ENGLISH Summary

Carbon prices for Cost-Benefit Analysis

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The objective of this report is to review the literature on carbon price paths consistent with the goal of limiting global average temperatures to 1.5˚C, and provide guidance i) on the target-consistent *level and price path* of the cost of carbon, interpreted as the marginal abatement/sequestration cost of reaching a net zero emission target in Europe by 2050, and ii) on *application* of carbon values within cost benefit analysis (CBA). By extracting results from a large sample of scenarios from different Integrated Assessment Models that have been used in the IPPC Special Report on Global Warming of 1.5 °C, we recommend applying a cost of carbon of 166 Euro per ton CO_2 equivalent in 2025, rising to 1014 Euro per ton in 2050. We recommend that this cost of carbon should be applied in CBAs throughout the economy, i.e., independent of whether the project emissions are regulated by the EU ETS or not.

When undertaking cost-benefit analysis (CBA) of projects with impacts on CO_2 emissions (or other greenhouse gas emissions), a value has to be put on these emissions. This value is often referred to as the cost of carbon, or simply carbon value or carbon price. The objective of this report is to research the literature on carbon price paths consistent with the goal of limiting global average temperatures to 1.5˚C, and provide guidance i) on the target-consistent *level and price path* of the cost of carbon, interpreted as the marginal abatement/sequestration cost of reaching a net zero emission target in Europe by 2050, and ii) on *application* of carbon values within cost benefit analysis (CBA).

In our context the cost of carbon is not related to the damages from climate change, but to the relationship between the economy and emissions. It is the shadow price related to reaching the climate target. Another way of interpreting *cost of carbon* is that if all emission sources face a carbon price corresponding to the cost of carbon, and no other supportive climate policies are implemented, then the emission target is exactly reached at lowest possible cost.

To derive an estimate for the cost of carbon, one needs good understanding of how costly it is to reduce carbon emissions, not only today but long into the future. For this purpose, so-called Integrated Assessment Models (IAMs) are usually applied. A number of scenarios based on such models exist, many of them consistent with the

1.5˚C and net zero emission targets. Most of them are retrieved from the database IAMC (Integrated Assessment Modeling Consortium) 1.5°C Scenario Explorer hosted by IIASA (Huppmann, Kriegler, Krey, et al., 2018) and summarized in IPCC (2018). This represents the combined findings of the world's leading research institutes, with a particularly strong representation from European research centres. In these scenarios, the modellers search for the (mostly global) carbon price path that is required to meet the target. In this report, we summarize the findings from these and other scenarios, and discuss possible reasons for the large variation in price trajectories. We explain that the large variation can be due to differences in model structure as well as different assumptions about future developments.

Choosing a proper range of carbon prices based on an ensemble of IAM scenarios, with a central estimate, comes with a range of concerns. In Huppmann, Rogelj, Kriegler, Krey, and Riahi (2018), the authors provide guidelines, and we have done our best to make judgements in the spirit of these. First, we do not cherry-pick a single scenario and extract one carbon price trajectory, but rather exploit as large a sample of scenarios as possible. Second, we convey several values; median, average, interquark-tile range and full range. Our goal is to exploit and communicate as much information as possible from scenarios that are consistent with the 1.5˚C target, but which do not have too much overshoot of the temperature target and are also not too reliant on high levels of Bio Energy with Carbon Capture and Storage (BECCS) (a lot of criticism has been raised against the huge amounts of BECCS in many scenarios, questioning whether it is realistic and sustainable, cf. Section 2.2.6).

Scenarios that largely rely on supportive policies (in addition to carbon pricing) make it difficult to pin down the correct cost of carbon (i.e., the shadow price of the target), and hence are not used directly but are still reviewed and taken notice of. Examples of such studies are European Commission (2018) and IEA (2019). Another influential study is from the High-Level Commission on Carbon Prices (Stiglitz et al., 2017), but there only carbon prices consistent with the 2˚C target are presented.

As most relevant scenarios are found in the IAMC database, we focus particularly on those scenarios. In Table S 1 we show the "process of elimination" as we go from a sample of 84 IAMC scenarios (first column) to a smaller sample where we exclude scenarios with too high overshoot (second column), and then exclude scenarios that are too reliant on huge levels of BECCS (third column). Following this process, we end up with the carbon price ranges for 2050 shown in Table S 1 (measured in 2016-Euros). We provide similar tables for every fifth year from 2020 to 2045 in Appendix C.

Table S 1 illustrates the large uncertainty with respect to carbon prices consistent with the 1.5˚C target. In this report we shed some light on *why* the range of carbon prices is so wide. Important factors are type of model, assumptions about the future (e.g., so-called Shared Socioeconomic Pathways – SSP), and access to and costs of climate-friendly technologies. We cannot say with certainty that any model or any scenario we have added to our sample is better than another, and so we are not able to recommend any single scenario or model.

There will also be some biases, however, since there is underrepresentation of certain scenarios and models in the IAMC database. For some future scenarios (SSPs), keeping global warming below 1.5˚C is not feasible in several models.

Table S 1: Descriptive statistics from the ensemble of carbon prices in the IAMC database for the year 2050 consistent with the 1.5˚C target, from starting sample (left), to applicable and consistent sample (right). Prices in 2016-Euros.

Prices in 2050	Original sample	Remove studies with high overshoot	Remove studies with unsustainable BECCS
N	84	50	20
Min price	112	125	125
25th pctile price	315	470	319
Median price	480	832	806
75th pctile price	1038	1179	1174
Max price	14236	14236	14236
Average price	1096	1433	1677

The most relevant study beyond the IAMC scenarios is a study for the French economy (France Stratégie, 2019). The proposed carbon prices in that report are quite close to the median in the selected IAMC scenarios (i.e., third column in Table S 1 for 2050). Studies that incorporate supportive climate policies in addition to carbon prices, such as European Commission (2018), tend to find lower carbon prices than the IAMC scenarios. This is not surprising. As mentioned above, however, it is difficult to derive the cost of carbon from these studies.

In addition to the underrepresentation of certain scenarios and models, there are also other issues to consider. The IAMC scenarios consider the 1.5˚C target, which require net zero *carbon* emissions globally around 2050 but not net zero *GHG* emissions globally before around 2070. There is also a question whether carbon prices should be higher in Europe and other rich countries than in poor countries, and to what degree risk aversion should be taken into account.

Consequently, it is difficult to present a clear recommendation for the cost of carbon for CBAs. This is partly because the price range is huge (e.g., in 2050, the 75th percentile price is almost four times higher than the 25th percentile in the third column of Table S 1) and partly because of the various issues discussed above. Taking the IAMC results as a starting point and summing up all the issues, the overall bias seems to go in the direction of underestimating the cost of carbon in a European context. There are scenarios that are "missing" since the models found them infeasible, and there is over-representation of models where the economy is highly responsive to carbon prices relative to models that are less responsive. A request for regional variation in CO_2 prices and accounting for risk aversion may also go in the direction of underestimating the cost of carbon, although these issues are more normative than descriptive.

Based on this assessment we present two alternative options for the recommended cost of carbon.

Option 1: Follow the median

The first and most straightforward option is to just apply the median from the final sample of the IAMC scenarios (i.e., third column of Table S 1 for 2050) as the main trajectory for the recommended cost of carbon, with low and high price trajectories based on the 25th and 75th percentiles percentiles to use for sensitivity analysis. This means a cost of carbon of 141 Euro per ton CO_2e in 2025, rising to 806 Euro per ton in

2050. As can be seen from Figure S 1, the median price trajectory is quite bumpy when using all the model year prices (dashed line). For practical purposes, we therefore smooth the price trajectory, using prices in 2025 and 2050 as anchors and apply the same annual growth rate in the years between. The associated growth rate is 7.2%, which is also applied for the period 2020-2025. We also create a similar smooth carbon price trajectory for the range, using their respective estimates for 2025 and 2050 as anchor points. The results are shown in Figure S 1.

Option 2: Upward adjustment

Our assessment suggests that the price range in the final sample of the IAMC scenarios is a slight underestimate of the recommended cost of carbon for CBA in a European context (even when disregarding the two normative issues, see below). It is difficult to assess by how much, however. Somewhat arbitrarily (but rather cautiously), in this second option we use the 55th percentile instead of the 50th (i.e. median) as the main trajectory for the recommended cost of carbon. This means a cost of carbon of 166 Euro per ton CO_2e in 2025, rising to 1014 Euro per ton in 2050.

As with the median value carbon price trajectory, the 55th percentile trajectory is quite bumpy (dashed line in Figure S 2). We therefore also smooth the price trajectory in Option 2, using prices in 2025 and 2050 as anchors, applying the same annual growth rate in the years between. This growth rate of 7.5% is also applied for the period 2020-25. We also adjust the recommended price range, using the 30th and 80th percentiles in 2025 and 2050. The results are shown in Figure S 2.

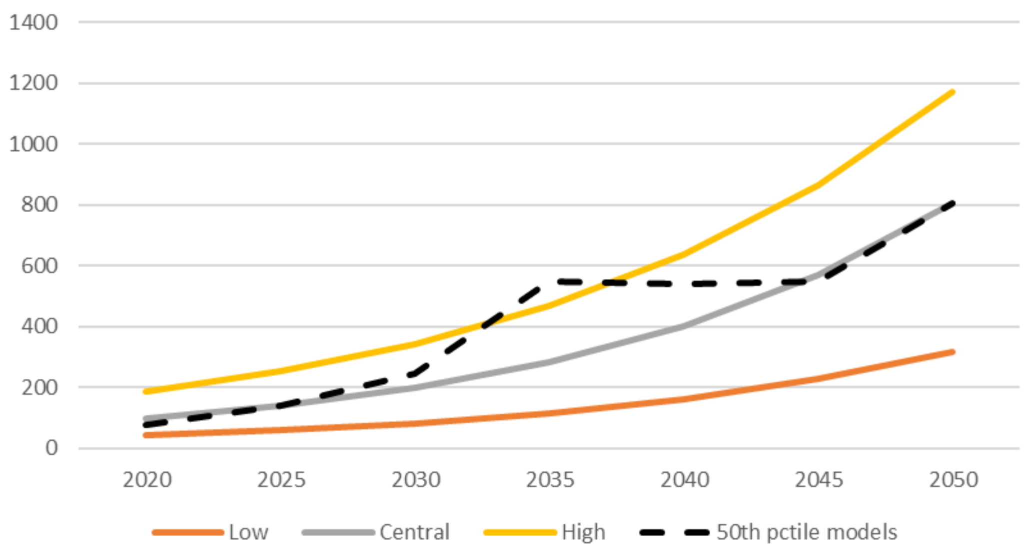

Figure S 1: Recommended carbon price range (EUR2016/tCO_2e) for the period 2020-2050 – Option 1.

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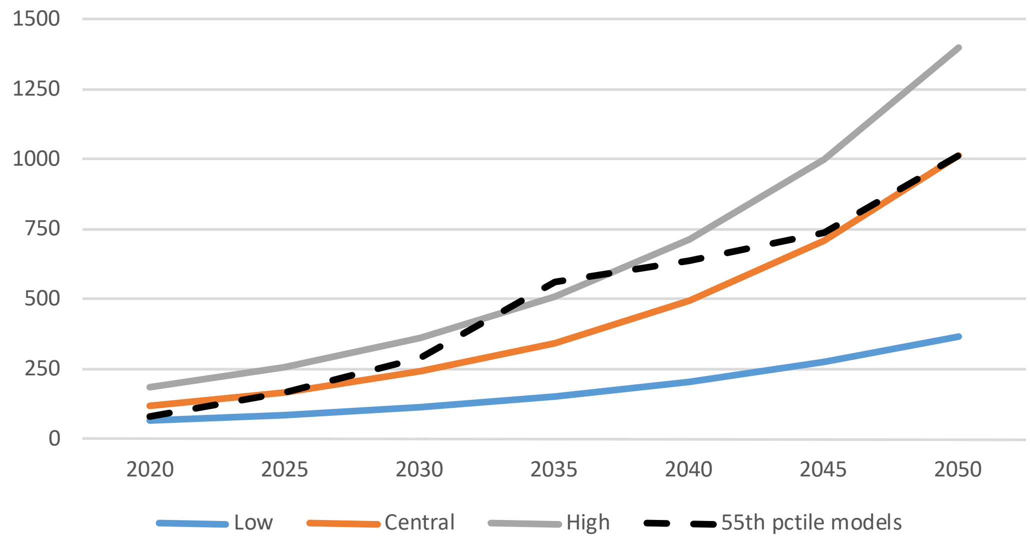

Figure S 2: Recommended carbon price range (EUR2016/tCO_2e) for the period 2020-2050 – Option 2.

Taking into account the two normative issues as well, the cost of carbon for European countries would be higher. This is especially the case in the first 1-2 decades, while it is more reasonable to apply more similar carbon prices around the middle of this century when developing countries have had time to grow their economy and had more time to prepare for strict climate regulation. However, we are not in a position to assess how much higher.

The recommended carbon prices for CBA are significantly higher than existing carbon prices in Europe and elsewhere. This reflects that complying with the 1.5˚C target and reaching net zero GHG emissions by 2050 is a very ambitious target, which according to most available studies will be very challenging with very high marginal abatement costs. However, how costly it will be this is highly uncertain, and this depends crucially on how the costs of zero-emissions technologies evolve in the next few decades.

Turning next to the application of carbon values within cost benefit analysis (CBA) in Europe, we first discuss, based on existing CBA literature, general principles on how to include carbon values in CBA. Here we distinguish in particular between project emissions regulated by an emissions trading system (ETS) and project emissions regulated by a tax (or unregulated). We argue that using the "inclusive principle" in CBA accounting is good practice, as it distinguishes clearly between transfers and real costs. To ease the discussion, we show several examples.

When considering the actual net cost of emissions in CBA, we focus on the two categories "Cost of abatement in other ETS firms" and "Cost of project carbon emissions", that is, the changes in these costs. In the tax (and unregulated) case, the net cost of emissions will be equal to the shadow price of the emissions target, in other words, what we refer to as the *cost of carbon*. In the ETS case, however, the net cost of emissions will be equal to the ETS price – *as long as the emissions cap is considered fixed*. If the ETS cap for some reason is endogenous, responding positively to the demand for emissions allowances, the situation can be characterized as a combination of the tax and the ETS case. In the extreme case where the cap responds 1:1 to allowance demand (in which case the ETS price is essentially fixed), we are for practical purposes in the tax case. If carbon prices are differentiated and/or supported by other climate policies, our conclusion does not change. Importantly, in the tax case it is not the tax level that determines the net cost of emissions – it is still the shadow price of the climate target that matters.

Based on the general discussion, we consider how to use carbon values in sectors regulated by the EU ETS. Implications of the Market Stability Reserve (MSR) in the EU ETS are discussed. The MSR makes the emissions cap endogenous, with the cap being an increasing function of the demand for allowances (at least in the short to medium term). We also point to regulatory changes as a response to e.g. lower than expected/ desired ETS prices. For these reasons we argue that considering the emissions cap in the EU ETS as fixed may seem a bit naïve. Additional emissions reductions in the short run will effectively reduce the emissions cap via the MSR (although not 1:1, but possibly quite close). Additional emissions reductions in the medium to long run will probably not have the same impact on the emissions cap via the MSR, but increase the likelyhood of more stringent emissions cap via regulatory changes. These impacts are, however, difficult to quantify.

For emissions in Non-ETS sectors, the general principles referred to above can more easily be applied. One possible exception may relate to short-term emissions, as there are specific Non-ETS targets for each EU/EEA country for the years 2021-30. The shadow price of reaching these targets may differ across countries, and may also differ from the shadow price of the long-term target.

For project emissions abroad, a cost-effective approach would suggest that the same CO_2 prices that are used domestically are also used abroad, as all greenhouse gas emissions have the same climate impacts. There are two potential arguments against, however. One is that Europe's target of net zero greenhouse gas emissions by 2050 seems to be slightly stricter than reaching the 1.5°C target with uniform CO_2 prices across the world (cf. discussion above). The other is that from a welfare or normative perspective one could argue that poor countries should have lower CO_2 prices than richer countries. However, one has to consider if this is likely to foster excessive investment in high-emitting projects in poor countries.

Based on our discussion, our recommendation is the following:

- The established *cost of carbon* (cf. discussion and recommendation above) should be applied throughout the economy, i.e., independent of whether the project emissions are regulated by the EU ETS or not.
- For an EU/EEA country, higher carbon values may be used in the short run (until 2030) in Non-ETS sectors if the shadow prices that follow from this country's Non-ETS target exceed the established *cost of carbon*.
- The established *cost of carbon* is also used in projects abroad (but financed by a European country), with possible exception for Low Income Countries where lower carbon values may be considered for normative purposes.

One main advantage of this recommendation is that the same carbon value is used across projects and sectors, at least throughout the domestic economy. This carbon value will then always be consistent with the best estimate for reaching the 1.5C target at least cost, and encourages consistency, simplicity and transparency in CBAs. There exist arguments for applying a different carbon value for emissions regulated by the EU ETS (e.g., using the ETS price instead), but the strength of these arguments are weakened as the cap on emissions in our view cannot be treated as fixed in the long run.

The commitment to the 1.5°C target will require a drastic upwards adjustment of the cost of carbon applied in CBA, compared to current practices in most countries. This conclusion is shared by France Stratégie (2019). France Stratégie (2019) also states that this update in the cost of carbon should be accompanied with other updates in methodology, in particular when evaluating decarbonization projects. In particular, guidelines should be updated to provide good methodology for 1) choosing the reference scenario and taking account of the risks involved, 2) how to account for long-term impacts of the decarbonization projects (e.g., carbon values after 2050), and 3) taking account of emissions during projects' entire lifespans (including the construction phase). We think these recommendations are applicable also for the updating of CBA guidelines in other countries.