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ENGLISH **Summary**

Review of the Shadow Price of Carbon in the EU

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The objective of this report is to review literature and modelling results and provide guidance i) on the *level and path* of the cost of carbon, interpreted here as the shadow price of reaching a net zero emission target in the EU by 2050, and ii) on *application* of the cost of carbon within cost-benefit analysis (CBA). In the AR6 Scenario Database (which served as valuable input to the IPCCs Sixth Assessment report (AR6)) there are in total 300 scenarios modelled by Integrated Assessment Models that have found carbon prices that lead to fulfilment of the 1.5˚C target at lowest cost. In this report, we summarize the findings from these and other scenarios, and analyse the data set of shadow prices in terms of their appropriateness for CBA. We also discuss reasons for the large variation in shadow price trajectories, potential biases and how to navigate this uncertainty.

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. The objective of this report is to provide guidance i) on the *level and path* of the cost of carbon, interpreted here as the shadow price of reaching a net zero emission target in the EU by 2050, and ii) on *application* of the cost of carbon within CBA. The guidance is based on a thorough review of the literature on carbon (shadow) price paths consistent with the goal of limiting the global average temperature to 1.5˚C and reaching net zero emissions in 2050. The cornerstone of the review is the ensemble of scenarios in the AR6 Scenario Database, based on simulations from a wide range of different Integrated Assessment Models.

In our context the *cost of carbon* is not directly 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. This target is usually set through political negotiations, like the Paris Agreement. The target *could* be chosen to maximize social benefits (including co-benefits not directly related to climate change) of limiting climate change to a given level, relative to the associated costs, but not necessarily. Another way of interpreting this *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 a 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. Several 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 AR6 Scenario Database representing the combined findings of the world's leading research institutes on integrated assessment modelling. In these scenarios, the modellers search for the (mostly global) carbon (shadow) price path that is required to meet the target at lowest cost. In this report, we summarize the findings from these and other scenarios, and discuss possible reasons for the large variation in shadow price trajectories. We explain that the large variation can be due to differences in model structure as well as different assumptions about future developments.

Selecting a proper range of carbon prices

Choosing a proper range of shadow prices of carbon based on an ensemble of IAM scenarios, with a central estimate, comes with a range of concerns. Huppmann, Rogelj, Kriegler, Krey, and Riahi (2018) 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 trajectory, but rather exploit as large a sample of scenarios as possible. Second, we convey several values: median, average, interquartile 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 and net zero emissions in 2050. However, we need to be mindful of scenarios where the temperature target is temporarily overshot but still achieved by the end of the century, and scenarios that are highly 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).

As most relevant scenarios are found in the AR6 database, we focus particularly on those scenarios. In Table S 1 we show the "process of elimination" as we go from a sample of 300 AR6 scenarios (first column) to a smaller sample where we exclude scenarios that failed a vetting procedure documented in IPCC (2022a) (second column), then remove scenarios with too high overshoot (third column), then exclude scenarios that are too reliant on huge levels of BECCS (fourth column), and finally take out scenarios that fail to reach net zero CO_2 emissions in 2050. We provide similar tables for every fifth year from 2025 to 2045 in Appendix B.

Table S 1 illustrates the large uncertainty with respect to shadow prices of carbon consistent with the 1.5˚C target and net zero CO_2 emissions in 2050. In this report we shed some light on *why* the range of shadow prices is so wide. Important factors are the 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 AR6 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 shadow prices of carbon in the AR6 database for the year 2050 consistent with the 1.5˚C target and net zero CO_2-emissions in 2050, from starting sample (left) to applicable and consistent sample (right). Prices in €$_{2022}$ per tCO_2e.

Prices in 2050	**Original sample**	**Remove scenarios that failed vetting**	**Remove scenarios with high overshoot**	**Remove scenarios with unsustainable BECCS**	**Remove scenarios that fail to reach net zero by 2050**
N	300	208	87	59	18
Min price	25	25	77	144	389
25th pctile price	285	281	503	527	849
Median price	532	524	729	810	1 203
75th pctile price	969	842	1 132	1 132	1 324
Max price	81 400	23 380	5 493	3 078	3 078
Average price	1 289	938	910	845	1 191

The most relevant study beyond the AR6 scenarios is a study for the French economy (France Stratégie, 2019). The proposed cost of carbon in that report is in the lower end of the range of selected AR6 scenarios (i.e., last column in Table S 1 for 2050). However, the model-generated shadow price for 2050 in the French study is significantly higher. This may be because the French study considers a stricter target (net zero GHG emissions by 2050) than the AR6 scenarios, see below.

Studies that incorporate supportive climate policies in addition to carbon prices, such as European Commission (2018, 2024) and IEA (2023), tend to have lower carbon prices than the shadow prices in the AR6 scenarios. However, it is difficult to derive the cost of carbon from these studies, as the carbon prices applied typically underestimate the shadow price of the climate target.

In addition to the underrepresentation of certain scenarios and models, there are also other issues to consider. While EU's stated goal is climate neutrality (i.e., net zero GHG emissions) in 2050, the AR6 scenarios consider the 1.5˚C target and net zero *CO_2* emissions globally around 2050, but not net zero *GHG* emissions globally before around 2070. There is also the question of whether abatement efforts should be higher in Europe and other rich countries than what a global cost-effective abatement suggests, possibly implying higher cost of carbon in the EU, and to what degree risk aversion should be considered.

Consequently, it is difficult to present a clear recommendation for the cost of carbon for CBAs in the EU. This is partly because the range of shadow prices is large in Table S 1 and partly because of the various issues discussed above. Taking the AR6 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 the EU. There are scenarios that are "missing" since the models found them infeasible, and there is overrepresentation of models where the economy is highly responsive to carbon prices relative to models that are less responsive. A request for regional variation in the cost of carbon and accounting for risk aversion may also go in the direction of underestimating the cost of carbon in the EU, although these issues are more normative than descriptive.

Based on this assessment we present two alternative options to estimate the shadow price of carbon.

Option 1: Follow the median

The first and most straightforward option is to apply the median from the final sample of the AR6 scenarios (i.e., last 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 to use for sensitivity analysis. This means a cost of carbon of €$_{2022}$ 221 per ton CO_2e in 2025, rising to €$_{2022}$ 1203 per ton in 2050. The results are shown in Figure S 1, which also shows the median from the scenarios that reach the 1.5˚C target but not necessarily the net zero CO_2 target (i.e., the second column from the right in Table S 1).

Option 2: Upward adjustment

Our assessment suggests that the price range in the final sample of the AR6 scenarios is a slight underestimate of the recommended cost of carbon for CBA in the EU (even when disregarding the two normative issues discussed above). 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 €$_{2022}$ 229 per ton CO_2e in 2025, rising to €$_{2022}$ 1,291 per ton in 2050. The results are shown in Figure S 2 (here, too, we also show the median from the scenarios that are consistent with the 1.5˚C target but not necessarily the net zero CO_2 target).

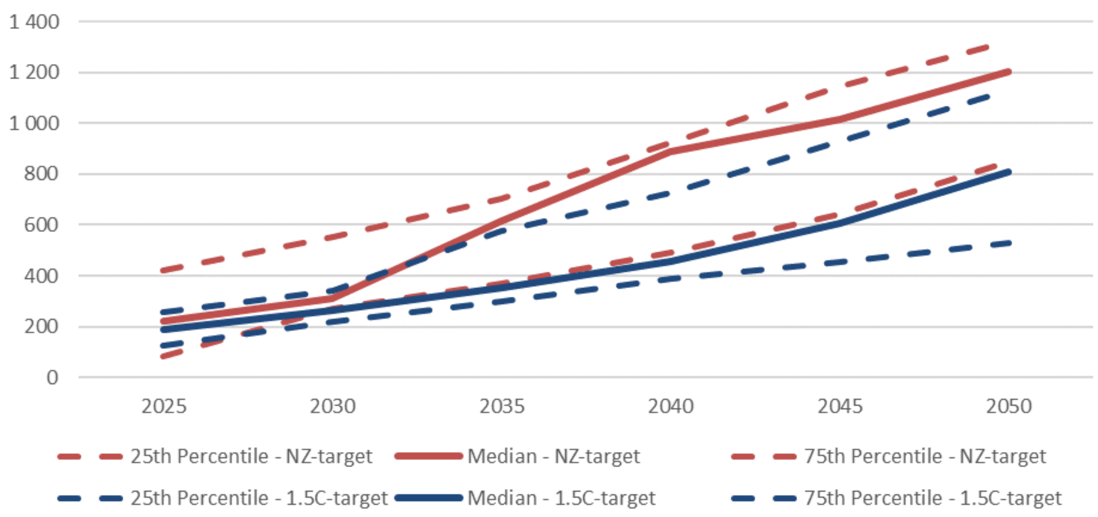

Figure S 1: Recommended cost of carbon range (€$_{2022}$/tCO_2e) for the period 2025–2050 – Option 1 (marked by red lines and "NZ-target"). The low, central and high price trajectories apply respectively to the 25th percentile, median, and 75th percentile from an ensemble of 18 scenarios from the AR6 Scenario Database consistent with the net zero CO_2 target. The blue lines ("1.5°C-target") are median, 25th and 75th percentile trajectories for scenarios that do not necessarily meet the net zero CO_2 target, but still reach the 1.5°C target without high overshoot and without undue reliance on BECCS.

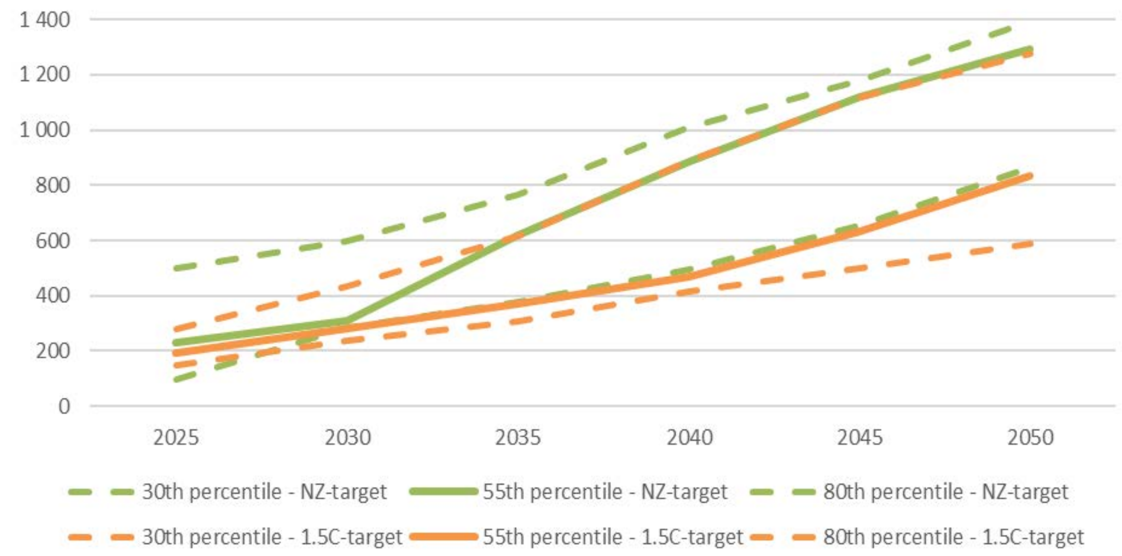

Figure S 2: Recommended cost of carbon range (€$_{2022}$2/tCO2e) for the period 2025–2050 – Option 2 (marked by green lines and "NZ-target"). The low, central and high price trajectories apply respectively to the 30th, 55th, and 80th percentile from an ensemble of 18 scenarios from the AR6 Scenario Database consistent with the net zero CO_2 target. The orange lines ("1.5°C-target") are 30th, 55th, and 80th percentile trajectories for scenarios that do not necessarily meet the net zero CO_2 target, but still reach the 1.5°C target without high overshoot and without undue reliance on BECCS.

Our assessment above may suggest that Option 1 is underestimating the cost of carbon in the EU. On the other hand, an argument against Option 2 is that the upward adjustment is somewhat arbitrary (although rather cautious).

Considering the two normative issues as well, the cost of carbon in the EU could be higher. One of the issues is related to distributional concerns, which might imply higher abatement efforts in the EU than what a global cost-effective abatement suggests, implying higher cost of carbon in the EU than the global shadow price suggests (this is mainly relevant in the next 1–2 decades). However, we are not in a position to assess how much higher.

The shadow price of carbon recommended above is significantly higher than existing carbon taxes (or emission trading prices) implemented in Europe and elsewhere. It is also higher than the cost of carbon currently applied in CBAs in many countries. This reflects that complying with the 1.5˚C target and reaching net zero GHG emissions by 2050 are very ambitious targets, which according to most available studies will be very challenging with very high marginal abatement costs. However, how costly it will be is highly uncertain, and this depends crucially on how the costs of zero-emissions technologies evolve in the next few decades.

Applying cost of carbon in Cost-Benefit Analysis

Turning next to the application of the cost of carbon within CBA in the EU, we first discuss, based on existing literature, general principles on how to include the cost of carbon 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.

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 generally refer to as the *cost of carbon* in the EU. For instance, in the tax case it is not the tax level (the tax itself is a transfer) that determines the net cost of emissions – it is still the shadow price of the climate target that matters. In the ETS case, however, the net cost of emissions will be equal to the ETS price, which reflects the marginal abatement cost in other ETS firms. However, this only holds *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 with fixed emissions. In the extreme case where the cap responds 1:1 to allowance demand, we are for practical purposes in the tax case. If carbon prices are differentiated and/or supported by other climate policies, it is still the shadow price of emissions that is the proper cost of carbon.

Based on the general discussion, we consider how to use the cost of carbon 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 (on the margin), 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 likelihood 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 country for the years until 2030. The shadow price of reaching these targets may differ across countries and may also differ from the shadow price of the long-term target. Still, we do not recommend different costs of carbon across member states, e.g., because trade in 'Non-ETS credits' is allowed.

For project emissions outside the EU, a cost-effective approach would suggest that the same cost of carbon that is used within the EU is also used outside the EU, as all greenhouse gas emissions have the same climate impacts. There are two potential arguments against this approach, however. One is that the EU's target of net zero greenhouse gas emissions by 2050 seems to be stricter than maintaining the 1.5°C target with uniform CO_2 prices across the world throughout the century (cf. discussion above). The other is the distributional issues mentioned above (which are not relevant if the EU is financing emissions reductions abroad). Anyway, this is a normative issue that we leave to the final decision makers for CBA guidelines.

Based on our discussion, our recommendation is the following:

- The established *cost of carbon* should be derived from the *shadow price* of reaching the EU's established climate targets, i.e., the 1.5°C target and the net zero emissions in 2050 target, as set out above.
- The established cost of carbon should be applied throughout the EU, i.e., independent of whether the project emissions are regulated by the EU ETS or not.
- A higher cost of carbon might be used in the short run (until 2030) in Non-ETS sectors if the shadow price that follows from the overall Non-ETS target exceeds the EU's established *cost of carbon*. We do not recommend different costs of carbon across EU member states.
- The established cost of carbon should also be used for emissions from international transport and in projects outside the EU.

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