *World Bank Policy Research Working Paper*, n° 6415.

Waisman, H.-D., C. Guivarch, and F. Lecocq. 2013. « The transportation sector and low-carbon growth pathways: modelling urban, infrastructure, and spatial determinants of mobility ». *Climate Policy* 13 (sup01): 106-29.

Weitzman, M.L. 2015. « Internalizing the Climate Externality: Can a Uniform Price Commitment Help? » *Economics of Energy & Environmental Policy* 4 (2).