Institute of Transport Economics
Norwegian Centre for Transport Research

Carbon prices for Cost-Benefit Analysis

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Summary

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). 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.

Kort sammendrag

Målet med denne rapporten er å gjennomgå littera-turen om karbonprisbaner i samsvar med målet om å begrense den globale gjennomsnittstemperaturen til 1,5 °C, og gi veiledning om i) målkonsistent nivå og prisbane for karbonkostnadene, tolket som marginal tiltakskostnad for å nå et netto null-utslippsmål i Europa innen 2050, og ii) om anvend-else av karbonpriser i samfunnsøkonomiske ana-lyser (SØA). Ved å trekke ut resultater fra et stort utvalg av scenarier fra ulike modeller (Integrated Assessment Models - IAMer) som har blitt brukt i IPPC sin spesialrapport om global oppvarming på 1,5 °C, anbefaler vi å bruke en karbonpris på 166 Euro per tonn CO_2 ekvivalenter i 2025, stigende til 1014 Euro per tonn i 2050. Vi anbefaler at denne karbonprisen brukes i SØA-er i hele økonomien, det vil si uavhengig av om prosjektets utslipp er regulert av EUs kvotesystem eller ikke.

Preface

During 2019 and 2020, as Paal Brevik Wangsness (Senior Research Economist at the Institute of Transport Economics) was completing his PhD in Economics at the Norwegian University of Life Sciences, where professor Knut Einar Rosendahl was his supervisor, some his research focused on carbon pricing in Cost-benefit Analysis (CBA). When undertaking CBA of projects with impacts on greenhouse gas emissions, a value has to be set 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 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 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 CBA.

The main authors of this report, Paal Brevik Wangsness and Knut Einar Rosendahl, carried out the main parts of the research for this report during the summer and autumn of 2020. However, the report also draws on research conducted in the project ELECTRANS (funded by the Research Council of Norway), GODSKOST (funded by The Norwegian Public Road Administration, The Norwegian Railway Directorate, Nye Veier AS, The Norwegian Coastal Administration and Avinor during the analysis period for the National Transport Plan 2022-2033) and funding for Strategic Institute Initiatives (SIS) by the Research Council of Norway. Gøril Louise Andreassen (PhD candidate at Norwegian University of Life Sciences) has assisted in the literature review. For various reasons the authors have been unable to complete the report before the summer of 2022.

The internal quality assurance of this report was done by PhD Askill Harkjerr Halse, Chief Research Economist for the Economic Analysis research group.

Oslo, October 2022
Institute of Transport Economics

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ENGLISH Summary

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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 recom-mend 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
25^{th} pctile price	315	470	319
Median price	480	832	806
75^{th} 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 75^{th} percentile price is almost four times higher than the 25^{th} 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 25^{th} and 75^{th} 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.

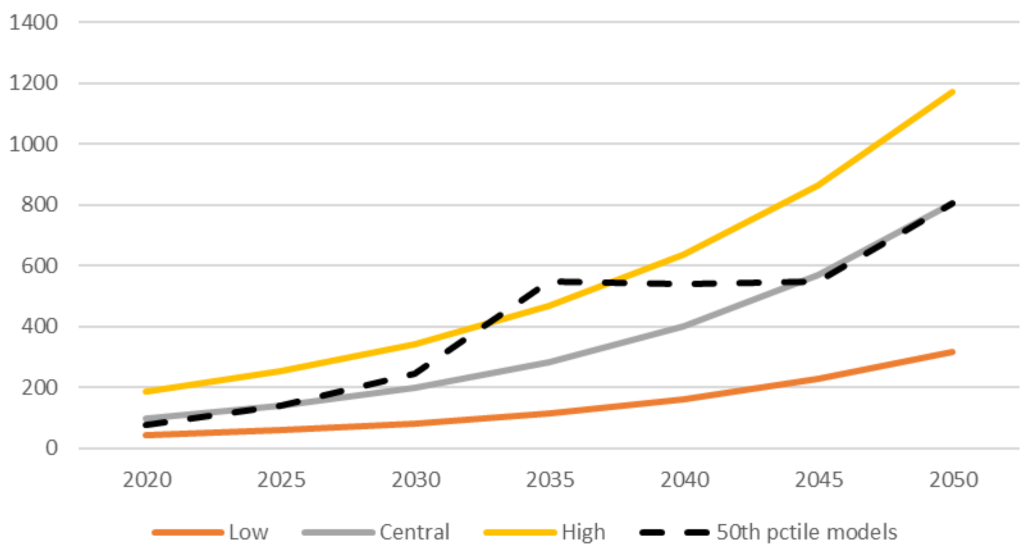

Figure S 1: Recommended carbon price range (EUR2016/tCO_2e) for the period 2020-2050 – Option 1.

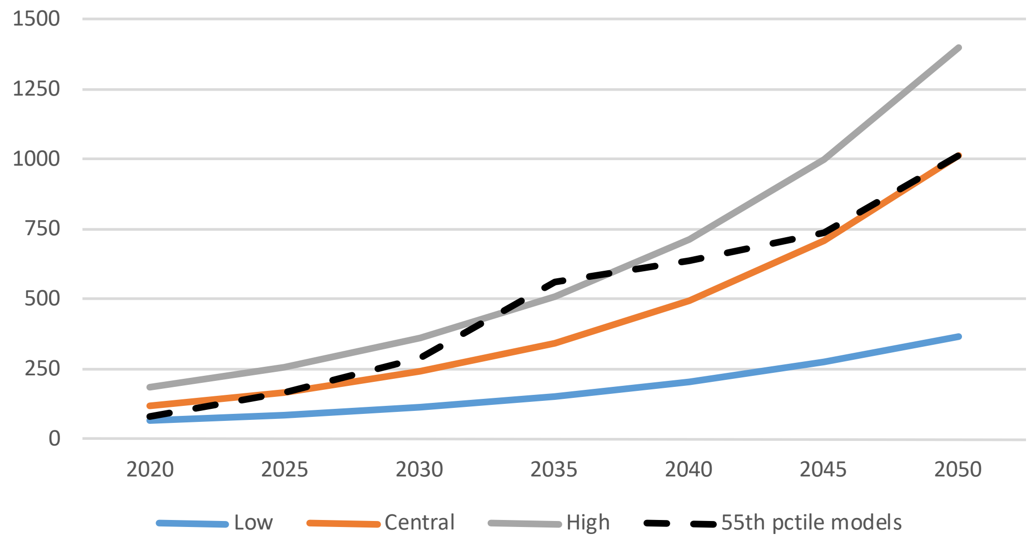

Figure S 2: Recommended carbon price range (EUR2016/tCO_2e) for the period 2020-2050 – Option 2.

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.

Transportøkonomisk institutt
Stiftelsen Norsk senter for samferdselsforskning

NORSK Sammendrag

Karbonpriser til bruk i nyttekostnadsanalyser

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Målet med denne rapporten er å gjennomgå litteraturen om karbonprisbaner i samsvar med målet om å begrense den globale gjennomsnittstemperaturen til 1,5 °C, og gi veiledning om i) målkonsistent *nivå og prisbane* for karbonkostnadene, tolket som marginal tiltakskostnad for å nå et netto nullutslippsmål i Europa innen 2050, og ii) om anvendelse av karbonpriser i samfunnsøkonomiske analyser (SØA). Ved å trekke ut resultater fra et stort utvalg av scenarier fra ulike modeller (Integrated Assessment Models - IAMer) som har blitt brukt i IPPC sin spesialrapport om global oppvarming på 1,5 °C, anbefaler vi å bruke en karbonpris på 166 Euro per tonn CO_2 ekvivalenter i 2025, stigende til 1014 Euro per tonn i 2050. Vi anbefaler at denne karbonprisen brukes i SØA-er i hele økonomien, det vil si uavhengig av om prosjektets utslipp er regulert av EUs kvotesystem eller ikke.

Ved gjennomføring av samfunnsøkonomiske analyser (SØAer) av prosjekter med konsekvenser for CO_2-utslipp (eller andre klimagassutslipp), skal disse utslippene verdsettes. Denne verdien blir ofte referert til som karbonprisen. Målet med denne rapporten er å undersøke litteraturen om karbonprisbaner i samsvar med målet om å begrense globale gjennomsnittstemperaturer til 1,5 °C, og gi veiledning om i) målkonsistent nivå og prisbane for karbonkostnadene, tolket som marginal tiltakskostnad for å nå et netto nullutslippsmål i Europa innen 2050, og ii) anvendelse av karbonverdier i SØAer.

I vår sammenheng er karbonprisen ikke knyttet til skadene fra klimaendringer, men til skyggeprisen knyttet til å nå klimamålet. En annen måte å tolke karbonkostnaden på er at hvis alle utslippskilder står overfor en karbonpris som tilsvarer tiltakskostnaden, og ingen annen støttende klimapolitikk implementeres, nås utslippsmålet nøyaktig til lavest mulig kostnad.

For å utlede et estimat for karbonprisen trenger man god forståelse av hvor kostbart det er å redusere karbonutslipp, ikke bare i dag, men langt inn i fremtiden. Til dette formål brukes vanligvis såkalte integrerte vurderingsmodeller (Integrated Assessment Models - IAM). Det finnes en rekke scenarier basert på slike modeller, mange av dem i samsvar med 1,5 °C og netto nullutslippsmål. De fleste av dem er hentet fra databasen IAMC (Integrated Assessment Modeling Consortium) 1.5°C Scenario Explorer håndtert av IIASA (Huppmann, Kriegler, Krey, et al., 2018) og oppsummert i IPCC (2018). Dette representerer de samlede funnene fra verdens ledende forskningsinstitutter, med en spesielt sterk representasjon fra europeiske forskningssentre. I disse scenariene søker modellørene etter den (for det meste globale) karbonprisbanen som kreves for å nå målet. I denne rapporten oppsummerer vi funnene fra disse og andre scenarier, og diskuterer mulige årsaker til den store variasjonen i prisbaner. Vi forklarer at den store variasjonen kan skyldes forskjeller i modellstruktur samt ulike forutsetninger om fremtidig utvikling.

Å velge et riktig fordeling av karbonprisbaner basert på et utvalg av IAM-scenarier, med et sentralt estimat, reiser en rekke problemstillinger. I Huppmann, Rogelj, Kriegler, Krey, and Riahi (2018) gir forfatterne retningslinjer, og vi har gjort vårt beste for å gjøre vurderinger i tråd med disse. For det første plukker vi ikke et enkelt scenario og trekker ut en karbonprisbane, men utnytter heller et så stort utvalg av scenarier som mulig. For det andre formidler vi flere verdier; median, gjennomsnitt, interkvartilbredde og full spredning. Vårt mål er å utnytte og kommunisere så mye informasjon som mulig fra scenarier som er i samsvar med 1,5°C-målet, men som ikke har for mye kortsiktig overskridelse av temperaturmålet og heller ikke er for avhengige av høye nivåer av bioenergi med karbonfangst og lagring (BECCS) siden mye kritikk har blitt reist mot de enorme mengdene BECCS i mange scenarier og det stilles spørsmål om det er realistisk og bærekraftig, jf. delkapittel 2.2.6.

Scenarier som i stor grad er avhengige av øvrig politikk og regulering i tillegg til karbonprising gjør det vanskelig å fastslå riktig skyggepris på klimamålet, og brukes derfor ikke direkte. Disse blir fortsatt gjennomgått og kommentert. Eksempler på slike studier er Europakommisjonen (2018) og IEA (2019). En annen innflytelsesrik studie er fra High-Level Commission on Carbon Prices (Stiglitz et al., 2017), men der presenteres bare karbonpriser i samsvar med 2°C-målet.

Siden de fleste relevante scenariene finnes i IAMC-databasen, fokuserer vi spesielt på disse scenariene. I Tabell S 1 viser vi "eliminasjonsprosessen" når vi går fra et utvalg av 84 IAMC-scenarier (første kolonne) til et mindre utvalg der vi ekskluderer scenarier med for høy overskridelse av temperaturmålet på kort sikt (andre kolonne), og deretter ekskluderer scenarier som er for avhengige av store nivåer av BECCS (tredje kolonne). Etter denne prosessen ender vi opp med karbonprisområdene for 2050 vist i Tabell S 1. Vi gir tilsvarende tabeller for hvert femte år fra 2020 til 2045 i vedlegg C.

Tabell S 1 illustrerer den store usikkerheten om karbonpriser i tråd med 1,5-gradersmålet. I denne rapporten belyser vi hvorfor denne spredningen er så stor. Viktige faktorer er type modell, forutsetninger om fremtiden f.eks. såkalte Shared Socioeconomic Pathways – SSP, og tilgang til og kostnader ved klimavennlige teknologier implementert i modellene. Vi kan ikke si med sikkerhet at noen modell eller noe scenario vi har lagt til i utvalget vårt er bedre enn en annen, og vi kan derfor ikke anbefale noe enkelt scenario eller modell.

Det vil imidlertid også være noen skjevheter i utvalget, siden det er underrepresentasjon av enkelte scenarier og modeller i IAMC-databasen. For noen fremtidsscenarioer (SSPer) det ikke mulig å holde den globale oppvarmingen under 1,5°C i flere modeller.

Tabell S 1: Deskriptiv statistikk for utvalget av karbonprisbaner konsistent med halvannen-gradersmålet hentet fra IAMC databasen for året 2050, fra det originale utvalget til et anvendbart utvalg hvor upassende prisbaner er eliminert. Priser i 2016-Euro.

Priser i 2050	Originale utvalg	Eliminert studier med store overskridelser	Eliminert studier med ikke-bærekraftig bruk av BECCS
N	84	50	20
Min pris	112	125	125
25th pctil pris	315	470	319
Median pris	480	832	806
75th pctil pris	1038	1179	1174
Max pris	14236	14236	14236
Gjennomsnittlig pris	1096	1433	1677

Den mest relevante studien utover IAMC-scenariene er en studie for Frankrike (France Stratégie, 2019). De foreslåtte karbonprisene i rapporten er ganske nær medianen i de valgte IAMC-scenariene (dvs. tredje kolonne i Tabell S 1 for 2050). Studier som inkluderer øvrig klimapolitikk og reguleringer i tillegg til karbonpriser, som EU-kommisjonen (2018), har en tendens til å finne lavere karbonpriser enn IAMC-scenariene. Dette er ikke overraskende. Som nevnt ovenfor er det imidlertid vanskelig å utlede skyggeprisen for klimamålet fra disse studiene.

I tillegg til underrepresentasjonen av visse scenarier og modeller, er det også andre problemer å vurdere. IAMC-scenariene vurderer 1.5 °C-målet, som krever netto null karbonutslipp globalt rundt 2050, men ikke netto null klimagassutslipp globalt før rundt 2070. Det er også et spørsmål om karbonprisene bør være høyere i Europa og andre rike land enn i fattige land, og i hvilken grad det bør tas hensyn til risikoaversjon.

Følgelig er det vanskelig å presentere en klar anbefaling for karbonprisbaner til SØAer. Dette skyldes delvis at spredningen er enorm (f.eks. i 2050 er 75. persentilpris nesten fire ganger høyere enn 25. persentil i tredje kolonne i Tabell S 1) og delvis på grunn av de ulike problemene diskutert ovenfor. Med utgangspunkt i IAMC-resultatene og oppsummering av alle utfordringene, synes den generelle skjevheten å gå i retning av å undervurdere kostnadene for karbon i europeisk sammenheng. Det er scenarier som "mangler" siden modellene fant dem umulige, og det er overrepresentasjon av modeller der økonomien er svært responsiv overfor karbonpriser i forhold til modeller som er mindre responsive.

Basert på denne vurderingen presenterer vi to alternativer for anbefalte karbonprisbaner.

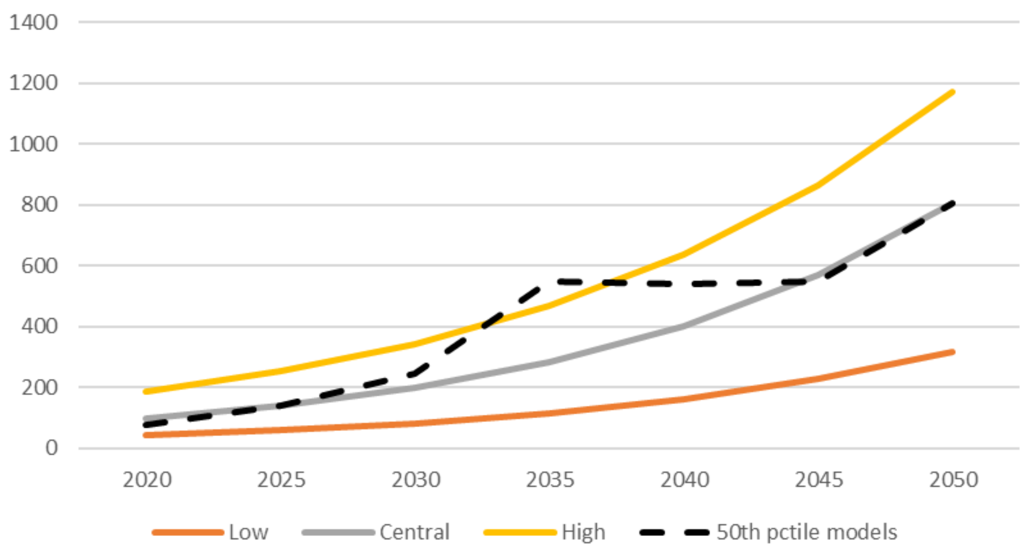
Alternativ 1: Følg medianen

Det første og enkleste alternativet er å bare bruke medianen fra det endelige utvalget av IAMC-scenariene (dvs. tredje kolonne Tabell S 1 for 2050) som hovedbane for den karbonprisen, med lave og høye prisbaner basert på persentilene 25 og 75 prosentiler som skal brukes til sensitivitetsanalyse. Dette betyr en karbonpris på 141 Euro per tonn CO_2ekvivalenter (tCO_2e) i 2025, stigende til 806 Euro per tonn i 2050. Som det fremgår Figur S 1.1, er medianprisbanen ganske humpete når du bruker alle modellårsprisene (stiplet linje). Av praktiske hensyn jevner vi derfor ut prisbanen ved å bruke prisene i 2025 og 2050 som ankere og benytte samme årlige vekstrate i årene mellom. Denne vekstraten er på 7.2%, som også gjelder for perioden 2020-2025. Vi lager også en lignende jevn karbonprisbane for prisbanene for følsomhetsanalyser, ved å bruke deres respektive estimater for 2025 og 2050 som ankerpunkter. Resultatene er vist i Figur S 1.1.

Alternativ 2: Justering oppover

Vår vurdering tyder på at prisbanene fra IAMC-scenariene i Alternativ 1 er en liten underestimering av hva som bør være anbefalt karbonpris for SØAer i europeisk sammenheng. Det er imidlertid vanskelig å vurdere hvor mye. Noe vilkårlig (men ganske forsiktig), anbefaler vi å bruke det 55. persentilet i Alternativ 2, framfor det 50. persentliet i Alternativ 1, den sentrale karbonprisbanen. Dette betyr en karbonkostnad på 166 Euro per tonn CO_2e i 2025, som stiger til 1014 Euro per tonn i 2050.

Som med median-karbonprisbanen, er banen til det 55. Persentilet også svært ujevn (se stiplet linje Figur S 1.2). Vi jevner derfor også ut prisbanen i Alternativ 2, med priser i 2025 og 2050 som ankere, med samme årlige vekstrate i årene mellom. Denne vekstraten på 7,5% gjelder også for perioden 2020-25. Vi justerer også den anbefalte prisbaner til følsomhetsanalyse ved å bruke persentilene 30. og 80. persentil i 2025 og 2050. Resultatene er vist i Figur S 1.2.



Figur S 1.1: Anbefalte karbonprisbaner (EUR$_{2016}$/tCO2$_2$e) for perioden 2020-2050. Høy og lav bane er anbefalt til følsomhetsanalyser. Alternativ 1.

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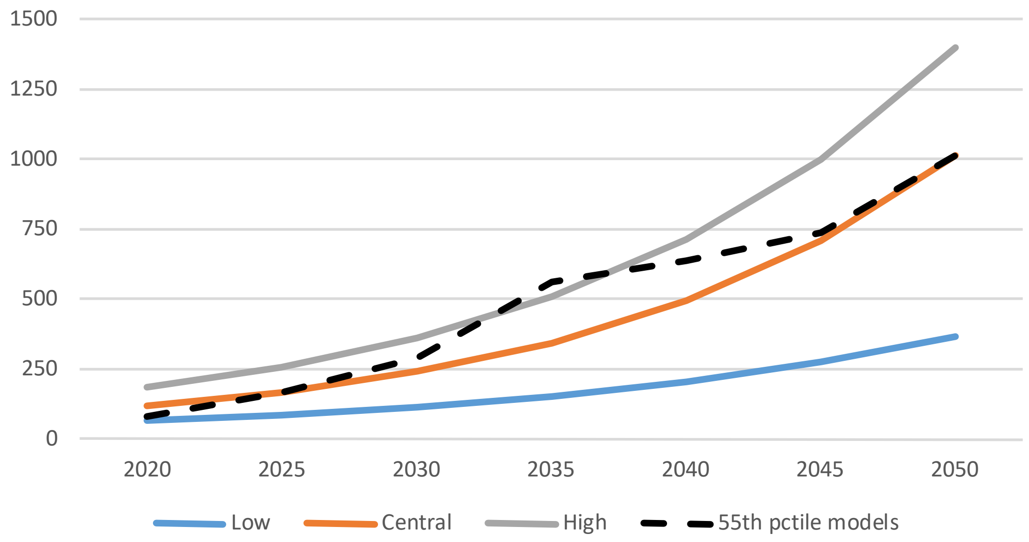

Figur S 1.2: Anbefalte karbonprisbaner (EUR_{2016}/tCO_2e) for perioden 2020-2050. Høy og lav bane er anbefalt til følsomhetsanalyser. Alternativ 2.

De anbefalte karbonprisene for SØA er betydelig høyere enn eksisterende karbonpriser i Europa og andre steder. Dette gjenspeiler at det å overholde 1,5°C-målet og nå netto null klimagassutslipp innen 2050 er et svært ambisiøst mål, som ifølge de fleste tilgjengelige studier vil være svært utfordrende å nå og med svært høye marginale reduksjonskostnader. Hvor kostbart dette blir er imidlertid høyst usikkert, og dette avhenger helt av hvordan kostnadene ved nullutslippsteknologier utvikler seg de neste tiårene.

Med fokus på anvendelsen av karbonpriser i SØAer i Europa, diskuterer vi først, basert på eksisterende SØA-litteratur, generelle prinsipper for hvordan man inkluderer karbonverdier i CBA. Her skiller vi spesielt mellom prosjektutslipp regulert av et kvotesystem (ETS) og prosjektutslipp regulert av en avgift (eller uregulert). Vi argumenterer for at bruk av "bruttoprinsippet" i SØA er god praksis, da det skiller klart mellom overføringer og reelle kostnader. For å lette diskusjonen viser vi flere eksempler.

Basert på gjennomgangen i de siste kapitlene kommer vi med følgende anbefalinger til praktisk anvendelse i SØA :

- De anbefalte karbonprisbanene (enten Alternativ 1 eller Alternativ 2) burde brukes i alle sektorer av økonomien, uavhengig om utslippene er regulert av EUs kvotemarked eller ikke.
- For et EU/EØS land kan det på kort sikt (fram til 2030) vurderes å bruke en høyere karbonprisbane i sektorer som ikke dekkes av EUs kvotemarked, dersom klimamålet for disse sektorene er såpass strenge at den korresponderende skyggeprisen overstiger de anbefalte karbonprisbanene.
- De anbefalte karbonprisbanene (enten Alternativ 1 eller Alternativ 2) bør også anvendes dersom europeiske land finansierer prosjekter utenfor Europa, med mulige unntak for Minst Utviklede Land (MUL) av normative hensyn.

En stor fordel med den første anbefalingen er at samme karbonpris brukes på tvers av prosjekter og sektorer, i det minste for innenlandske utslipp. Denne karbonprisen vil da alltid være i samsvar med det beste estimatet for å nå halvannengradersmålet til minst kostnad, og oppmuntrer til konsistens, enkelhet og transparens i SØAer. Det finnes argumenter for å legge til grunn en annen karbonpris for utslipp som reguleres av EUs kvotesystem (for eksempel ved å bruke kvoteprisen i stedet), men styrken i disse argumentene svekkes ved at utslippstaket etter vårt syn ikke kan behandles som fast på lang sikt, men vil bli påvirket av faktiske utslipp.

Overenstemmelse med forpliktelsen til halvannengradersmålet vil kreve en drastisk oppjustering av karbonprisene som brukes i SØA, sammenlignet med dagens praksis i de fleste land. Denne konklusjonen deles av France Stratégie (2019). France Stratégie (2019) sier også at denne oppdateringen i karbonpriser bør få følge av andre oppdateringer i metodikk, spesielt når man vurderer avkarboniseringsprosjekter. Spesielt bør retningslinjene oppdateres for å gi god metodikk for 1) valg av referansescenario og hensyntagen til de involverte risikoene, 2) hvordan man skal ta hensyn til langsiktige virkninger av avkarboniseringsprosjektene (f.eks. karbonpriser etter 2050), og 3) ta hensyn til utslipp under hele prosjektets levetid inkludert byggefasen. Vi mener at disse anbefalingene også er relevante for oppdatering av SØA-retningslinjer i andre land.

1 Introduction

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 *level and price path* of the cost of carbon in the context of reaching a net zero emission target by 2050, and ii) on *application* of carbon values within cost benefit analysis". Our interest mainly lies in carbon values in Europe, such as EU/EEA countries, but the discussion can easily translate into other parts of the world.

When the cost of carbon is deduced from a specific emissions target, the appropriate procedure is to consider the marginal abatement/sequestration cost of reaching the target at least cost. This carbon cost (and price path) that reflects cost-efficient reaching of national climate targets (which often are derived from global targets), is recommended for valuing changes in emissions in CBA. However, it is a non-trivial task of identifying all the right principles for defining the actual emissions target and its context, and then finding the appropriate data (carbon price modelling scenarios) to apply to make recommendations for carbon price paths for CBA.

In section 2 we discuss this in detail, and give our operational definition of the cost of carbon for this report, and how we operationalize it in light of aspects like multiple targets, temporal profile, uncertainty and overlapping policies. In section 3 we outline our review of Integrated Assessment Models (IAMs) and their 1.5˚C target consistent scenarios. We provide a brief introduction to the main models that have generated carbon prices in scenarios consistent with the 1.5˚C target in section 4. In section 5 we present the core of the sample of scenarios in this report, the ensemble of relevant scenarios from the IAMC database (Huppmann, Kriegler, Krey, et al., 2018). In section 6 we describe key differences between models and scenarios in order give some explanation for the vast range of different carbon prices in the literature, in particular from scenarios from the IAMC database. We present the results from our assessment of these scenarios in section 7. In section 8 we summarize recent studies with carbon prices consistent with the 1.5˚C target that supplements the scenarios from the IAMC database. In section 9 we discuss the results and provide recommendations for which carbon price paths to use in CBAs.

Turning next to the application of carbon values within CBAs, we provide a general discussion of how to account for emissions in CBA in section 10, based on general principles and previous literature. We distinguish in particular between emissions regulated by a tax and emissions regulated by an emissions trading system (ETS), and also discuss implications of an ETS with endogenous emissions cap. In section 11 we briefly review current guidelines in some selected countries. Sections 12-15 then consider how to apply carbon values in emissions regulated by the EU ETS, emissions in Non-ETS sectors, and emissions abroad, respectively. In section 16 we summarize our discussion and present our recommendation.

2 Defining cost of carbon

2.1 Cost of carbon: General interpretation in our context

The concept *cost of carbon* can have different interpretations. A commonly used concept is the *social cost of carbon* (SCC), which usually refers to the additional environmental damage costs of emitting one extra unit of carbon into the atmosphere (Greenstone, Kopits, & Wolverton, 2013). Thus, this concept is related to the *damages* from climate change, and therefore not related to the efforts or costs of reaching a specific temperature goal such as 1.5 ˚C or 2˚C warming.

The *cost of carbon* in our context is different. As stated in the introduction, we are interested in the marginal abatement/sequestration cost of reaching the net zero emission target by 2050. Thus, in our context the cost of carbon is not related to the damages from climate change, but rather to the relationship between the economy and emissions.[1]

A simplistic but intuitive way of explaining this is the following (see Figure 2.1): Assume that the we can rank all possible abatement/sequestration measures from the cheapest to the most expensive ones (per unit emission reduction, e.g., Euro per ton CO_2). This is basically a marginal abatement cost curve (including sequestration). Assume further that we want to reach an emission target cost-effectively, i.e., at lowest cost possible. Then we should start with the cheapest ones and move up the marginal abatement cost (MAC) curve until we reach the target. The *cost of carbon* is then the unit cost of the last chosen measure (i.e., the most expensive one in terms of Euro per ton).

It follows from this that if we for some reason want to emit one more unit of CO_2, then in order to still reach the target we need to abate one more unit of CO_2. The cost of this is then again the cost of carbon. Hence, this is often also referred to as the shadow price of emissions. On the other hand, if we for some other reason are able to reduce emissions by one ton, this has a benefit equal to the cost of carbon as we can drop the most expensive measure. This interpretation is particularly relevant for cost-benefit analysis of investments that affect emissions positively or negatively. The cost of carbon is then the appropriate value of any emission reductions and the appropriate unit cost of any emission increases (assuming that the target is binding).

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 climate policies are implemented, then the emission target is exactly reached. We return to this interpretation below.

[1] It is possible to make the argument that the Paris agreement approximates a Coase-solution, where representatives from all countries in the world have participated in negotiations. The result of these negotiations, the negotiated target of well-below 2˚C (strengthened to 1.5˚C at the COP meeting in Glasgow in 2021), would in principle balance the external damage cost of emissions to society as a whole with the corresponding economic benefits from emissions (Pindyck, 2017), given the information available at the time of negotiation, and the valuations of the negotiating parts. If the Paris agreement is a good approximation for a Coasian solution, then the shadow price of upholding the agreement coincide well with the marginal damage cost in equilibrium.

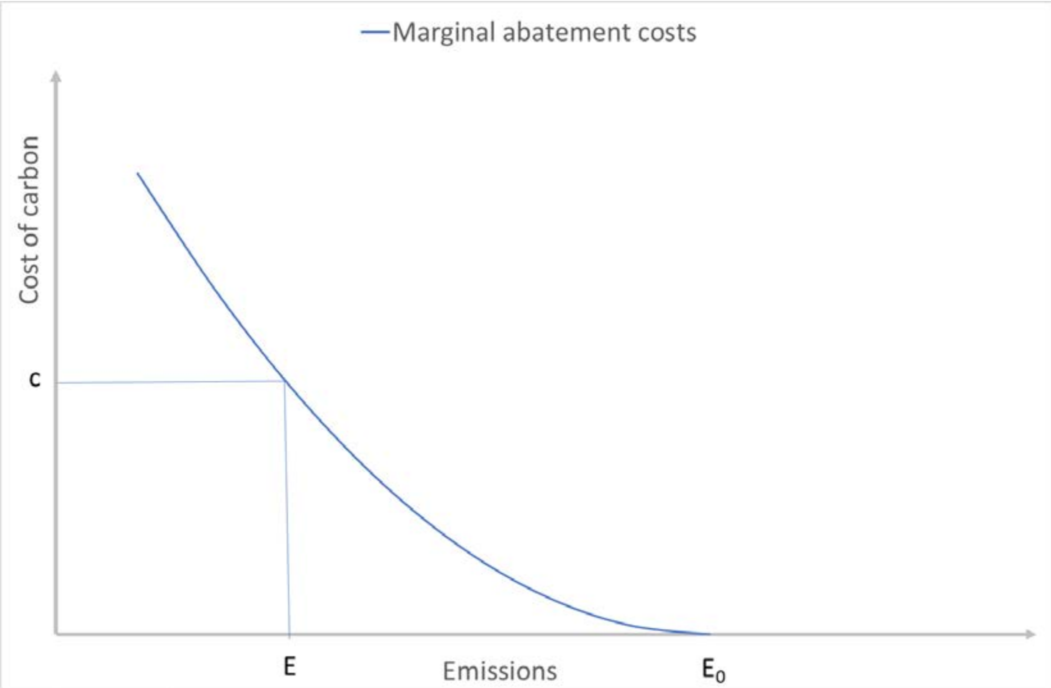

Figure 2.1: Illustration of cost of carbon. To reach the carbon emission target E cost-effectively, all abatement/sequestration measures with unit costs lower than c must be realized. The cost of carbon related to the emission target E is therefore c.

2.2 Cost of carbon: More detailed interpretation

The previous subsection sets out the general interpretation of the cost of carbon. Here we want to go more into detail about some specific issues.

2.2.1 Cost of carbon: Two different targets

The long-term goal in the Paris agreement is to keep global warming below 1.5˚C. At the same time, EU and other countries in Europe (e.g. Norway) have established goals of net zero emissions by 2050.[2] It is not a priori given that these two targets are consistent. However, most model simulations suggest that they are in fact quite consistent, provided that the whole world becomes carbon-neutral by 2050. This is shown in Table 2.1, where we depict the top rows from Table 2.4 in the Special Report on Global Warming of 1.5 °C (SR15) IPCC (2018). The median emissions pathway in the scenarios that reach the 1.5°C target with low or no overshoot, reaches carbon-neutrality in 2050 globally, with an interquartile range between 2046 and 2055. Aamaas, Peters, Wei, and Kor (2019) look at the regional distribution of net-zero years and find that the median emissions pathway for OECD reaches net-zero in 2058, while Non-OECD countries (in aggregate) reach net zero a few years sooner (in many cases thanks to CO_2 removal from forestry). Thus, a target of net zero emissions in

[2] The Norwegian official goal is to reduce emissions by 90-95 percent by 2050, but the current government has pledged to a net zero emissions goal by 2050 in its platform.

Europe by 2050 will likely imply a somewhat stricter target and hence a higher cost of carbon than either a target of net zero emissions globally by 2050, or the 1.5°C target.

Table 2.1: Emissions in 2030, 2050 and 2100 in 1.5°C and 2°C scenario classes and absolute annual rates of change between 2010–2030, 2020–2030 and 2030–2050, respectively. Values show median and interquartile range across available scenarios (25th and 75th percentile given in brackets). If fewer than seven scenarios are available (*), the minimum–maximum range is given instead. From IPCC (2018).

			Annual emissions/sequestration ($GtCO_2\ yr^{-1}$)			Absolute Annual Change ($GtCO_2/yr^{-1}$)			Timing of Global Zero
Name	Category	#	2030	2050	2100	2010–2030	2020–2030	2030–2050	Year
Total CO_2 (net)	Below-1.5°C	5*	13.4 (15.4, 11.4)	−3.0 (1.7, −10.6)	−8.0 (−2.6, −14.2)	−1.2 (−1.0, −1.3)	−2.5 (−1.8, −2.8)	−0.8 (−0.7, −1.2)	2044 (2037, 2054)
	1.5°C-low-OS	37	20.8 (22.2, 18.0)	−0.4 (2.7, −2.0)	−10.8 (−8.1, −14.3)	−0.8 (−0.7, −1.0)	−1.7 (−1.4, −2.3)	−1.0 (−0.8, −1.2)	2050 (2047, 2055)
	1.5°C with no or limited OS	42	20.3 (22.0, 15.9)	−0.5 (2.2, −2.8)	−10.2 (−7.6, −14.2)	−0.9 (−0.7, −1.1)	−1.8 (−1.5, −2.3)	−1.0 (−0.8, −1.2)	2050 (2046, 2055)
	1.5°C-high-OS	36	29.1 (36.4, 26.0)	1.0 (6.3, −1.2)	−13.8 (−11.1, −16.4)	−0.4 (0.0, −0.6)	−1.1 (−0.5, −1.5)	−1.3 (−1.1, −1.8)	2052 (2049, 2059)
	Lower-2°C	54	28.9 (33.7, 24.5)	9.9 (13.1, 6.5)	−5.1 (−2.6, −10.3)	−0.4 (−0.2, −0.6)	−1.1 (−0.8, −1.6)	−0.9 (−0.8, −1.2)	2070 (2063, 2079)
	Higher-2°C	54	33.5 (35.0, 31.0)	17.9 (19.1, 12.2)	−3.3 (0.6, −11.5)	−0.2 (−0.0, −0.4)	−0.7 (−0.5, −0.9)	−0.8 (−0.6, −1.0)	2085 (2070, post−2100)

There are of course other greenhouse gases (GHGs) than CO_2, and the global temperature increase also depends on how their emissions develop. In most model simulations reaching the 1.5˚C target, total GHG emissions reach net zero around 2070, i.e., a couple of decades after carbon alone reaches net zero IPCC (2018). Hence, this further suggests that reaching a target of zero GHG emissions within Europe by 2050 is an even stricter target than net zero carbon emissions, and hence will imply an even higher cost of carbon than a target of net zero CO_2 emissions by 2050.

In our final assessment, we will consider all model scenarios that are either explicitly consistent with the 1.5˚C target, and/or with the net zero emission target in 2050. For the latter target, we will consider scenarios that reach this target either globally, within Europe or for a major European country.

2.2.2 Cost of carbon: Regional differences

Most model simulations search for a global *cost of carbon*, either by searching for the global shadow price of emissions (for a given emission or temperature target), or by searching for the global price on CO_2 that via changes in market behaviour throughout the global economy leads to exactly the given target. This will typically be the globally cost-effective way of reaching the target.[3]

From a global welfare perspective, where distributional impacts are also considered, it could be argued that a cost-effective approach leads to too much abatement in poor countries and too little in rich countries, especially if (sufficient amounts of) transfers from rich to poor countries are not feasible, either directly or indirectly. For instance, a global emissions trading system similar to the one in the Kyoto protocol, where developing countries are given a large share of emission quotas, could lead to indirect transfer to developing

[3] This assumes that there are no other market failures and no other policy instruments also implemented. We return to this below.

countries. The question is, however, whether this is politically feasible – the Paris agreement is a very different type of agreement.

Without extensive transfers, one could argue that the cost of carbon should differ between countries, with highest cost of carbon in rich countries, as advocated by e.g. Stiglitz et al. (2017). With some exceptions, most model simulations do not consider different cost of carbon across regions. However, this must not be interpreted as a policy recommendation – assuming equal cost of carbon across countries is a technical assumption. A first-best solution would likely involve equal cost of carbon across countries, but a second-best solution taking into account possible restrictions on transfers between countries may involve differentiated costs of carbon.[4] We return to this issue later in our report.

2.2.3 Cost of carbon: Temporal profile

To reach a long-term target, the cost of carbon can have different time profiles. That is, for any given simulation model and parameters, there is a range of time profiles that can lead to the given target of e.g. keeping global warming below 1.5˚C. Most model simulations then search for time profiles that reach the target at lowest costs. For intertemporal models, this is taken care of by the model itself, and the optimal time path is normally a cost of carbon that increases with the discount rate.[5] For recursive models, where a CO_2 price is typically implemented into a market with myopic agents, the cost of carbon normally starts higher to initiate sufficient action early on, but then it increases more slowly. We will not enter into a discussion here whether the cost of carbon should rise with the discount rate (nor which discount rate to use), or have some other particular time profile, and will hence rather present cost of carbon in different time periods based on the results of the relevant assessed scenarios. We return briefly to this issue at the end.

2.2.4 Cost of carbon: Uncertainty

When it comes to the 1.5˚C target, there are uncertainties involved regarding the relationships between emissions, concentrations, and temperature increase. In the model simulations, it is usually assumed either 50% or 66% likelihood of reaching the temperature target (see Figure 2.2, which depicts the Table 2.1. from SR15 (IPCC, 2018))

[4] One reason for assuming equal cost of carbon is of course its simplicity – if different costs of carbon are assumed, then it easily becomes difficult to decide how they should differ.

[5] The choice of discount rate varies across models. The discount rate used in Detailed Process IAMs in the IAMC database (see next section) is around 5-6%, based on market interest rates (Emmerling et al., 2019).

Table 2.1 | Classification of pathways that this chapter draws upon, along with the number of available pathways in each class. The definition of each class is based on probabilities derived from the MAGICC model in a setup identical to AR5 WGIII (Clarke et al., 2014), as detailed in Supplementary Material 2.SM.1.4.

Pathway group	Pathway Class	Pathway Selection Criteria and Description	Number of Scenarios	Number of Scenarios
1.5°C or 1.5°C-consistent**	Below-1.5°C	Pathways limiting peak warming to below 1.5°C during the entire 21st century with 50–66% likelihood*	9	90
	1.5°C-low-OS	Pathways limiting median warming to below 1.5°C in 2100 and with a 50–67% probability of temporarily overshooting that level earlier, generally implying less than 0.1°C higher peak warming than Below-1.5°C pathways	44	
	1.5°C-high-OS	Pathways limiting median warming to below 1.5°C in 2100 and with a greater than 67% probability of temporarily overshooting that level earlier, generally implying 0.1–0.4°C higher peak warming than Below-1.5°C pathways	37	
2°C or 2°C-consistent	Lower-2°C	Pathways limiting peak warming to below 2°C during the entire 21st century with greater than 66% likelihood	74	132
	Higher-2°C	Pathways assessed to keep peak warming to below 2°C during the entire 21st century with 50–66% likelihood	58	

* No pathways were available that achieve a greater than 66% probability of limiting warming below 1.5°C during the entire 21st century based on the MAGICC model projections.

** This chapter uses the term 1.5°C-consistent pathways to refer to pathways with no overshoot, with limited (low) overshoot, and with high overshoot. However, the Summary for Policymakers focusses on pathways with no or limited (low) overshoot.

Figure 2.2: Table 2.1 from SR15 showing the main classification of scenarios used in the report.

There are of course also uncertainties involved when it comes to the relationship between the economy and emissions, which is reflected in the wide range of carbon prices reported below. Furthermore, there are uncertainties about to which extent the different models give the "best applicable" description of mechanisms at play in the atmosphere, biosphere and the economy. Differences in model mechanisms, level of detail, parameters, and other assumptions can lead to vastly different carbon prices, even under very similar scenario assumptions. We go into some depth of these questions in section 6.

2.2.5 Cost of carbon: Overshoot of temperature target

In scenarios that reach the 1.5˚C target, there is usually some overshoot before the target is reached. That is, the global temperature increase exceeds 1.5˚C for some time before it declines down to the 1.5˚C target due to net negative emissions after 2050 (see Table 2.1). The extent of overshoot (both with respect to how much above the target and for how long) varies across scenarios. Following Aamaas et al. (2019), we will narrow down the sample of scenarios to the ones with no or low overshoot, i.e., less than 0.1˚C overshoot. The main reason for this restriction is that too big overshoot basically violates the target. In addition, it requires huge amounts of negative emissions, which is a rather risky strategy (see next subsection).

2.2.6 Cost of carbon: Extent of BECCS

There are different types of negative emissions. In most scenarios, the largest contributor is 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 (Arneth et al., 2019). Again, we follow Aamaas et al. (2019). After considering several approaches, they set the criteria at 500 GtCO_2 cumulative storage through BECCS by 2100 and a yearly usage of BECCS in 2100 at 12GtCO_2. The authors state: "*While not ideal on every dimension, the choice does seem to limit the overall land impacts, without removing all scenarios. The choice appears to be practical, but it is not perfect.*"

2.2.7 Cost of carbon: Overlapping policies

Some scenarios consistent with the 1.5˚C or net zero emission target take a different approach than the one depicted in Section 2.1. That is, they implement a range of climate-related policies into the model, that together are sufficient to reach the target. In these scenarios, the CO_2 price (whether tax or quota price) plays a more limited role and is typically lower than in studies that only consider CO_2-pricing. In extreme cases, the CO_2 price may only function as a fall back policy, and then be very low.

The CO_2 prices coming out of such studies are *not* the cost of carbon, at least not in our context (i.e., the MAC of reaching the target). In this case, a low CO_2 price does not imply that the costs of reducing emissions are small. Typically, the overall costs of reaching a target will be higher when a mixture of policy instruments are used than when only CO_2 prices are used (see e.g. Böhringer and Rosendahl (2011)).[6]

This also probably holds for the marginal abatement cost, i.e., the shadow price of emissions, although here it is more unclear what the marginal cost (shadow price) would be. Using the illustration in Figure 2.1, one could argue that some but not all of the cheaper measures to the right of the 1.5˚C marker have been realized, and some of the more expensive ones. It is then not clear what the next measure in line would be. That is, if an additional investment is undertaken, leading to higher emissions, then some additional abatement measures must be implemented to still reach the target. It's then not clear which measure (at which unit cost) this would be. The most natural assumption might be that all the existing policies would be strengthened, in which case it is likely that the also the marginal cost (shadow price) would be higher than if only CO_2 pricing was used.

In any case, the CO_2 prices in these studies cannot be interpreted as the cost of carbon. Instead it seems likely that the cost of carbon is higher than these CO_2 prices. How much higher depends on how many other policies are also implemented, and the relative importance of the CO_2 price. This will typically be difficult to assess. We will return to this issue in section 10, when we discuss how to use the cost of carbon e.g. when some sectors are regulated by an emissions trading scheme ala EU ETS.

It should be mentioned here though that a good climate policy does not only involve CO_2 prices, but most likely also policies directed towards technological progress for climate-friendly technologies (see e.g., Acemoglu, Aghion, Bursztyn, & Hemous, 2012). The more extensive such policies are, the more likely the future costs of abatement will be lower than otherwise. On the one hand, this will tend to bring the cost of carbon down. On the other hand, although such policies are recommended, they are not without costs related to more R&D spending etc. Further, the more difficult it is to reach a climate target the more extensive such policies should be. In other words, higher emissions due to some new project could lead to higher costs both via more R&D and via more abatement.

[6] This is not always the case, however, see the discussion below about innovation externalities. In reality, however, other climate policies are often not implemented to correct for such externalities, but rather because of political feasibility.

3 On reviewing IAM models and their 1.5˚C target consistent scenarios

All the carbon prices in this report have been collected from relevant literature, published in peer-reviewed journals or in high-level reports. The literature on the subject of carbon prices is vast. Our scope is limited to studies that have calculated carbon prices consistent with the 1.5˚C target and net zero emissions in 2050. Most of these studies have applied Integrated Assessment Models (IAMs) to calculate the carbon price trajectory that leads to a cost-effective fulfilment of the target, given the specified scenario for the specified model.

All IAMs contain some representation of the economic and natural processes that produce GHG emissions, which further increase GHG concentration in the atmosphere and subsequently lead to higher global temperature and corresponding climate changes. Most IAMs then project how those changes impact natural systems on earth, which then again affects some representation of the human economy and society (Weyant, 2017). Putting all these different aspects from different disciplines (climate science, economics, energy systems etc.) into a comprehensive modeling framework is what makes the models *integrated*. These models can be used for *assessments* of different policies, technological developments or other developments in the economy/society.

IAMs differ tremendously in their level of detail and the complexity and interconnections they consider (Weyant, 2017). For example, some models represent the whole earth system with a small number of fairly simple equations, such as the DICE model (Nordhaus, 2014), while others include thousands of equations drawn from physics, chemistry, biology, and economics, such as the MIT IGSM (Reilly et al., 2013).

According to Weyant (2017), about 20 global scale IAMs had been developed at the time of writing. These can be split into two main groups: detailed process (DP) IAMs and benefit–cost (BC) IAMs. DP IAMs are more disaggregated and seek to provide projections of climate change impacts at detailed regional and sectoral levels. BC IAMs, on the other hand, give a more aggregated representation of climate change impacts and mitigation costs, and are often used for cost-benefit analysis and/or identifying "optimal" climate policies.

The IAM results that have contributed to IPCC (2018), the IPCC work with the Special Report on Global Warming of 1.5 °C (SR15), are mainly detailed, process-based IAMs (p. 100). These contributions have been compiled in the database IAMC 1.5°C Scenario Explorer hosted by IIASA (Huppmann, Kriegler, Krey, et al., 2018). All of the submitted scenarios have been documented in a total of 23 studies, most of them in peer-reviewed scientific journals.

Since the main work on our report was completed in the autumn of 2020, the Working Group III (WG III) contribution of the IPCC's Sixth Assessment Report has been released*; Mitigation of Climate Change* (IPCC, 2022) (although this report is currently still subject to revisions). As part of this report the authors have expanded on the dataset of model-based scenarios used in the SR15 and collected a larger dataset that has been compiled in the AR6 Scenario Explorer and Scenarios Database hosted by IIASA (Byers et al., 2022). It is out of scope for this report to redo our analysis with the new dataset, but a brief comparison of the distribution of the modelled carbon prices in 2050 indicates that the price range is roughly the same with the dataset for AR6 as for SR15. We will briefly comment on this in section 7.

With our focus on scenarios consistent with the 1.5˚C target, we first gather from the IAMC database 84 scenarios based on 8 different modeling frameworks. When we also add carbon prices from studies not covered by the IAMC database, we end up with 121 scenarios from in total 12 different modeling frameworks for this report. The modeling frameworks in question are AIM/GCE, GCAM, IMAGE, MESSAGE, POLES, REMIND, WITCH, MERGE, IMACLIM, TIMES, ThreeME and PRIMES. We will briefly describe the models in upcoming sections.

Most of the scenarios are retrieved from the IAMC database from Huppmann, Kriegler, Krey, et al. (2018). It is also from these scenarios where we get the most detailed data on developments in price, energy-mix and use of negative-emissions options. This report will therefore focus on these scenarios and the models used, in order to explain how and why the carbon prices generated in these scenarios differ so much.

A few other studies also add to the picture of possible futures with possible carbon prices that may lead to fulfilment of the long-term climate targets. Some of the carbon prices from these studies will, alongside the carbon prices from the IAMC database, be included in our final assessment of a proper range of carbon prices to use for CBA. Other carbon prices will not be included, following the discussion in Section 2.

The question of a proper range is an important one. When looking at an ensemble of carbon price trajectories from different model-scenario combinations, one is stricken by the vast spread in prices. A common illustration of this is Figure 2.26 in IPCC (2018), which shows more than 200 different carbon prices, belonging to different targets for limiting global warming (i.e., not only the 1.5C target). It is displayed in Figure 3.1. Each colored box displays the inter-quartile range of model-estimated carbon prices for a given year for a given climate target. Notice that the y-axis is log-scaled, visualizing the vast spread in prices. The figure also highlights a few single scenarios, namely S1, S2 and S5, which correspond to three of the five different Shared Socioeconomic Pathways (SSP1, SSP2 and SSP5), a set of common scenarios to use in IAMs. More on this in section 6.1. The figure below also highlights the LED (Low Energy Demand) scenario from Grubler et al. (2018).

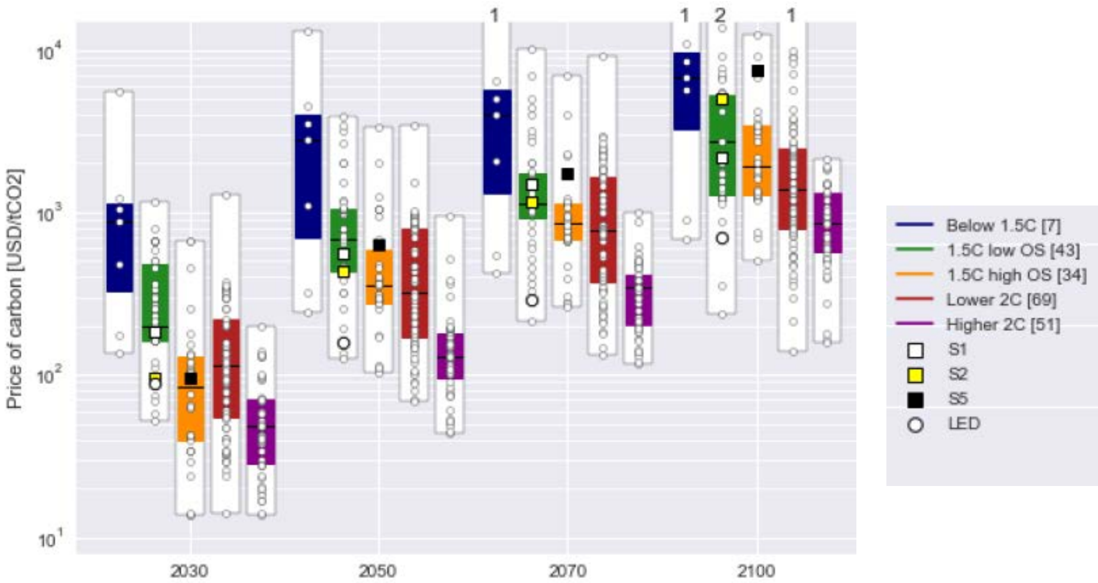

Figure 3.1: Global carbon price trajectories (undiscounted) consistent with different degrees of global warming. Source: Figure 2.2.6 in IPCC (2018).

We will in this report provide some explanation for the key differences between the various modelling exercises that lead to these vast differences in carbon price trajectories.

The short answer is that each carbon price trajectory is a model simulation with a set of scenario assumptions. One expects different scenario assumptions to lead to different carbon prices. However, it is also the case that identical scenario assumptions run by different modelling frameworks lead to vastly different carbon prices. We will discuss this in later sections.

4 A brief introduction to the main models

We mentioned earlier that differences in model characteristics are important drivers of different carbon prices. In this section, we give a brief introduction to the main models.

4.1 Model overview

As mentioned in Section 3, the relevant reviewed scenarios consistent with the 1.5˚C target are generated under 12 different modelling frameworks. Eight of these are used in the IAMC scenarios. Table 4.1 provides a simple overview of the models, indicating whether the model is a general or a partial equilibrium model, and whether the model is recursive-dynamic or has intertemporal optimization. In the following subsections we give a brief description of these models.

Table 4.1: Models that have generated carbon prices relevant for the final round of assessment in this report.

Model Name	Equilibrium Type	Modelling Approach	Main institution
AIM/GCE	General equilibrium	Recursive-dynamic	National Institute for Environmental Studies (NIES), Japan
GCAM	Partial equilibrium	Recursive-dynamic	Joint Global Change Research Institute (JGCRI), University of Maryland, USA
IMAGE	Partial equilibrium	Recursive-dynamic	PBL Netherlands Environmental Assessment Agency (PBL), Netherlands
MESSAGE	General equilibrium	Intertemporal optimization	International Institute for Applied Systems Analysis (IIASA), Austria
POLES	Partial equilibrium	Recursive-dynamic	JRC - Joint Research Centre - European Commission (EC-JRC), Belgium
REMIND	General equilibrium	Intertemporal optimization	Potsdam Institut für Klimafolgenforschung (PIK), Germany
WITCH	General equilibrium	Intertemporal optimization	European Institute on Economics and the Environment (RFF-CMCC EIEE), Italy
IMACLIM	General equilibrium	Recursive-dynamic	Centre international de recherche sur l'environnement et le développement (CIRED), France
TIMES	Partial equlibrium	Intertemporal optimization	The Energy Technology Systems Analysis Program (ETSAP) -Technology Collaboration Programme of the International Energy Agency (IEA)
ThreeME	General equilibrium	Recursive-dynamic	Collaboration between ADEME (French Environment and Energy Management Agency), OFCE (French Economic Observatory) and NEO (Netherlands Economic Observatory)
PRIMES	General equilibrium	Intertemporal optimization	E3MLab/ICCS of NTUA, Greece
MERGE	General equilibrium	Intertemporal optimization	Energy Economics Group, PSI, Switzerland

4.2 Description of individual models[7]

4.2.1 AIM/CGE

AIM/CGE is a general equilibrium model which is recursive-dynamic.[8] The model includes technology-specific modules for the power sector Fujimori, Masui, and Matsuoka (2014). The energy system modelling is quite disaggregated both on the supply side and the demand side. In order to model land use changes, the agricultural sector is also quite disaggregated. The industry sector is divided into five separate sectors.

4.2.2 GCAM

GCAM (Global Change Assessment Model) is a partial equilibrium model which is recursive-dynamic.[9] The model includes interactions between the following five systems: energy, water, agriculture and land use, the economy, and the climate. The model captures the market behaviour of representative agents such as e.g. energy users and energy producers, but also agricultural producers and consumers.

4.2.3 IMAGE

IMAGE is a partial equilibrium model which is recursive-dynamic.[10] The objective of the model is to analyze interactions between human development and the natural environment, identify response strategies to global environmental change based on assessment of options, and indicate key interlinkages and associated levels of uncertainty in processes of global environmental change. The model has a detailed representation of the relevant processes with respect to human use of energy, land and water in relation to relevant environmental processes. It also includes some representation of learning by doing for technologies in the energy systems[11].

4.2.4 MESSAGE

MESSAGE-GLOBIOM is a general equilibrium model with intertemporal optimization (Fricko et al., 2017).[12] It is designed to assess the transformation of the energy and land systems taking into account climate change and other sustainability issues. MESSAGE-GLOBIOM consists of the energy model MESSAGE, the land use model GLOBIOM, the air pollution and GHG model GAINS, the aggregated macro-economic model MACRO and the simple climate model MAGICC6. Technological change in MESSAGE is generally treated exogenously,

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[7] This is partly based on Aamaas et al. (2019) and France Stratégie (2019).

[8] https://www.iamcdocumentation.eu/index.php/Model_Documentation_-_AIM-CGE

[9] https://jgcri.github.io/gcam-doc/v4.2/

[10] https://models.pbl.nl/image/index.php/Welcome_to_IMAGE_3.0_Documentation

[11] Learning by doing could be represented in more of the models presented in this section, but we have been unable to find it described in the easily-available parts of the model documentation

[12] http://data.ene.iiasa.ac.at/message-globiom/

although there is some representation of endogenous technological change via learning curves.

4.2.5 POLES

POLES EMF33 is a partial equilibrium model which is recursive-dynamic.[13] It has a detailed description of energy demand, transformation and primary supply for all energy vectors. It applies frequent data updates to deliver robust forecasts for both short and long-term horizons. It is used to assess energy-related CO_2 mitigation policies. Other GHG emissions are also included, as well as linkages with agricultural and land use models. The model includes some representation of learning-by-doing, where learning is assumed to take place as a function of the installed capacity of a certain technology worldwide.

4.2.6 REMIND

REMIND (Regionalized model of investment and development) is a general equilibrium model with intertemporal optimization.[14] It incorporates the economy, the climate system and a detailed representation of the energy sector. It models regional energy investments and interregional trade in goods. It also includes some representation of learning by doing for immature technologies.

The model version REMIND-MAgPIE is a version linking the REMIND model to the model of Agricultural Production and its Impact on the Environment (MAgPIE), which is a global land use allocation model.[15] MAgPIE derives future projections of spatial land use patterns, yields and regional costs of agricultural production.

4.2.7 WITCH-GLOBIOM

WITCH is a general equilibrium model with intertemporal optimization.[16] It is a hybrid optimal growth model, which includes a bottom-up energy sector and a simple climate model, embedded in a game theory framework. The model accounts for positive externalities from learning-by-doing and learning-by-researching in technological change.

4.2.8 IMACLIM

In this report, scenarios run by IMACLIM are only retrieved from France Stratégie (2019). IMACLIM is a general equilibrium model which is recursive-dynamic.[17] The model version IMACLIM-R France represents the French economy, divided into 15 economic sectors (a global model version also exists, dividing the world into 12 regions). The model includes endogenous techno-economic modules representing the evolution of the electricity mix, stocks of residential buildings, and fleets of vehicles. In this way, the model incorporates some of the characteristics of techno-economic models with respect to technological details

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[13] https://ec.europa.eu/jrc/en/poles

[14] https://www.pik-potsdam.de/research/transformation-pathways/models/remind

[15] https://www.pik-potsdam.de/research/projects/activities/land-use-modelling/magpie

[16] https://www.witchmodel.org/

[17] http://www2.centre-cired.fr/IMACLIM?lang=en

and induced technological change, through e.g., some representation of learning by doing. As the model is recursive, agents' expectations are mostly adaptive except for future carbon prices, where expectations may be either adaptive or perfect.

4.2.9 TIMES

In this report, scenarios run by TIMES are only retrieved from France Stratégie (2019). TIMES is a partial equilibrium model with intertemporal optimization.[18] The model version TIMES-France represents the French energy system. Different subsectors of the energy sector are represented. The model searches for a choice of technologies satisfying demand while minimizing the total discounted cost for the French energy system over a given time period. Reductions of greenhouse gas emissions in the energy system are taken into account. Both investment costs, running, operational and maintenance costs, and the value of equipment buyback at the end of the model's time horizon are accounted for. The model also includes some representation of learning by doing.

4.2.10 ThreeME

In this report, scenarios run by ThreeME are only retrieved from France Stratégie (2019). ThreeME is a general equilibrium model which is recursive-dynamic.[19] The French version of the model represents the French economy, divided into 37 sectors (including 17 energy sectors). ThreeME is a hybrid model that combines a top-down GE approach with a bottom-up approach similar to energy models. It is a neo-Keynesian model that includes different market imperfections. The model integrates various techno-economic aspects, and includes some representation of endogenous energy efficiency effects. It is designed to evaluate macroeconomic impacts of energy and environmental policies and other public policies.

4.2.11 PRIMES

In this report, scenarios run by PRIMES are only retrieved from European Commission (2018). In that study, PRIMES is combined with several other models (e.g., GEM-E3, GAINS and GLOBIOM), and thus European Commission (2018) refers to this as a model suite. Although PRIMES alone is a partial equilibrium model for the energy system, GEM-E3 is a general equilibrium model and hence we refer to the model suite as a general equilibrium model, with intertemporal optimization.[20] The PRIMES model simulates the energy market in the EU and in each Member State, specifying technology vintages. The model includes some learning by doing effects for energy technologies.

4.2.12 MERGE-ETL

In this report, scenarios run by MERGE-ETL (Model for Evaluating Regional and Global Effects of GHG reductions policies) are retrieved from Marcucci, Panos, Kypreos, and Fragkos (2019)

[18] https://iea-etsap.org/index.php/etsap-tools/model-generators/times

[19] https://www.threeme.org/

[20] https://ec.europa.eu/clima/policies/strategies/analysis/models_en

(cf. Section 8.5).[21] MERGE-ETL is a general equilibrium model with intertemporal optimization. It combines a top-down Ramsey-type economic model with a bottom-up engineering model. The energy system is disaggregated into electric and non-electric sectors. Investment costs for major energy conversion technologies are determined based on a two-factor learning curve, including both learning-by-doing and learning by searching (i.e., knowledge accumulation through research and development).

[21] http://www.simlab.ethz.ch/mergeetl.php

5 IAMC database: The ensemble of scenarios

In the IAMC database there are in total 84 scenarios where models have found carbon prices that lead to fulfilment of the 1.5˚C target. When only including scenarios with low or no overshoot, we are left with 50 scenarios. All these scenarios give a spread of carbon prices in the range USD_{2010} 126–14300 in 2050 (or $Euro_{2016}$ 125–14236).[22] All the carbon prices displayed in the table are uniform, global carbon prices.

These scenarios are depicted in Table 5.1. We show the price development in 10-year leaps from 2020 to 2050. In the final column we also show whether the scenarios is to be considered to be highly reliant on BECCS, where we follow the criteria that Aamaas et al. (2019) set forth. Highly reliant on BECCS then refers to scenarios considered to include unsustainable or infeasible use of BECCS. In our final sample selection we thus exclude these scenarios, see Section 2.2.

Notice that the 2020 prices in many scenarios are very low, with very high growth rates between 2020 and 2030 (mostly between 2020 and 2025). For instance, all the POLES EMF scenarios have a CO_2 price at 0.7 USD2016 in 2020, while the price range in 2030 is 198-6050. This seems like more of a choice mindful of the political reality in the short run than a cost-effective choice of CO_2 price, assuming that it is politically difficult to start with a high CO_2 price. Hence, we will rely less on the 2020 prices in our recommendation.

[22] 2010-USD are converted to 2016-Euros (as used in France Stratégie (2019)), by first adjusting 2010-USD to 2016-USD with the US Consumer Price Index, and then converting 2016-USD to 2016-Euros by using the average exchange rate for 2016. The final conversion rate is 0.995.

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Table 5.1: Scenarios from the IAMC database, showing CO_2 prices for 2020, 2030, 2040 and 2050 (USD per ton CO_2)

No.	Model/Scenario	Model Core	Category	2020	2030	2040	2050	High BECCS
1	AIM/CGE 2.0|ADVANCE_2020_1.5C-2100	AIM/CGE	1.5C low overshoot	4.8	298	900	1690	Yes
2	AIM/CGE 2.0|SSP1-19	AIM/CGE	1.5C low overshoot	15.9	204	383	621	No
3	AIM/CGE 2.0|SSP2-19	AIM/CGE	1.5C low overshoot	16.8	375	744	1080	No
4	AIM/CGE 2.1|CD-LINKS_NPi2020_400	AIM/CGE	1.5C low overshoot	3.8	112	338	999	No
5	AIM/CGE 2.1|TERL_15D_LowCarbonTransportPolicy	AIM/CGE	1.5C low overshoot	5.0	231	511	318	No
6	AIM/CGE 2.1|TERL_15D_NoTransportPolicy	AIM/CGE	1.5C low overshoot	5.9	258	577	388	No
7	GCAM 4.2|SSP1-19	GCAM	1.5C low overshoot	13.0	63	103	168	Yes
8	IMAGE 3.0.1|IMA15-AGInt	IMAGE	1.5C low overshoot	82.7	673	967	1042	Yes
9	IMAGE 3.0.1|IMA15-Def	IMAGE	1.5C low overshoot	82.7	673	967	1042	Yes
10	IMAGE 3.0.1|IMA15-Eff	IMAGE	1.5C low overshoot	82.7	673	967	1042	Yes
11	IMAGE 3.0.1|IMA15-LiStCh	IMAGE	1.5C low overshoot	82.7	673	967	1042	No
12	IMAGE 3.0.1|IMA15-Pop	IMAGE	1.5C low overshoot	82.7	673	967	1042	Yes
13	IMAGE 3.0.1|IMA15-TOT	IMAGE	1.5C low overshoot	82.7	673	967	1042	No
14	IMAGE 3.0.1|SSP1-19	IMAGE	1.5C low overshoot		334	601	716	Yes
15	MERGE-ETL 6.0|DAC15_50	MERGE	1.5C low overshoot	61.3	168	294	471	Yes
16	MESSAGE-GLOBIOM 1.0|ADVANCE_2020_1.5C-2100	MESSAGE	1.5C low overshoot	172.0	280	456	744	Yes
17	MESSAGE-GLOBIOM 1.0|EMF33_1.5C_cost100	MESSAGE	1.5C low overshoot	0.2	189	308	501	Yes
18	MESSAGE-GLOBIOM 1.0|EMF33_1.5C_full	MESSAGE	1.5C low overshoot	0.2	183	297	484	Yes
19	MESSAGE-GLOBIOM 1.0|SSP1-19	MESSAGE	1.5C low overshoot	34.9	57	93	151	No
20	MESSAGE-GLOBIOM 1.0|SSP2-19	MESSAGE	1.5C low overshoot	34.9	105	294	479	Yes
21	MESSAGEix-GLOBIOM 1.0|LowEnergyDemand	MESSAGE	1.5C low overshoot	0.2	89	119	161	Yes
22	POLES ADVANCE|ADVANCE_2020_1.5C-2100	POLES	1.5C low overshoot	2.7	195	1155	2250	Yes
23	POLES EMF33|EMF33_1.5C_cost100	POLES	Below 1.5C	0.7	1155	2502	3850	Yes
24	POLES EMF33|EMF33_1.5C_full	POLES	Below 1.5C	0.7	960	1967	3071	Yes
25	POLES EMF33|EMF33_1.5C_limbio	POLES	Below 1.5C	0.7	6050	12100	14300	No
26	POLES EMF33|EMF33_1.5C_nofuel	POLES	Below 1.5C	0.7	1353	3157	4961	Yes
27	POLES EMF33|EMF33_WB2C_cost100	POLES	1.5C low overshoot	0.7	220	550	880	Yes
28	POLES EMF33|EMF33_WB2C_full	POLES	1.5C low overshoot	0.7	198	484	792	Yes

29	POLES EMF33|EMF33_WB2C_limbio	POLES	1.5C low overshoot	0.7	330	1320	2200	No
30	POLES EMF33|EMF33_WB2C_nobeccs	POLES	1.5C low overshoot	0.7	550	1980	3520	No
31	POLES EMF33|EMF33_WB2C_nofuel	POLES	1.5C low overshoot	0.7	220	550	880	Yes
32	POLES EMF33|EMF33_WB2C_none	POLES	1.5C low overshoot	0.7	550	2090	3740	No
33	REMIND 1.5|EMC_Def_100$	REMIND	1.5C low overshoot	110.0	179	292	475	Yes
34	REMIND 1.5|EMC_LimSW_100$	REMIND	1.5C low overshoot	110.0	179	292	475	Yes
35	REMIND 1.5|EMC_NucPO_100$	REMIND	1.5C low overshoot	110.0	179	292	475	Yes
36	REMIND 1.5|EMC_lowEI_100$	REMIND	1.5C low overshoot	110.0	179	292	475	Yes
37	REMIND 1.7|CEMICS-1.5-CDR12	REMIND	1.5C low overshoot	1.8	215	351	572	No
38	REMIND 1.7|CEMICS-1.5-CDR8	REMIND	1.5C low overshoot	1.8	454	740	1205	No
39	REMIND-MAgPIE 1.7-3.0|PEP_1p5C_red_eff	REMIND	1.5C low overshoot	3.1	361	718	1170	No
40	REMIND-MAgPIE 1.7-3.0|SMP_1p5C_Def	REMIND	1.5C low overshoot	59.3	97	157	256	Yes
41	REMIND-MAgPIE 1.7-3.0|SMP_1p5C_Sust	REMIND	Below 1.5C	101.0	136	182	245	No
42	REMIND-MAgPIE 1.7-3.0|SMP_1p5C_early	REMIND	Below 1.5C	131.3	176	237	319	Yes
43	REMIND-MAgPIE 1.7-3.0|SMP_1p5C_lifesty	REMIND	1.5C low overshoot	45.2	74	120	196	No
44	REMIND-MAgPIE 1.7-3.0|SMP_1p5C_regul	REMIND	1.5C low overshoot	74.3	121	197	321	No
45	REMIND-MAgPIE 1.7-3.0|SMP_2C_Sust	REMIND	1.5C low overshoot	51.7	70	93	126	No
46	WITCH-GLOBIOM 3.1|SSP1-19	WITCH	1.5C low overshoot	7.1	1275	2455	4304	Yes
47	WITCH-GLOBIOM 3.1|SSP4-19	WITCH	1.5C low overshoot	7.3	875	1684	2953	Yes
48	WITCH-GLOBIOM 4.2|ADVANCE_2020_1.5C-2100	WITCH	1.5C low overshoot		653	882	1189	Yes
49	WITCH-GLOBIOM 4.4|CD-LINKS_NPi2020_1000	WITCH	1.5C low overshoot		186	316	456	No
50	WITCH-GLOBIOM 4.4|CD-LINKS_NPi2020_400	WITCH	Below 1.5C		475	777	1099	Yes

6 IAMC database: Important model-scenario differences

6.1 Same scenario, different prices

There is a vast number of possible futures that can be modelled, where the models assess the feasibility and cost of achieving the given emissions target. A common way to display the different kinds of possible futures, is through the so-called Shared Socioeconomic Pathways (SSPs). These pathways differ along many dimensions, like population and economic growth (see Figure 6.1), but also around social developments and inequality. The SSPs have different narratives that describe the underlying logic for each SSP, and they provide storylines that cover more than the variables that are included in the formal models. The storylines (Riahi et al., 2017) are summarized in their following respective titles:

- SSP1: Sustainability – Taking the Green Road (Low challenges to mitigation and adaptation)
- SSP2: Middle of the Road (Medium challenges to mitigation and adaptation)
- SSP3: Regional Rivalry – A Rocky Road (High challenges to mitigation and adaptation)
- SSP4: Inequality – A Road Divided (Low challenges to mitigation, high challenges to adaptation)
- SSP5: Fossil-fueled Development – Taking the Highway (High challenges to mitigation, low challenges to adaptation)

A brief introduction to the 5 different SSPs is given in Appendix A.

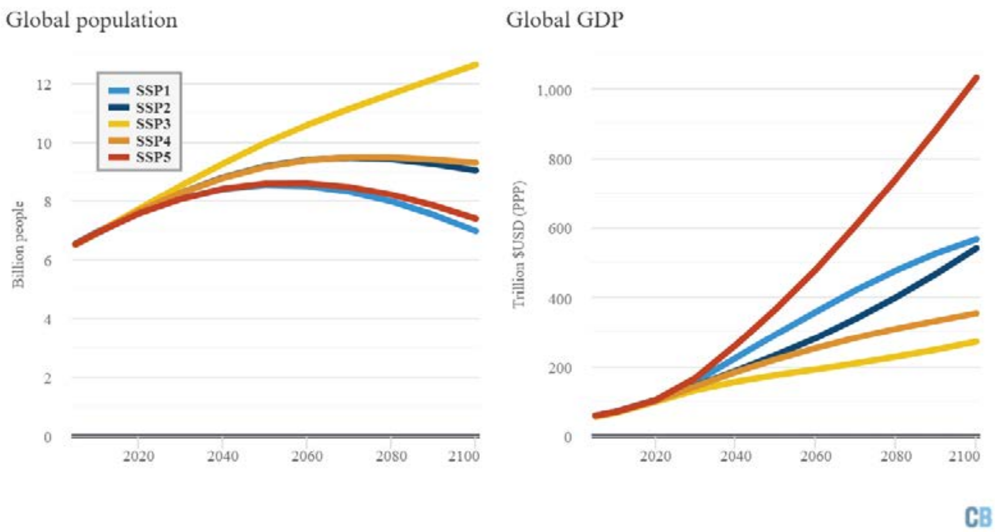

Figure 6.1: Global population (left) in billions and global gross domestic product (right) in trillion US dollars on a purchasing power parity (PPP) basis. Figures from Hausfather (2018).

A benefit from the SSPs is the standardization of scenario assumptions that the IAM community can use in their modelling. One would expect large differences in carbon prices in different SSPs, even if run by the same model. However, we also see some systematic differences between models, even for the same SSPs.

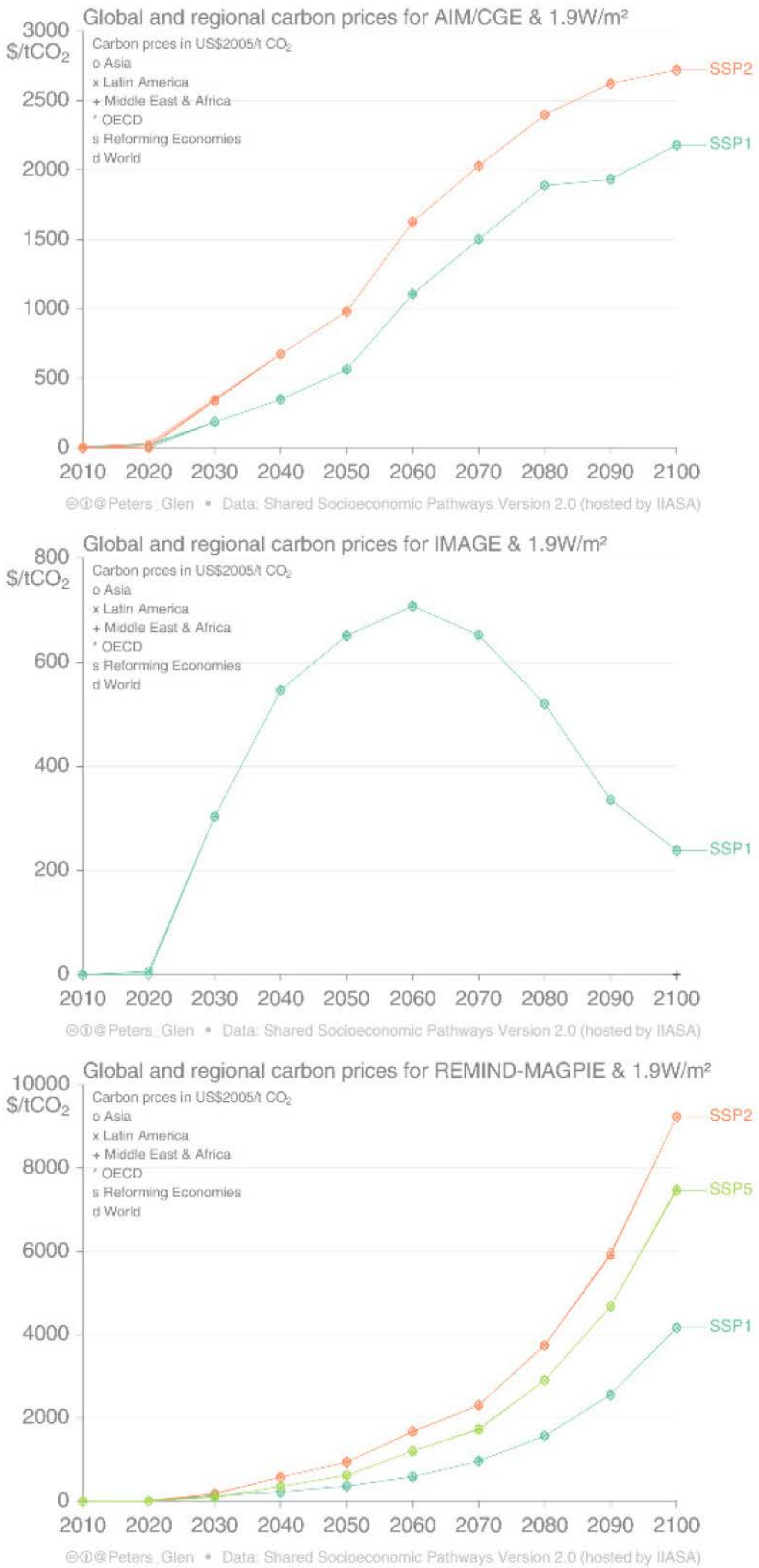

Figure 6.2: The carbon prices for 1.5°C scenarios with each panel representing a different model. From Aamaas et al. (2019).

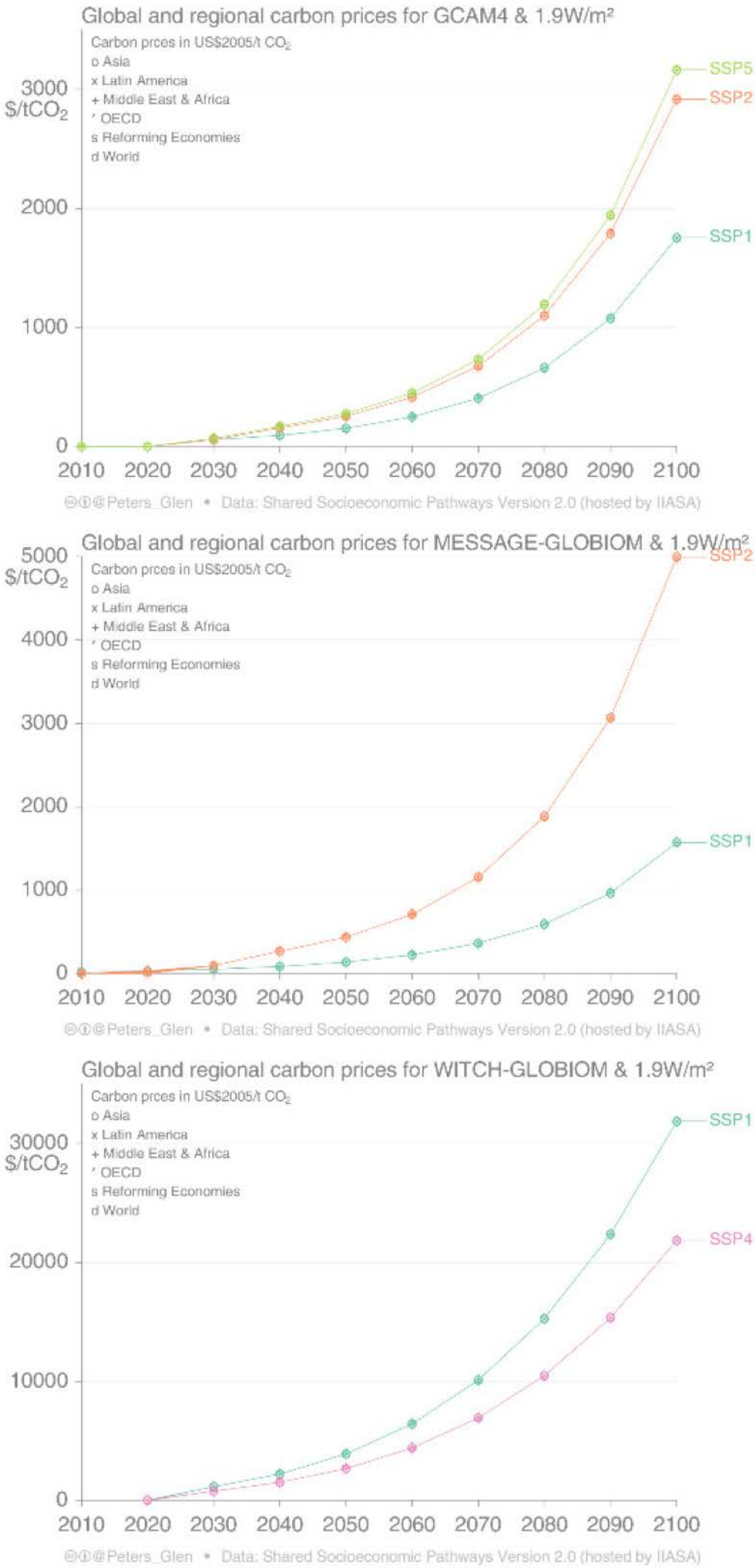

Figure 6.3: The carbon prices for 1.5°C scenarios with each panel representing a different model. From Aamaas et al. (2019).

Aamaas et al. (2019) give a useful visual display of these differences, based on data from the SSP-web database[23] (Riahi et al., 2017). In Figure 6.2and Figure 6.3, we first show how different SSPs differ between each other, even if they are run in the same model. Each of the six panels represents simulations from the same models, and it becomes clear that none of the models could solve for all SSPs. This is further elaborated in Figure A.3 in Appendix A. With the exception of WITCH-GLOBIOM, we see that carbon prices are generally lower for SSP1 than for other scenarios. This is expected as the scenario is designed with a narrative and a set of assumptions that entails low challenges to mitigation and adaptation. Besides that, the comparing of model runs does not reveal whether some SSPs will systematically drive the carbon price upward or downward. This is because there are not enough available combinations of models and SSPs, and in the few places were comparisons are possible, they are inconclusive. For example, carbon prices are higher in SSP5 than in SSP2 when simulated by GCAM4, but they are lower than SSP2 when simulated by REMIND-MAgPIE.

When looking at the y-axis of the panels in Figure 6.2and Figure 6.3 we also see that the various models generate carbon prices of very different orders of magnitude. This becomes even more evident in Figure 6.4, where we show how the models generate different carbon price trajectories under the same SSPs. Again, we see that SSP3 is not represented, and that SSP5 and SSP4 are very *under*represented, with only two and one model run, respectively. However, a few patterns become visible. WITCH-GLOBIOM generates carbon prices that in 2050 are at least twice as high as any of the other models generate, regardless of scenario. And in SSP1, WITCH-GLOBIOM gets carbon prices in 2050 that are more than 6 times as high as the model with the second highest price. We also see that REMIND-MAgPIE generates higher carbon prices than GCAM4, AIM/CGE, MESSAGE-GLOBIOM and IMAGE in all SSPs where they can be compared.

[23] https://secure.iiasa.ac.at/web-apps/ene/SspDb

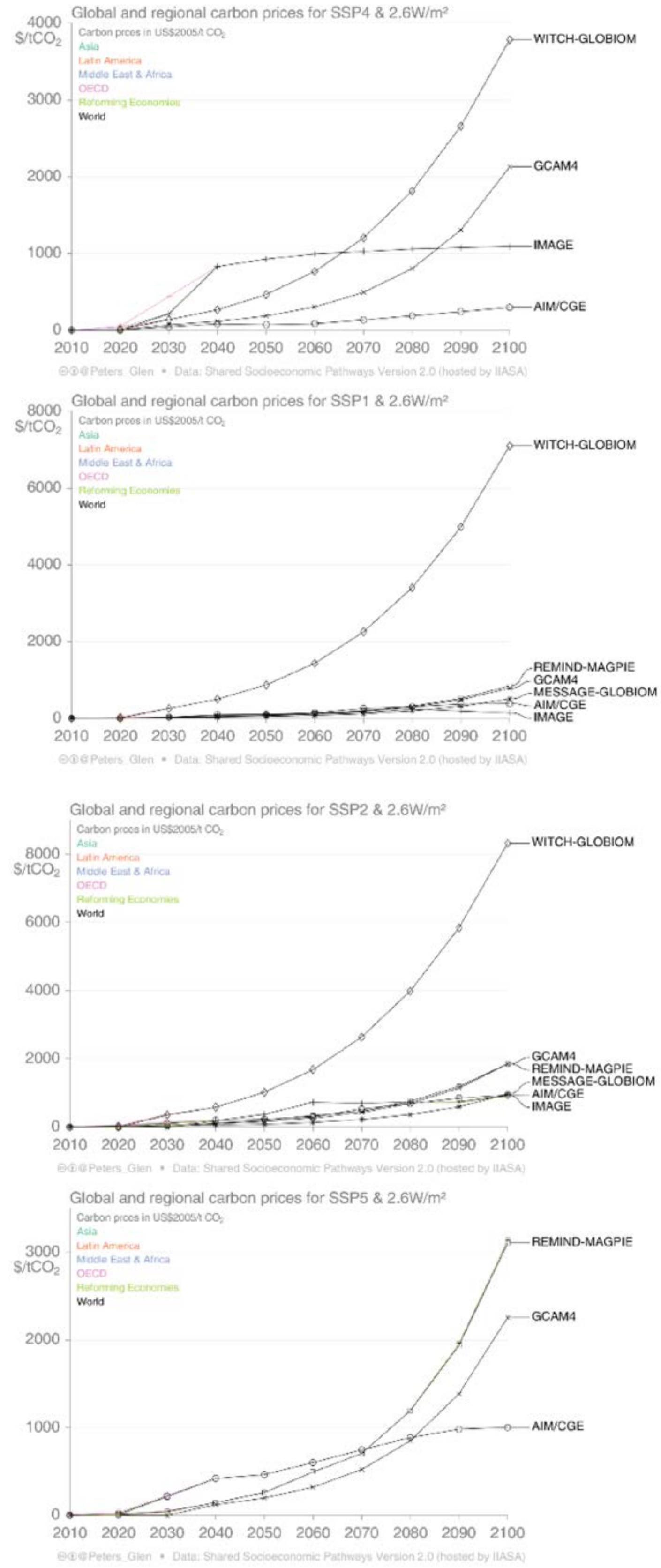

Figure 6.4: The carbon prices for RCP1.9 and SSP1, SSP2, SSP4, and SSP5 for various models and regions. If the regional color coded is not clearly shown, it is because they sit behind the black line (global price). From Aamaas et al. (2019).

This graphical presentation of model-scenario combinations reveals several challenges in the search for a usable carbon price. First, the various SSPs are unequally represented, and the models are unequally represented. The sample of carbon price trajectories is biased. Also, as we see the models generating vastly different carbon prices even under the same SSP, it appears that the differences in model structure and parameters could matter a lot.

6.2 Reasons for model differences – a top-down view

There are many ways to assess how differences in model structure and parameters lead to different carbon price trajectories, even in the same scenario. One way is to use a comprehensive bottom-up approach, where the models are classified based on e.g., the level of detail in the model economy or what assumptions about time preferences and myopia are made. However, the model taxonomy of state-of-the-art IAMs has become very complex, making it harder to perform simple classifications along these lines (Kriegler et al., 2015). In contrast, Kriegler et al. (2015) classifies the most important IAMs based on a top-down approach, where they perform diagnostics on the results from model runs with identical carbon price trajectories. The models that gave a high response to a given carbon price trajectory are the models that would require a lower carbon price for a given emission reduction target.

Kriegler et al. (2015) break down the model response into different aspects of how the models respond. These aspects are then indexed, and how the different models score on these indices seem to give a good indication of how responsive they are to the carbon price.

One of the indices is a transformation index for the primary energy mix. This index quantifies the rate of change, i.e., how responsive the energy system is with regard to the energy mix. It is an index of how much the relative shares of the three primary energy categories coal, oil & gas, and non-fossil change in response to the carbon price. In Kriegler et al. (2015) the models are classified according to their score on this index in terms of high, medium or low score. GCAM was the model with the highest score, meaning that it is the model that would incorporate the highest change in primary energy mix, while IMAGE and IMACLIM had the lowest.

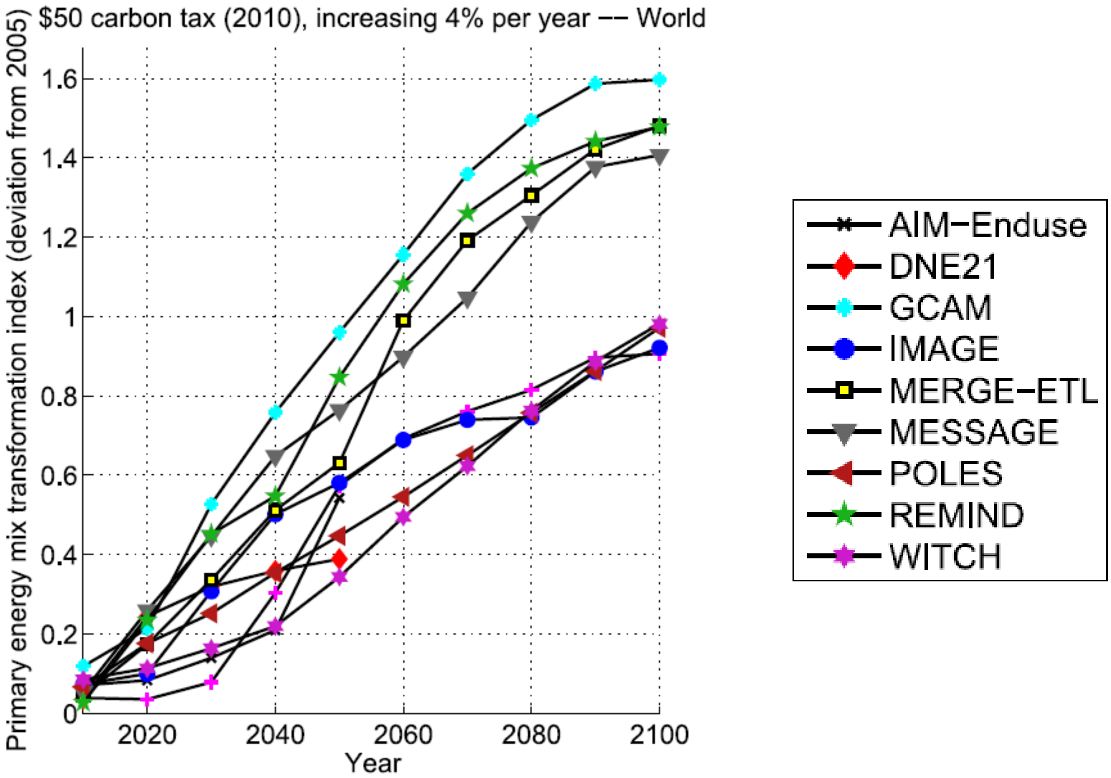

Figure 6.5: Development of the primary energy mix transformation index over time (deviation from 2005). From Kriegler et al. (2015).

Another index is the ratio between the reduction in energy intensity in the economy and the reduction in carbon intensity in energy production. All models reduce carbon intensity in response to the carbon price, and all more so than the reduction in energy intensity. Some models even go to negative carbon intensity towards the end of the century, as they respond with negative emission technologies at the tested carbon prices. However, the drop in carbon intensity *relative* to the drop in energy intensity, says something about the ability in the modelled world to get carbon out of the energy mix without having to be forced to reduce energy production for a given unit of GDP. The GCAM model had the steepest drop in carbon intensity relative to energy intensity (due to extensive use of BECCS), while WITCH and IMACLIM were among the models with the least steep drop.

The final index used for their classification is simply the relative emission reduction for a given carbon price, for a given model. This consists of the elasticity of abatement with respect to carbon price, which can then be translated into marginal abatement cost (MAC) curves for each model. The steeper the MAC curve the less abatement you get for a given carbon price (or the higher price you need for given abatement). Notably again, the GCAM model was the model with the least steep MAC curve, at least after the carbon prices above USD 100. At the other end of the spectrum we find the IMACLIM model.

Kriegler et al. (2015) provides a summary of their classification, which we reproduce in Table 6.1.

Table 6.1: Criteria for a preliminary classification of models based on qualitative descriptions of indicator values. From Kriegler et al. (2015)

Relative abatement index	Indicator carbon/ energy intensity	Transformation index (primary energy)	Model classification
Low	High	Low	Low response
Medium/Mixed	Medium/Mixed	Medium/Mixed	Medium response
High	Low	High	High response

The carbon price trajectories are also affected by whether the models use a recursive-dynamic approach, or an intertemporal optimization approach. In the former, the future carbon prices are not known by the market participants and actions are taken as a response to current carbon prices, while in the latter, there is perfect foresight so that all investments now are based on the knowledge of future prices. With the former, in order to reach any ambitious climate goal, the prices will have to start off higher in order to stimulate green investment early on, and then possibly level off later in the century. With the latter, prices will rise exponentially, but from lower levels earlier in the century as market participants correctly expect the prices to rise and take this into consideration in their current investments (Guivarch & Rogelj, 2017).

When analysing SSPs run by different models with the goal of achieving the 2C target with 66% probability (2.6 W m^{-2} in radiative forcing), Guivarch and Rogelj (2017) find that structural modeling differences matter more than the different socioeconomic conditions in the SSPS. Using an ANOVA analysis they find that 90% (with p-value << 0.01) of the variation in carbon prices is due to intermodal differences. However, this is partly because some of the scenarios cannot be simulated by some models. In particular, no model was able to reach the 2C target based on the SSP3 assumptions.

With the classification of models done in Kriegler et al. (2015) in terms of low/medium/high response, Table 6.2 gives an indication of how high carbon prices they tend to generate, relative to each other, under similar socioeconomic scenarios.

Table 6.2: Classification of the main models in this report

Model Name	Equilibrium Type	Modelling Approach	Classification diagnostics
AIM/GCE	General equilibrium	Recursive-dynamic	Medium response
GCAM	Partial equilibrium	Recursive-dynamic	High response
IMAGE	Partial equilibrium	Recursive-dynamic	High response
MESSAGE	General equilibrium	Intertemporal optimization	High response
POLES	Partial equilibrium	Recursive-dynamic	Medium response*
REMIND	General equilibrium	Intertemporal optimization	High response
WITCH	General equilibrium	Intertemporal optimization	Low response
IMACLIM	General equilibrium	Recursive-dynamic	Low response

* POLES has low response in the short and medium term, while high response in the long term (Kriegler et al. (2015))

6.3 Reasons for model differences – a bottom-up view

6.3.1 Costs of zero- and negative carbon solutions

To further investigate what drives the differences in CO_2 prices in the different models, we have assessed the relationship between the assumed unit capital costs of three important climate-friendly technologies in 2050 (taken from Appendix C in Krey et al. (2019)[24]) and the CO_2 prices in 2050 in the different models. For each model where we have such information, we have taken the lowest and highest CO_2 price in 2050 from the relevant sample of scenarios (i.e., scenarios that are consistent with the net zero target and without too much BECCS).[25] For the same models, we have found unit capital costs in 2050 for respectively Bioenergy with CCS, PV (photovoltaics – solar energy) and Wind offshore. In order to include them in the same figure, we have indexed each of the unit costs by dividing by the average unit cost in 2020 (i.e., average across models).[26] Thus, if for instance the index for one technology and one model is 0.5, it means that the assumed unit capital cost for this technology in 2050 in this model is 50% of the average assumed unit capital cost for this technology in 2020 (across all models).

For this comparison we have information from four models, i.e., IMAGE, POLES, REMIND and WITCH. For the latter model, however, we don't have information about costs of Bioenergy with CCS. Further, for two of the models (IMAGE and WITCH) there is only one CO_2 price available.

The results are shown in Figure 6.6, where we show each pair of CO_2 price and unit capital cost as well as a trendline for each of the three technologies. For all technologies we see that there is an increasing trend, that is, models that assume relatively high unit capital costs for any of the three technologies tend to have a higher CO_2 price in 2050. This is not surprising – the more costly climate-friendly technologies are, the higher CO_2 price will be necessary to reach a certain emission target.

[24] Appendix C Krey et al. (2019) is an online Excel-spreadsheet that is available with this Open Access article at https://doi.org/10.1016/j.energy.2018.12.131

[25] As the POLES model has one scenario with extremely high CO2 price (due to no overshoot of the 1.5˚C target), we rather used the second-highest CO2 price, which still is higher than all other CO2 prices in this sample (see the figure).

[26] These are respectively 4002 USD_{2010}/kWe, 1566 USD_{2010}/kWe and 2629 USD_{2010}/kWe for bioenergy with CCS, PV and Wind offshore (in 2020).

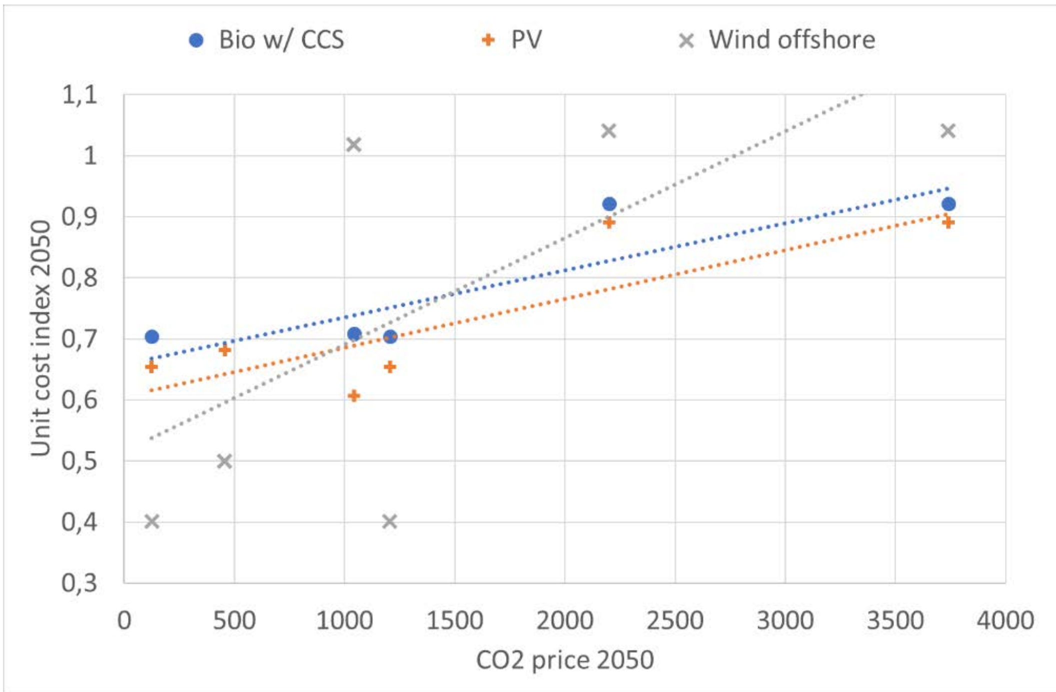

Figure 6.6: Correlations between unit cost index for different zero-carbon solutions in different models and the models' estimated CO_2 prices. The models behind the six different CO_2 prices are respectively (from lowest to highest CO_2 price): REMIND, WITCH, IMAGE, REMIND, POLES and POLES.

It is also worth noticing that there is a clear correlation between the cost assumptions for the three technologies. That is, models that assume high unit capital cost for one technology tend to assume high unit capital costs for the other technologies, too. This is especially true for Bioenergy with CCS and PV, with a correlation of 0.98. For Bioenergy with CCS and Wind offshore the correlation is 0.54, while for PV and Wind offshore it is 0.41. The model with the highest costs (for all three technologies) is POLES, while the model with lowest costs varies between technologies. However, since the sample of models with this information is very limited, one should be somewhat careful in drawing strong implications of this assessment.

6.3.2 Detail in abatement options

Another relevant assessment is to compare the CO_2 prices in 2050 with the inclusion of various abatement options or measures in the different models. If incorporated, these options may be explicitly or implicitly included, and treated endogenously or exogenously. We have such information about 67 different abatement options/measures, retrieved from Huppmann, Kriegler, Mundaca, et al. (2018). The measures are divided into one group of demand-side measures and five groups of supply-side measures (Decarbonization of Electricity; Decarbonization of Non-Electric Fuels; Other Processes; AFOLU Measures; and Carbon Dioxide (Greenhouse Gas) Removal). The inclusion of these measures can be either endogenous and explicit (1), exogenous and explicit (2), endogenous and implicit (3), exogenous and implicit (4), or not included (5). Thus, the lower the number, the better representation (although one could argue whether (2) or (3) is best). For each model (here we also have information from the AIM model) and each of the six groups mentioned above, we compute an average score representing how good this group of measures are incorporated. Then we plot these scores with the CO_2 prices in 2050, as in the previous figure. The result is shown in Figure 6.7, where we also plot trendlines for each group of measures.

First of all, we notice that there are large differences between the groups of measures with respect to how they are included in the models. Decarbonization of electricity has low scores, meaning usually explicitly modeled and often endogenously treated, while CO_2 (GHG) removal has high scores, meaning usually either implicit and exogenous or not included at all.

Second, we see that there is a clear negative relationship for three of the groups of measures, that is, Decarbonization of Electricity, Decarbonization of Non-Electric Fuels, and Other Processes. Further, there is a slightly negative relationship for AFOLU Measures, a slightly positive relationship for Demand, and no clear relationship for CO_2 (GHG) Removal. A negative relationship suggests that models with good representation of abatement options tend to produce higher CO_2 prices than models with less good representation. This may seem a bit surprising, possibly indicating that models with a less good representation of abatement measures are too optimistic in their more implicit way of modeling (i.e., through parameter choices etc.). Alternatively, it might be the case that models with a good representation of abatement measures treat aggregate abatement too rigidly by focusing too much on specific measures.

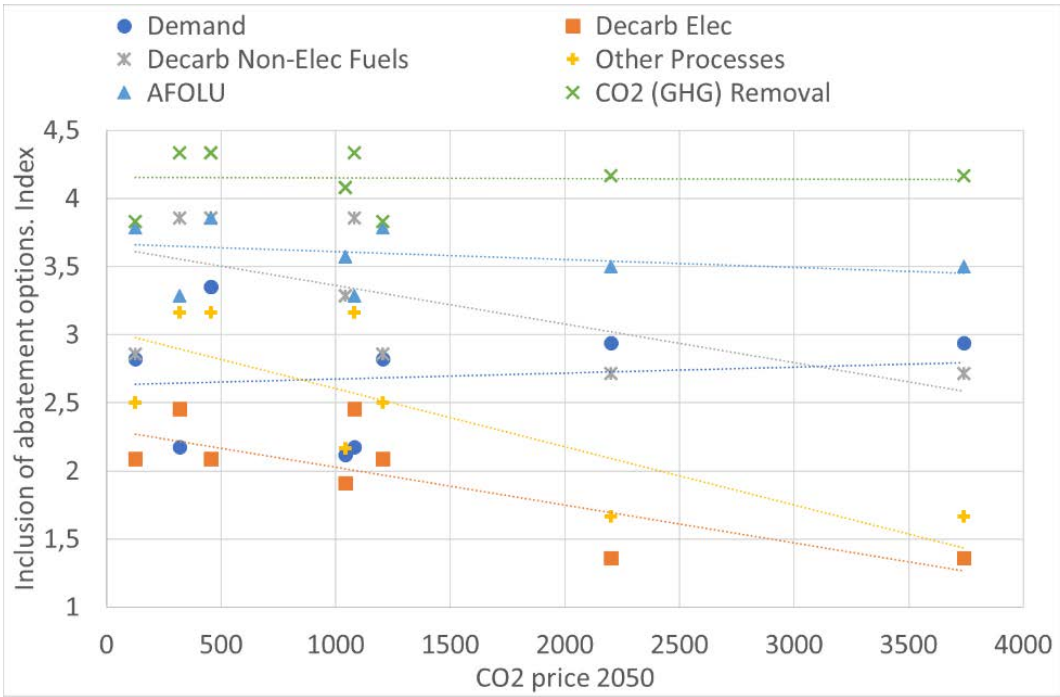

Figure 6.7: Correlations between unit cost index for different zero-carbon solutions in different models and the models' estimated CO_2 prices. The models behind the eight different CO_2 prices are respectively (from lowest to highest CO_2 price): REMIND, AIM, WITCH, IMAGE, AIM, REMIND, POLES and POLES.

Here, too, we would like to remind that the sample of models is very limited, and thus one should be careful in drawing too strong conclusions based on this assessment.[27] Moreover, according to Kriegler et al. (2015) partial equilibrium models tend to show lower mitigation costs than general equilibrium models, possibly contradicting our findings here.

6.3.3 Differences in CCS assumptions

It is feasible for IAMs to find solutions to the 1.5˚C target without relying on negative emission technologies in certain scenarios (Grubler et al., 2018). However, should some fossil fuels be a part of the energy mix, negative emission technologies such as CCS will be necessary in order to reach the target (Budinis, Krevor, Mac Dowell, Brandon, & Hawkes, 2018).The different models vary in which CCS options they include in the model, and at what detail. Aamaas et al. (2019) give a more thorough description of the CCS options in the various models, with some examples of unit costs and developments over time. In Table 6.3 we summarize these descriptions and also show the range of carbon prices generated by each model in the IAMC database. Note that we here also include scenarios with large amounts of BECCS.

Table 6.3: The availability of different CCS technology options in the main models providing relevant scenarios for this report. Based on section 10.1 in Aamaas et al. (2019).

	AIM/GCE	GCAM	IMAGE	MESSAGE	REMIND	WITCH
From energy production						
Coal, unspecified	x					
Coal-to-liquids		x		x	x	
IGCC - integrated coal gasification combined cycle		x		x	x	
Coal to hydrogen		x		x	x	
Pre-combustion coal (IGCC)			x			x
Post-combustion coal (pulverized)			x			x
Ultrasupercritical coal				x		
Coal, oxyfuel						x
Oil, unspecified	x					
Gas, unspecified	x					x
Gas to hydrogen		x		x		
Pre-combustion natural gas (NGCC)			x			
Post-combustion natural gas (NGCC)			x			
Post-combustion natural gas, fired (steam)			x			
Gas to liquids				x		
NGCC, unspecified				x	x	
Steam methane reforming						

[27] As is evident from the figure, the POLES model has the two highest CO2 prices, and much higher than the other models. Thus, one may ask whether the negative trendlines are only due to low numbers for this model. If we take out the POLES model from the sample, the trendlines are still negative – even the trendline for Demand turns negative then.

	AIM/GCE	GCAM	IMAGE	MESSAGE	REMIND	WITCH
Bioenergy, unspecified	x					x
Cellulosic ethanol CCS level 1		x				
Cellulosic ethanol CCS level 1		x				
Fischer-Tropsch biofuels CCS level 1		x				
Fischer-Tropsch biofuels CCS level 2		x				
Biomass to hydrogen		x		x	x	
Biomass to liquids				x	x	
Biomass integrated coal gasification combined cycle					x	
From manufacturing						
Petroleum refinery coal transformation	x					
Non-metal and mineral	x					
Paper and pulp	x					
Chemical	x					
Cement plants			x			
Iron and steel plants			x			
Ammonia plants (flue gas)			x			
Ammonia plants (pure CO_2)			x			
Refineries			x			
Hydrogen (flue gas)			x			
Hydrogen (pure CO_2)			x			
Petrochemical plants			x			
SUM	8	9	13	9	7	5
Lowest 2050 carbon price (in low or no overshoot scenarios)	318	168	1042	151	126	456
Highest 2050 carbon price (in low or no overshoot scenarios)	1690	168	1042	744	1205	4304
Lowest 2050 carbon price (in low or no overshoot scenarios) – high BECCS scenarios excluded	318	N/A	1042	151	126	456
Highest 2050 carbon price (in low or no overshoot scenarios) – high BECCS scenarios excluded	1080	N/A	1042	151	1205	456

We see that the model with fewest number of CCS options (WITCH) has the highest carbon price. Otherwise, there seems to be no clear relationship between the number of CCS options and the carbon price.

6.4 Important differences – reaching the goal with different energy use and mix

As the two previous subsections have shown, there are large differences between both models and scenarios that contribute to large differences in carbon prices. High carbon prices reflect the difficulties in that particular model-scenario combination with regards to energy demand, cost of renewables, availability of low carbon technology options etc. The size and mix of energy production in the different model-scenario combinations can therefore provide a good illustration of how the scenarios differ and what consequences this may have for the generated carbon prices.

In Table 6.4 we show the energy mix in 2050 for a sample of 20 model scenarios from the IAMC database (Huppmann, Kriegler, Krey, et al., 2018) that are consistent with the 1.5˚C target. The corresponding CO_2-prices in 2050 are also shown, and the scenarios are ordered from the highest to the lowest CO_2-price. All of these scenarios are included in the final round of assessment in section 8, i.e., when scenarios with huge amounts of BECCS are removed. The numbering of the scenarios corresponds to the same numbering in Table 5.1.

In the table we summarize the model-projected production of primary energy in the world, measured in Exajoules (EJs – 1 EJ = one quintillion (10^{18}) joules). The total consumption is broken down into the categories renewables (non-biomass), biomass, coal, oil, gas and nuclear power. Within each energy category, i.e. column, the colour coding gives a visual representation of the values, from the highest (white) to the lowest (blue). As the table shows, there are substantial differences between scenarios in the amount of energy produced, end the total energy mix.

With regards to total energy production, the largest difference is found between model-scenario 44 (with the highest production) and 25 (the lowest), with the former having more than twice as much production than the latter. There are also large differences with regards to the share of non-fossil energy production in 2050, with the lowest share being 46% (scenario 5) and the highest with 91% (scenario 38).

We see that of the non-fossil energy sources, nuclear generally has the lowest production (though never zero). We also see a strong correlation between scenarios with the highest overall energy production and the scenarios with the highest renewable energy production.

When it comes to correlations between the carbon price and level of production, we see a negative correlation with respect to total energy production. That is, scenarios with low carbon prices tend to have large volumes of energy. Such scenarios are those with relatively high energy intensity compared to carbon intensity, cf. the findings from Kriegler et al. (2015) in section 6.2. In these scenarios, switching to low-carbon energy (or even energy with negative emissions such as BECCS) is relatively cheap and hence quite low carbon prices are required. We also see the same negative correlation with respect to all three fossil fuels, suggesting that the climate target can be reached by extensive use of CCS, both linked with fossil fuels and BECCS. If not, high carbon prices are needed, leading to reduced use of fossil fuels.

We also see a negative correlation between the carbon price and volumes of renewables, while a positive correlation with respect to nuclear. The former is likely because the required carbon price to a large degree depends on the assumptions about costs and availability of renewable energy. Thus, optimistic assumptions about renewables lead to low carbon prices. For nuclear, we suspect the causality in the model scenarios to go in the opposite direction, i.e., a higher carbon price increases the profitability of nuclear (while the cost assumptions for nuclear has limited impact on the carbon price).

Even though there are large differences between all scenarios, there seems to be a pattern where model outcomes are more similar for scenarios run by the same model, comparing e.g., scenarios run by the POLES model (scenarios 25, 29, 30 and 32) and the IMAGE model (scenarios 11 and 13). This coincides with the findings from Aamaas et al. (2019), where they point out that different scenarios run by the same model will have more similar results, than the same scenario run by different models (p41). This may suggest that different views on how the economy works may be as important for the results as the assumed baseline scenario (SSP). On the other hand, this also reflects that for some ("difficult") SSPs there are very few (or even none) scenarios consistent with the 1.5˚C target.

All of these scenarios entail net-zero (or close to net-zero) CO_2 emissions in 2050. However, all of the scenarios still have emissions from fossil fuel energy. Hence, in order to reach the net-zero target, there is a need for negative emissions from CCS, BECCS, afforestation and direct air capture (DAC). Table 6.5 shows the model-projected magnitudes of negative emissions by the various technologies for the 20 selected model-scenario-combinations. Again, the corresponding CO_2-prices in 2050 are also shown, and the scenarios are ordered from highest to lowest CO_2-price.

Again, we see that there are large differences between scenarios, and in particular between models. We also see order of magnitude differences between the scenarios with the most CCS and/or BECCS and the ones with the least. When comparing with Table 6.4, we see that there is a strong correlation between the amount of CCS and the amount of fossil generated energy in the model output. We also see a strong correlation between high levels of CCS and lower carbon prices generated.

With regards to other negative emission technologies, we see large differences between models. Some models do not even include afforestation and DAC. This, along with the observed pattern for CCS, coincide with the finding that results from different scenarios from the same model are relatively similar compared to the same scenario run by different models.

Table 6.4: World energy production (EJs) and CO_2-price (USD per ton) in 2050 in different 1.5°C model-scenarios

	Model/Scenario	Renewables	Biomass	Coal	Oil	Gas	Nuclear	SUM	Price
25	POLES EMF33|EMF33_1.5C_limbio	89	105	11	28	22	38	293	14300
32	POLES EMF33|EMF33_WB2C_none	103	179	15	57	47	29	430	3740
30	POLES EMF33|EMF33_WB2C_nobeccs	104	188	16	55	52	28	443	3520
29	POLES EMF33|EMF33_WB2C_limbio	100	112	24	86	102	24	448	2200
38	REMIND 1.7|CEMICS-1.5-CDR8	410	175	3	21	33	23	666	1205
39	REMIND-MAgPIE 1.7-3.0|PEP_1p5C_red_eff	352	118	1	71	35	24	601	1170
3	AIM/CGE 2.0|SSP2-19	161	131	57	116	79	21	565	1080
11	IMAGE 3.0.1|IMA15-LiStCh	79	115	37	30	122	36	419	1042
13	IMAGE 3.0.1|IMA15-TOT	136	40	21	28	107	10	343	1042
4	AIM/CGE 2.1|CD-LINKS_NPi2020_400	202	163	23	76	92	25	581	999
2	AIM/CGE 2.0|SSP1-19	191	67	30	84	48	22	442	621
37	REMIND 1.7|CEMICS-1.5-CDR12	367	130	7	73	70	23	670	572
49	WITCH-GLOBIOM 4.4|CD-LINKS_NPi2020_1000	123	96	52	143	71	15	501	456
6	AIM/CGE 2.1|TERL_15D_NoTransportPolicy	138	156	71	150	120	14	648	388
44	REMIND-MAgPIE 1.7-3.0|SMP_1p5C_regul	370	126	4	135	60	3	698	321
5	AIM/CGE 2.1|TERL_15D_LowCarbonTransportPolicy	129	141	71	139	128	14	621	318
41	REMIND-MAgPIE 1.7-3.0|SMP_1p5C_Sust	321	103	4	134	73	3	638	245
43	REMIND-MAgPIE 1.7-3.0|SMP_1p5C_lifesty	280	114	7	149	89	21	660	196
19	MESSAGE-GLOBIOM 1.0|SSP1-19	157	88	30	69	199	28	572	151
45	REMIND-MAgPIE 1.7-3.0|SMP_2C_Sust	283	67	11	168	121	3	652	126
	Correllation with carbon price	-0,36	0,09	-0,19	-0,45	-0,45	0,54	-0,63	

Table 6.5: Use of negative emission technologies (measured in $GtCO_2$) and CO_2-price (USD per ton) in 2050 in different 1.5°C model-scenarios

	Model/Scenario	Total CCS	BECCS	Afforestation	DAC	Price
25	POLES EMF33|EMF33_1.5C_limbio	2	1,8	0,0	0,0000	14300
32	POLES EMF33|EMF33_WB2C_none	1	0,0	0,0	0,0000	3740
30	POLES EMF33|EMF33_WB2C_nobeccs	2	0,0	0,0	0,0000	3520
29	POLES EMF33|EMF33_WB2C_limbio	5	3,3	0,0	0,0000	2200
38	REMIND 1.7|CEMICS-1.5-CDR8	5	3,5	4,5	0,0013	1205
39	REMIND-MAgPIE 1.7-3.0|PEP_1p5C_red_eff	8	6,1	6,1	0,0000	1170
3	AIM/CGE 2.0|SSP2-19	15	4,5	0,0	0,0000	1080
11	IMAGE 3.0.1|IMA15-LiStCh	10	3,2	6,5	0,0000	1042
13	IMAGE 3.0.1|IMA15-TOT	4	0,0	10,1	0,0000	1042
4	AIM/CGE 2.1|CD-LINKS_NPi2020_400	13	5,0	0,0	0,0000	999
2	AIM/CGE 2.0|SSP1-19	6	1,4	0,0	0,0000	621
37	REMIND 1.7|CEMICS-1.5-CDR12	7	4,3	7,7	0,0002	572
49	WITCH-GLOBIOM 4.4|CD-LINKS_NPi2020_1000	7	3,8	2,3	0,0000	456
6	AIM/CGE 2.1|TERL_15D_NoTransportPolicy	16	4,7	0,0	0,0000	388
44	REMIND-MAgPIE 1.7-3.0|SMP_1p5C_regul	7	4,3	8,6	0,0000	321
5	AIM/CGE 2.1|TERL_15D_LowCarbonTransportPolicy	16	4,6	0,0	0,0000	318
41	REMIND-MAgPIE 1.7-3.0|SMP_1p5C_Sust	7	3,4	10,5	0,0000	245
43	REMIND-MAgPIE 1.7-3.0|SMP_1p5C_lifesty	9	4,5	8,1	0,0000	196
19	MESSAGE-GLOBIOM 1.0|SSP1-19	14	4,4	3,8	0,0000	151
45	REMIND-MAgPIE 1.7-3.0|SMP_2C_Sust	5	1,0	8,8	0,0000	126
	Correllation with carbon price	-0,46	-0,34	-0,35	-0,05	

7 IAMC database: Summary of results

In Table 7.1 we present descriptive statistics from the ensemble of carbon prices in the IAMC database. We show the "process of elimination" as we go from a sample of 84 scenarios consistent with the 1.5˚C target (first column) to a smaller sample where we filter out scenarios with too much overshoot (second column), and then to an even smaller sample where neither of the scenarios are too reliant on high levels of BECCS (third column). The table shows carbon prices for 2050, measured in 2016-Euros[28]. We provide similar tables for every fifth year from 2020 to 2045 in Appendix C.

Table 7.1: Descriptive statistics from the ensemble of carbon prices in the IAMC database for the year 2050, 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

When moving from the original sample of scenarios that are consistent with the 1.5˚C target to the subsample without high overshoot, we see that the distribution of carbon prices generally shifts rightwards towards higher prices. This is shown e.g., by the interquartile range of €315-1038 in the original sample to €470-1179[29] in the sample with low overshoot. The direction of this change is expected as we would expect the shadow price to increase when the requirements become stricter.

We also notice that removing studies with large amounts of BECCS does not in fact change the sample statistics of the carbon prices dramatically. The minimum and maximum value is unchanged, and we see minor drops in the values for the median and 75th percentile. However, it is evident that the sample has become more skewed to the right, with an increase in the sample average of about 17%, along with a more than 30% reduction of the 25th percentile. Figure 7.1 shows the spread of the carbon price paths from 2020 to 2050, after removing scenarios with too high overshoot and/or too much BECCS.

Removal of scenarios with too much overshoot and/or unsustainable levels of BECCS is based on our reasoning in Section 2. We return to this issue in Section 9, where we also discuss the difficulties in extracting information from a wide range of models with a wide

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[28] Scenarios from the IAMC database are provided in 2010-USD. 2010-USD are converted to 2016-Euros, by first adjusting 2010-USD to 2016-USD with the US Consumer Price Index, and then converting 2016-USD to 2016-Euros by using the average exchange rate for 2016.

[29] We do a brief comparison with the scenarios in the same category in the newer AR6 Scenario Explorer and Scenarios Database hosted by IIASA, which have 99 vetted scenarios in this category. The updated scenario ensemble has an interquartile range of €397-1022, about 15% lower than the results in Table 7.1.

range of scenario assumptions. In addition to much uncertainty, there will also be some biases, since there is underrepresentation of both scenarios and models.

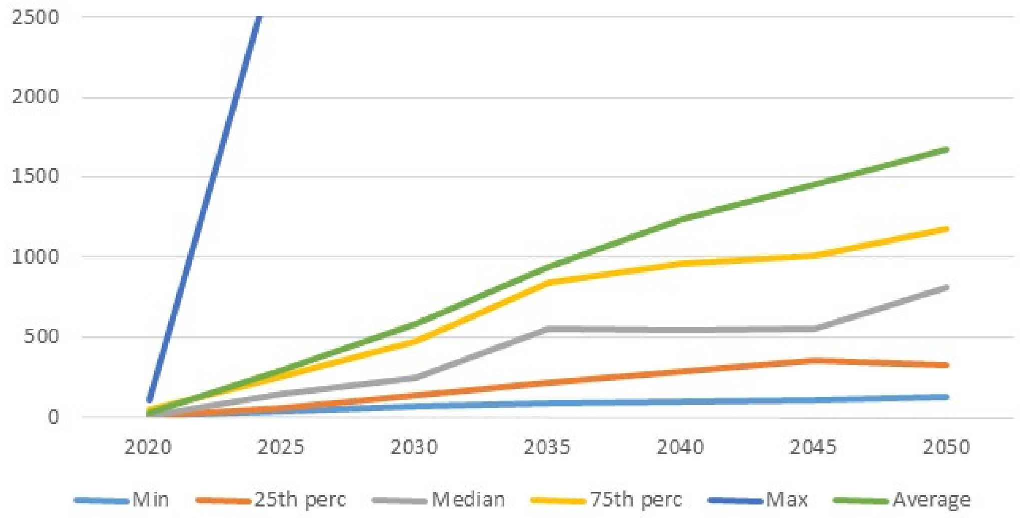

Figure 7.1: Carbon price trajectories from scenario sample in the IAMC database after removal of scenarios with high overshoot and/or unsustainable BECCS; minimum, 25th percentile, median, 75th percentile, maximum and average (EUR$_{2016}$/tCO_2e) for the period 2020-2050.

8 Scenarios from other studies

Although most of the relevant scenarios are found in the IAMC database, as described above, there are also other studies that are relevant to consider when assessing carbon price trajectories consistent with the 1.5˚C target and net zero emissions in 2050.

8.1 France Strategie

In the report *The Value For Climate Action - A Shadow Price Of Carbon For Evaluation Of Investments And Public Policies* (France Stratégie, 2019), the models that are run have a clear objective of net-zero GHG emissions by 2050. Compared to the scenarios consistent with the 1.5˚C target in the IAMC database, this is a considerably more stringent target. The scenarios in the IAMC database aim to uphold the implied GHG budget by 2100 in order to stay within the 1.5˚C target, which does not tend to imply that a target net-zero GHG emissions is reached by 2050. In these scenarios, 2050 is the median year for when net-zero carbon (not all GHGs) emissions is achieved globally, and a few years later for the OECD+EU (cf. Section 2). This is important to remember when comparing scenarios from these different sources.

The most important reference scenario (in the absence of climate policy) assumptions are 1.6% average annual GDP growth in France, energy prices following the IEAs "New Policy Scenario", and the models' default energy efficiency trajectory (30%-50% reduced energy intensity from 2015-2050, depending on the model). They run five models (some are the same as the ones discussed in Section 6, while some are not) to find carbon prices that achieve the target, of which four give carbon prices all the way to 2050. For each model they also test the implication of a conservative (75MtCO_2eq) and optimistic (95MtCO_2eq) size of the carbon sinks[30]. In total, there are nine model-based carbon price pathways relevant for our report, shown in Table 8.1.

However, these model results are just one of the "ingredients" that the commission uses in order to make a final recommendation for a shadow price of carbon. After presenting the results, they discuss the notable rise in all the models' carbon prices between 2040 and 2050. They argue that this dramatic rise reflects *"difficulty of simulating a deep decarbonization scenario at the end of the period, as models of all kinds have a hard time simulating the radical changes required for deep decarbonization of the economy, so that the carbon value obtained tends to "take off" in order to try and achieve the goal."*

[30] The hypothesis adopted is that land use, land-use change and forestry (LULUCF) sequestration capacity may reach 75 to 95 MtCO2eq in 2050. Natural sinks would be complemented by 20 MtCO2eq of sequestration capacities coming from the expected development of carbon capture and storage technology.

Table 8.1: Relevant carbon price scenarios from France Stratégie (2019)

Model/Scenario	Model Core	Category	2020	2030	2040	2050	High BECCS
France-TIMES-LargeSinks	TIMES	Net-zero, France 2050	N/A	322	375	1365	No
France-TIMES-SmallSinks	TIMES	Net-zero, France 2050	N/A	288	465	2451	No
France-Poles-LargeSinks	POLES	Net-zero, France 2050	N/A	253	575	1958	No
France-Poles-SmallSinks	POLES	Net-zero, France 2050	N/A	351	845	3513	No
France-IMACLIM-LargeSinks	IMACLIM	Net-zero, France 2050	N/A	168	168	1453	No
France-IMACLIM-SmallSinks	IMACLIM	Net-zero, France 2050	N/A	168	168	3132	No
France-IMACLIM-myopic-LargeSinks	IMACLIM	Net-zero, France 2050	N/A	228	537	3328	No
France-ThreeME-LargeSinks	ThreeMe	Net-zero, France 2050	N/A	143	363	511	No
France-ThreeME-SmallSinks	ThreeMe	Net-zero, France 2050	N/A	143	1128	2389	No

The commission considers the model-based carbon prices after 2040 not to be applicable, as *"the capacity for deep decarbonization of the economy to achieve net zero GHG emissions requires enabling policies (land use and development in particular), innovation and international coordination, all of which are more difficult to model."* The commission therefore supplements the model results with a technological foresight exercise. The purpose of the exercise is to *"identify the most expensive marginal technologies required for deep decarbonization of human activities. By 2050, carbon value should logically reflect the probable cost of the most expensive enabling technologies to achieve the goal."* This exercise concludes that with a shadow price ranging from €600 to €900[31]/tCO_2eq by 2050, it is possible to make a portfolio of enabling technologies cost-effective in achieving the "Net-Zero" goal.

By applying Hotelling's rule with an annual growth rate equal to the public discount rate of 4.5% from 2040, at a price close to the median model results (€$_{2018}$500 in 2040), a carbon price of €$_{2018}$775 is reached in 2050, well within the range from the technological foresight exercise. For the years before 2030, the commission uses the price in 2030 and the current French shadow price (54 Euros in 2018) as anchor prices and draws a trajectory between these two. In Figure 8.1 we display the modelled carbon price trajectories along with the commission's proposed trajectory:

[31] The commission stresses that these cost levels are subject to major uncertainties, and thus for the sake of caution, does not assume the emergence of an inexpensive high-potential disruptive technology.

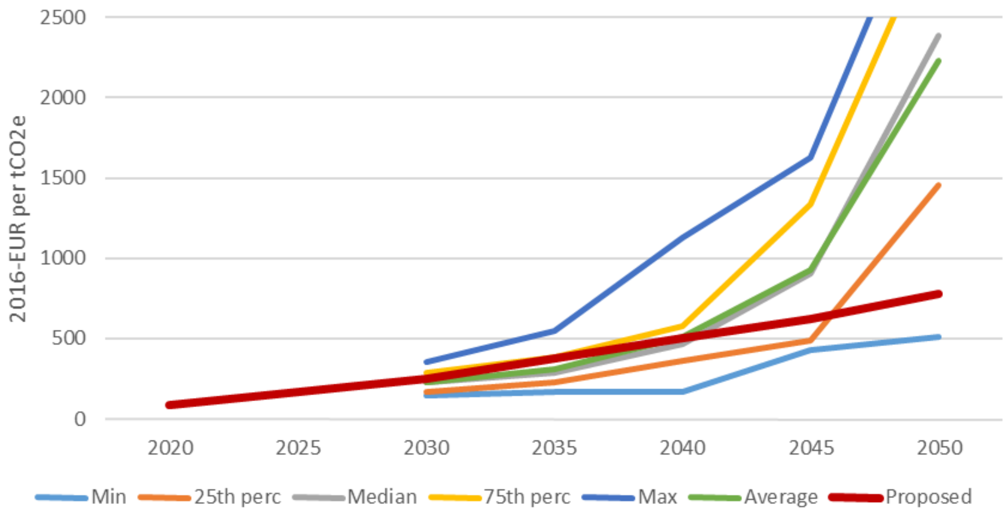

Figure 8.1: Carbon price trajectories from scenario sample from France Stratégie (2019); minimum, 25th percentile, median, 75th percentile, maximum and average (EUR$_{2016}$/tCO_2e) and the commission's proposed carbon price trajectory for the period 2020-2050 (EUR$_{2018}$/tCO_2e).

When comparing these results with the chosen scenarios in the IAMC database in section 7, the prices tend to lie lower in the period 2030 to 2040 in France Stratégie (2019) (7% and 15% lower, respectively). This is completely reversed in 2045 and 2050, when the median from France Stratégie (2019) grows to more than twice as high as the median from the chosen IAMC scenarios. As mentioned above, however, the French study then proposes a carbon price path originating from the 2040 price, which in 2050 is only 4% below the median from the chosen IAMC scenarios.

8.2 European Commission

In the report *A Clean planet for all - A European strategic long-term vision for a prosperous, modern, competitive and climate neutral economy* (European Commission, 2018), an extensive set of interlinked models is used. The models cover all energy sectors (PRIMES and its satellite models on biomass and transport), agriculture (CAPRI), forestry and land use (GLOBIOM-G4M), atmospheric dispersion, health and ecosystems (GAINS); macro-economy with multiple sectors, employment and social welfare (GEM-E3). This set of models is used to run eight different scenarios. The baseline assumptions are based on *EU Reference Scenario 2016 – Energy, transport and GHG emissions - Trends to 2050*.[32]

Three categories of scenarios are considered. Scenario Category 1 *"contains scenarios achieving emissions reduction contributing to Paris Agreement goal of well below 2°C, translated into a target of -80% GHG in 2050 (excluding Land Use, Land-Use Change and Forestry - LULUCF)"*. Scenario Category 3 includes "GHG reductions scenarios, contributing to Paris Agreement goal of pursuing efforts to limit to a 1.5°C temperature change, translated to a target of around -100% GHG (including sinks), i.e. net zero GHG emissions in 2050". Scenario Category 2 is between the two others. Scenario Category 2 and 3 seem most

[32] https://ec.europa.eu/energy/sites/ener/files/documents/ref2016_report_finalweb.pdf

relevant for our purpose. The net zero target in Category 3 is somewhat stronger than the 1.5°C target applied in the IAMC scenario in Section 7 (where the net zero emissions target applies to CO_2 only, and takes place shortly after 2050 in OECD regions).

In all scenarios, carbon pricing is only one of many different policies and regulations implemented to reduce GHG emissions. Such regulations include directives for energy performance of buildings, renewable energy, energy efficiency, Eurovignette, clean vehicles etc. This implies that a lower CO_2 price is needed to reach the target compared to if CO_2 pricing was the only policy instrument. For instance, in the Category 3 scenarios, the "CO_2 standards for new cars, vans and buses are assumed to be zero starting from 2040" (p. 325). With such strict standards, CO_2 prices are in fact superfluous for these emission sources – emissions will be zero anyway given the standards. However, this does not imply that the cost of carbon for these emission sources is zero – strict standards also come with a cost. The same applies to other regulations – the more additional policies and regulations are added, the lower is the necessary CO_2 price to reach a target. The costs of reaching the target are probably not reduced, however (it is more likely they increase). As explained in Section 2, this further means that the carbon price used in these scenarios cannot be interpreted as the shadow price of reaching the stated targets, in other words the *cost of carbon*. The shadow price (in these scenarios) will be higher, but it is difficult to know by how much (we refer to Section 2 for a general discussion of this issue).

Looking at the CO_2 prices applied in the scenarios in (European Commission, 2018), these are about 28 EUR/tCO_2 in 2030, and reach 250 EUR/tCO_2 (Category 1) and 350 EUR/tCO_2 (Category 3) in 2050, respectively (p. 316-318). The report does not give any more details about the CO_2 price developments in any of the scenarios, underlining that this is not the only important policy measure implemented. Comparing with the CO_2 prices in 2050 from the IAMC database (see Section 7), we notice that the prices in (European Commission, 2018) are significantly lower than the median in Figure 7.1 but close to the 25th percentile. This is in accordance with what we stated above, that the shadow price (and thus the cost of carbon) is higher than the CO_2 price.

Since it is difficult to know what the shadow price of emissions is in the scenarios in European Commission (2018), we will not make *direct* use of the results in that report when we derive our recommended cost of carbon in Section 9. However, we will refer to those results, as this is an extensive and impressive study for the EU, consistent with the considered emissions target.

8.3 International Energy Agency

The Sustainable Development Scenario in World Energy Outlook 2019 (IEA, 2019) is constructed on the basis of limiting the temperature rise to below 1.8 °C with a 66% probability, although without any reliance on net-negative CO_2 emissions.

Global GDP growth is assumed to average of 3.4% per year to 2040 and population is assumed to rise to just over 9 billion in 2040. The modelling also includes a process of learning-by-doing that affects the costs of various fuels and technologies, including the cost of investing in energy efficiency.

The carbon prices in this scenario are not determined by the model in order to reach the emissions target. Instead, they are assumed and supplemented by a variety of other policies such as vehicle and building efficiency standards, renewable energy targets and support for new technology development which together lead to the required reduction in emissions. Thus, as in the case above for the study by the European Commission (2018), the carbon prices cannot be interpreted as the shadow price of reaching the target. The reported carbon prices will be lower than the shadow price in these scenario – again it is difficult to know by how much (cf. Section 2 for discussion about this). Hence, we will also not make direct use of these carbon prices when deriving a recommended cost of carbon.

In advanced economies, the carbon prices in IEA (2019) are assumed to be USD 100/tonne in 2030 and USD 140/tonne in 2040. In selected developing countries the corresponding prices are assumed to be USD 75/tonne and USD 125/tonne. The scenarios end in 2040, so carbon prices for 2050 are not provided in IEA (2019).

8.4 High-Level Commission on Carbon Prices

The report from the High-Level Commission on Carbon Prices (Stiglitz et al., 2017) explores carbon-pricing options and levels "needed to deliver on the temperature objective of the Paris Agreement". As part of their report, they present results from previous studies that have analyzed carbon prices needed to comply with the Paris agreement (mostly using the same models as in the IAMC database discussed in Section 7). These studies include scenarios that are consistent with limiting global warming to 2˚C, but no scenarios consistent with the 1.5˚C target.[33] Hence, they cannot be used to derive the shadow price of reaching the 1.5˚C target (or net zero emissions by 2050), and will therefore not be brought forward in our assessment of the recommended cost of carbon.

The Commission concludes that "the explicit carbon-price level consistent with achieving the Paris temperature target is at least US$40–80/t$CO_2$ by 2020 and US$50–100/t$CO_2$ by 2030". Not surprisingly, this is in the lower range of carbon prices consistent with the 1.5˚C target.

8.5 Recent peer-reviewed studies with IAMs

Méjean, Guivarch, Lefèvre, and Hamdi-Cherif (2019) use the IMACLIM model to test a range of scenarios consistent with the 1.5˚C target. The scenarios are combinations of *when* global emissions peak (2016/2020/2025/2030), energy demand levels (high/low), fossil fuel resource availability (high/low) and low-carbon technology availability (high/low). The authors find no feasible solutions in the scenarios where emissions peaked in 2030. For the other 24 scenarios the carbon prices in 2030 range between 147 and 458 USD per tCO_2. When translated into €$_{2016}$ the median value is €$_{2016}$ 296, which is about 20% higher than the median value for the 20 scenarios in the final column of Table in Appendix C. No carbon prices for any other years are given in this article.

Marcucci et al. (2019) use the Integrated Assessment Model MERGE-ETL, along with stochastic output from the PROMETHEUS world energy model. Applying Monte Carlo simulations over a range of scenario variables; macroeconomic parameters, energy resource

[33] They write as follows in a footnote (p. 32): "Few scenarios are currently available that achieve the 1.5°C target, but work is under way to produce more of these scenarios, in view of the Special Report of the IPCC on the 1.5°C target."

availability, technology costs, learning-by-doing rates etc., the authors find a probability distribution for carbon prices. The interquartile range for carbon prices is found to be USD_{2010} 609-778 per tCO_2 in 2050 (which is about 4%-25% lower than the median value for the 20 scenarios in the final column of Table 7.1), and USD_{2010} 1677-2617 per tCO_2 in 2100. We have not been able to retrieve further information on the carbon prices from this study.

Because of this limited information, prices from these two studies are only included in the original unfiltered sample of carbon prices, and will be removed early in the process of assessing prices for CBA.

We also acknowledge that after the main work on this report was completed in 2020, a larger dataset has been compiled in the AR6 Scenario Explorer and Scenarios Database hosted by IIASA (Byers et al., 2022), but it has been out of scope for this report to redo our analysis with the new dataset.

9 Discussion and recommendations on the cost of carbon

9.1 General discussion

Choosing a proper range of carbon prices based on an ensemble of IAM scenarios, with a central estimate, to use in CBA, comes with a range of concerns. In Huppmann, Rogelj, et al. (2018), the authors provide guidelines in a section called "A user's guide to the analysis and interpretation of scenario ensembles". We give a slightly edited version of this section in Table 9.1.

We have done our best to make judgements in the spirit of these guidelines. First, we do not cherry-pick a single scenario and extract one carbon price trajectory for recommendation, 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 has been to exploit and communicate as much information as possible from scenarios that are consistent with the 1.5˚C target (without too much overshoot), but not too reliant on high levels of BECCS. Furthermore, scenarios that to a large degree rely on supportive policies make it difficult to pin down the correct cost of carbon (i.e., the shadow price), and hence will not be directly used. We will comment on these studies below, however, especially European Commission (2018). We have made our judgements with a high degree of humility, as it entails accepting a high degree of uncertainty. In addition, there will also be some biases, since there is underrepresentation of both scenarios and models.

Thus, before making any recommendation on the *cost of carbon*, it is useful to discuss potential biases in the scenarios, both with respect to the sample of scenarios and models used, and with respect to other important issues.

In the next subsection, we discuss the results in the IAMC database (IPCC, 2018), pointing to possible biases. Then, in Section 9.3 we discuss the implications of the studies presented in Section 8 and other relevant issues. In Section 9.4, we present our recommendations.

Table 9.1: A user's guide to the analysis and interpretation of scenario ensembles. From Huppmann, Rogelj, et al. (2018).

The "Do's and don'ts" for analyzing ensembles of opportunity of IAM scenarios: In this context, an 'ensemble of opportunity' refers to a serendipitous collection of scenario data from a variety of sources and studies. We here provide a list of do's and don'ts for analyzing such ensembles, as well as some examples.
1) Don't interpret the scenario ensemble as a statistical sample or in terms of likelihood/agreement in the literature. A number of scenarios show that limiting global warming to 1.5°C can be achieved without deployment of bioenergy with carbon capture and sequestration (BECCS), while the majority of scenarios use it. This information by itself does not imply that reaching ambitious climate goals is less likely without BECCS – instead, it shows that pathways with and without BECCS exist for implementing the Paris agreement, highlighting that different societal preferences and strategies can result in vastly different outcomes.
2) Don't focus only on the medians, but consider the full range over the scenario set. While it is often easier to communicate single numbers rather than ranges, the full breadth of indicators or trajectories within a scenario set carries important information about the available options.
3) Don't cherry-pick individual scenarios to make general conclusions. Select an appropriate subset of scenarios instead, in such a way that differences or alternative developments between scenarios within one category can be highlighted.
4) Don't over-interpret scenario results and do not venture too far from the original research focus. All scenarios in this compilation analyze the emission pathways and the energy system transformation in mitigation pathways; therefore, comparing emissions and similar indicators is a valid meta-analysis. In contrast, most scenario designs implicitly optimize global welfare (e.g., they often look for the least cost solution with respect to mitigation efforts) and are not designed to consider inter-regional fairness or burden-sharing methods. Therefore, regional GDP changes under mitigation policies from these scenarios provide little information about who will ultimately "win or lose from climate action" and is taking the meta-analysis outside of the application domain of these scenarios.
5) Don't conclude that the absence of a particular scenario (necessarily) means that this scenario is not feasible or possible. The solution space in an 'ensemble of opportunity' is not comprehensive. Scenarios might be "missing" because no study asked a research question that would require such a scenario to be developed, or, even more banal, because such a scenario was published in the literature but not included in the ensemble for other reasons. Unavailable scenarios do not preclude them from being possible, unless a study specifically indicates that a particular scenario was attempted but could not be produced by a modelling framework (e.g., limiting radiative forcing in 2100 to 1.9W/m2 under SSP3 socioeconomic assumptions).

9.2 Discussion of IAMC scenarios

As shown in Section 7, there is a wide range of CO_2 price paths that come out of modelling scenarios consistent with the 1.5°C target or net zero CO_2 emissions in 2050. Even when removing scenarios with high overshoot of the 1.5°C target and those with very high levels of BECCS (last column of Table 7.1 in Section 7), the price range is huge (Figure 7.1 in Section 7).

Another important pattern relates to growth rates. As can be seen in Table 5.1 in section 5, there are many model runs that have CO_2 prices close to zero, or have not even started generating prices, in 2020[34]. After that, CO_2 prices increase quickly, with the median

[34] Such a late start implies, all else equal, a less cost-effective attainment of the 1.5C target, as relatively cheap abatement options are postponed, and we are forced to undertake more relatively expensive abatement options later. In the recommendations we derive 2020-prices based on the trajectories between 2030 and 2050.

reaching 141 Euro in 2030, and continuing to grow to 806 Euro in 2050. The 25th percentile price in 2050 is 319 Euro, whereas the 75th percentile is more than six times higher: 2389 Euro. All prices are in 2016-Euros.

As already indicated, there is a bias in the sample of scenarios. Many of the scenarios take as a starting point one of the Shared Socioeconomic Pathways (SSPs) (cf. Section 6). However, whereas most models can find a feasible solution consistent with the 1.5°C target when based on SSP1, SSP2 and SSP4, only a few models are able to do so when based on SSP5, and none when based on SSP3 (cf. Appendix A for details). According to Guivarch and Rogelj (2017), who considered 2C prices, "the carbon prices trajectories are ordered in the following order: SSP4<SSP1<SSP2<SSP5", while again no models were able to solve when using SSP3. Thus, the scenarios consistent with the 1.5°C target will tend to be biased towards optimistic baselines with corresponding lower CO_2 prices (optimistic with respect to ability to meet the target), as pessimistic baselines often do not provide any feasible CO_2 price paths. See also point 5) in Table 9.1, which gives a good description of the many ways scenarios can be "missing".

A similar bias to some degree also relates to the selection of models. The starting sample in Table 7.1 contains only 3 scenarios from GCAM, but 30 scenarios from REMIND. In the final sample (third column of Table 7.1), there are six models behind the 20 scenarios. Some of the models (e.g., REMIND, POLES and AIM) are behind 4-7 scenarios each, while other models (e.g., MESSAGE and WITCH) are behind only one scenario each. One reason may again be that some models are less able to find feasible solutions consistent with the 1.5°C target, unless they either assume an optimistic baseline or incorporate large amounts of BECCS.

The three models with many scenarios are all categorized as either high- or medium-responsive (cf. Table 6.2 in Section 6.2). Much of this responsiveness is about the degree of change in the energy mix in response to a given carbon price (Kriegler et al., 2015). A large degree of change in energy mix allows for a relatively larger reduction in carbon intensity than energy intensity, all else being equal. This would be, all else being equal, a world where it is less costly to achieve the 1.5˚C target. We see from section 6.3 that these highly responsive models tend to have lower cost indexes for PV and wind energy. We also see in 6.4 that they tend to end up with energy mixes that have a higher share of renewables, and altogether higher energy production.

The two models with only one scenario each are categorized as either high- or low-responsive. Thus, as one of the high-responsive models (MESSAGE) is only used in one of the scenarios, the pattern here is not clear-cut.[35] What is more clear is that the large variation in the number of scenarios for each model makes the results sensitive to the features of the models used most frequently. Ideally, some sort of weighing would be in order here, but then one should also weight with respect to the choice of baseline, which seems rather difficult.

[35] One reason why the MESSAGE model is only represented by one scenario in the final sample may be that the model usually includes a large volume of BECCS, and thus those scenarios have been excluded from the final sample (see Table 2 in Section 5).

We removed scenarios with higher overshoot than 0.1˚C. As Table 7.1 in Section 7 shows, the median CO_2 price in 2050 is about half as high when these are included. The differences in other statistics are smaller. We removed scenarios with high overshoot because we believe they violate the given target (they could still be consistent with a target of well below 2˚C though), see Section 2. The decision to remove scenarios with huge amounts of BECCS can obviously be discussed. However, we notice from the tables in section 7 that this choice does not play an important role in changing the median price or the interquartile range. This is a bit surprising, as one would intuitively expect that large amounts of BECCS would make it easier to reach the 1.5˚C target, and thus require lower CO_2 prices. There are two possible explanations for this. One is that scenarios that are infeasible without large amounts of BECCS may become feasible with large amounts of BECCS. Thus, instead of an infinitely high CO_2 price with restriction on BECCS (which is then not included in the sample) one has a feasible scenario in which one obtains a relatively high CO_2 price with large amounts of BECCS. A second possible explanation might be that the assumed unit costs of BECCS in many models are high but rather insensitive to the scale of BECCS, i.e., functioning almost as a backstop technology. However, we do not have enough information to be conclusive about this. In any case, less available abatement technology should, all else being equal, lead us to expect that the shadow price of reaching the climate target will be higher.

To sum up, if scenarios with high overshoot and/or huge amounts of BECCS are deemed unacceptable out of principle, the issue of underrepresentation of models and scenario assumptions in the sample becomes larger. This underrepresentation seems to point to downward bias in the CO_2 prices in the applied sample from the IAMC database, suggesting that the recommended central estimate for the cost of carbon should exceed the median shown in Figure 7.1. However, before making any recommendation we must bring in the other relevant studies as well as some other issues.

9.3 Discussion of other studies and issues

Among the studies presented in Section 8, the French study (Section 8.1) stands out as the most relevant study to derive recommended estimates for the cost of carbon from. Since this is a single study for a single (yet large) European country, we consider this supplemental to the IAMC scenarios discussed above, and the objective here is to consider how it compares with the IAMC results. Up to 2040, the simulated carbon prices in the French study are quite similar to the IAMC results. In 2030 and 2040, the median price in the French study is 7% and 15% lower than in the selected IAMC scenarios. The range is also fairly similar, although it is somewhat difficult to compare since the number of scenarios is much smaller in the French study. After 2040, the simulated carbon prices in the French study are much higher than the IAMC prices. However, as explained in Section 8.1, the authors of the French study argue that their simulated prices post-2040 are likely to be too high. Instead they propose carbon prices that increase with the social discount rate after 2040, leading to a proposed carbon price in 2050 which is also close to the median carbon price in 2050 in the selected IAMC scenarios (4% lower). One important difference between the French study and the IAMC scenarios is that the former considers a target of net zero GHG emissions in 2050 (in France), while the latter consider net zero CO_2 emissions around 2050 (globally) which is a less strict target as explained above (see discussion below).

The studies by the European Commission (Section 8.2) and the IEA (Section 8.3) are extensive and impressive studies of scenarios consistent with net zero emissions by 2050 and/or temperature increases below 2˚C. However, as explained in Section 8, CO_2 pricing is not the only policy used to reach the target. For instance, in the most ambitious scenario (Category 3) in (European Commission, 2018), the "CO_2 standards for new cars, vans and buses are assumed to be zero starting from 2040" (p. 325). With such strict standards, CO_2 prices are in fact superfluous for these emission sources – emissions will be zero anyway given the standards. However, this does not imply that the cost of carbon for these emission sources is zero – strict standards also come with a cost. Hence, even though carbon pricing seems to be the most important policy instrument in the scenarios presented in European Commission (2018),[36] they will likely underestimate the cost of carbon in the EU, and it is difficult to know by how much. In other words, the CO_2 prices in European Commission (2018) and IEA (2019) do not inform us properly about the cost of carbon. We refer to our discussion in Section 2 for more details.[37] The CO_2 price in 2050 in the Category 3 scenario in European Commission (2018) is 350 EUR/tCO_2, which is 57% lower than the median in the IAMC scenarios (final column of Table 7.1).

The other studies briefly presented in Section 8 contain too little information to really be useful for this report, in particular as they have only published carbon price results for a few years, and not for the entire time period of interest. However, for the years with reported carbon prices, we notice that these prices all lie within the interquartile range of prices from the 20 chosen scenarios from the IAMC database, with some prices above the median and some below.

When it comes to other relevant issues, a potential bias is related to the choice of target. As mentioned above, the IAMC scenarios focus on the 1.5˚C target, and find that this is consistent with net zero CO_2 emissions globally around 2050. Net zero GHG emissions do not take place until around 2070 in these scenarios. The IAMC scenarios indicate that climate neutrality (i.e., net zero GHG emissions) in 2050 seems to be a slightly stricter target than carbon neutrality in 2050 and the 1.5˚C target. The French study considers the former target, i.e., net zero GHG emissions by 2050, which is the official EU target. Further, although global CO_2 emissions are net zero in 2050 in the IAMC scenarios, net CO_2 emissions in OECD are still slightly positive and become zero a few years later. To sum up, this may indicate that there is a slight downward bias in the IAMC scenarios when it comes to the cost of carbon if the target is net zero GHG emissions in 2050.

There is also a question about how risk averse one should be. While we should not interpret the scenario ensemble as a statistical sample, the large spread shows that decision-makers need to navigate through this uncertainty. From a risk neutral position, one would probably prefer a CO_2 price path that seems likely to reach the target in half of the studied scenarios, i.e., the median price path (when disregarding any biases). With a more risk averse position,

[36] The report, which is otherwise very detailed, only displays CO2 prices in 2030 and 2050 though.

[37] When it comes to technology policies, which we discuss specifically in Section 2, most of the model scenarios presented in this report do not incorporate such policies explicitly. Several models incorporate learning-by-doing though, cf. Section 4. The WITCH model also accounts for positive externalities from learning-by-researching. In general, it is difficult to assess to what degree cost reductions in the model scenarios depend on green technology policies.

one could argue that the CO_2 path should be higher, to reduce the risk of not reaching the target. Note, however, that the scenarios already to some degree take risk into account, as it is usually assumed either 50% or 66% likelihood of reaching the temperature target.

By construction, the CO_2 prices in the model scenarios are mostly assumed to be equal across regions. As explained in Section 2, there are some good reasons for this in the analysis, both with respect to simplicity and because a uniform CO_2 price across the world typically reaches the 1.5˚C target cost-effectively. However, from a normative point of view, one could argue that a uniform CO_2 price implies that a too large share of global abatement takes place in poor countries, and a too small share in rich countries. In principle, this could be taken care of by supplementing the policy with huge transfers from rich to poor countries, or by a global emissions trading system ala Kyoto where developing countries are given a large share of emission quotas. The question is, however, whether this is feasible. The Kyoto protocol turned out to be not very successful, and only limited to developed countries. Extending such a framework to the whole world (with large number of quotas to developed countries) seems infeasible in the short run. Thus, Stiglitz et al. (2017) argue that developing countries should have lower CO_2 prices than developed countries, writing (p. 18):

"In a simple theoretical setting, assuming the possibility of unlimited and lump sum international transfers … and in the absence of other relevant market failures, it is possible to separate the question of where emission reductions should take place and who should pay for them, and therefore to separate global efficiency from distributional considerations. … In a more realistic setting, such unlimited lump sum transfers are impossible and, as a result, efficiency and equity cannot be separated, nor can distributional and ethical considerations as well as other market failures be ignored when deciding where emission reductions should be implemented first. In such a situation … it is optimal for carbon prices to differ across countries."

IEA (2019) applies differentiated CO_2 prices in their scenario, writing (p. 125):

"Achieving a 1.5 °C stabilisation would imply that advanced economies reach net-zero energy-related CO_2 emissions around 2045 and developing economies around 2050."

Following the reasoning by Stiglitz et al. (2017), one could thus argue that the cost of carbon in Europe should be higher than what comes out of the model scenarios.[38] However, this also depends on whether the main objective for European countries is to reach the global 1.5˚C target, or simply to reach net zero emissions domestically by 2050. In the latter case, the arguments for differentiated CO_2 prices across the world is not really relevant, while in the former case it is. Then it could be argued that Europe should reach net zero emissions *before* 2050, enabling poorer countries to reach net zero emissions slightly after 2050 (and hence requiring higher cost of carbon within Europe than in poorer countries).

All scenarios considered assume that sufficiently high CO_2 prices are incorporated from the start, and that they are economy-wide. If several years pass without sufficiently strong climate policies, it is evident that it becomes more and more difficult to reach the 1.5˚C target (or net zero emissions in 2050). Hence, the cost of carbon will then increase

[38] One could argue that even within Europe there are large income differences among countries, which might call for differentiated carbon prices also within Europe.

compared to the price levels shown above. More and more 1.5˚C scenarios will become infeasible.

In any case, as time goes by, one will learn more also about the baseline scenario, both with respect to economy-wide trends and in particular with respect to the costs and potential for abatement measures. Hence, the CO_2 prices shown in the previous section will likely have to be updated regularly.

To sum up this subsection, taking the results from the IAMC as a starting point, different factors seem to go in different directions. The other available studies tend to find carbon prices around or just below the median in the selected IAMC scenarios. Other issues, however, may suggest that the IAMC scenarios underestimate the cost of carbon in Europe.

9.4 Recommendation

Our report has shown that the range of carbon prices consistent with the 1.5˚C target (or net zero emissions in 2050) is wide. We have attempted to shed some light on *why* the range is so wide, and also pointed to various biases in the sample. Furthermore, we cannot say with any certainty that any model or any scenario we have added to our sample is better than another, and so we are not able to cherry-pick any scenarios or models. We have, however, argued that some scenarios are less relevant due to either too high overshoot of the temperature target, too much use of BECCS, or too many other supportive policies that mask the cost of carbon in their scenarios.

Consequently, it is difficult to present a clear recommendation for the cost of carbon in Europe. 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 IAMC scenarios, see third column of Table 7.1), and partly because of the issues raised in the two previous subsections.

Besides the IAMC scenarios, few other relevant scenarios exist, and hence we take the results from the IAMC scenarios as our starting point and consider whether to deviate from those results. The discussion in Section 9.2 suggested that there is a downward bias in the IAMC results. The discussion in Section 9.3 suggested that other studies and other issues could imply either lower or higher estimates. Summing up all the discussed issues, the overall bias seems to go in the direction of underestimating the cost of carbon for Europe. As mentioned in Section 9.2, there are scenarios that are "missing" since the models found them infeasible. Also, there is overrepresentation of models where the economy is highly responsive to carbon prices relative to models that are less responsive. The target considered in the IAMC scenarios may also be less strict than the net zero GHG target. Furthermore, the need for regional variation in CO_2 prices and to account for risk aversion may also go in the direction of underestimating the cost of carbon. On the other hand, other studies (in particular the French study) find carbon prices quite similar to the ones in the IAMC scenarios.

Based on this assessment we propose 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 7.1 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. These are shown in Table 9.2 and Figure 9.*1*. Detailed numbers are found in Appendix C. 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 9.*1*, the median price trajectory (dashed line) is quite bumpy. 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.[39] We also create a similar smooth carbon price trajectory for the range, using their respective estimates for 2025 and 2050 as anchor points.

Option 2: Upwards adjustment

Our assessment above suggests that the price range in the final sample of the IAMC scenarios is a slight underestimate for the recommended cost of carbon for CBA in Europe (even if we disregard 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 propose to 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. We therefore also smooth the price trajectory in Option 2, using prices in 2025 and 2050 as anchors (the 55th percentiles) and apply the same annual growth rate in the years between. This growth rate of 7.5% is also applied for the period 2020-2025. As we adjust the recommended central estimate, we also adjust the recommended price range for sensitivity analysis, using the 30th and 80th percentile. We also create a smooth carbon price trajectory for this range, using their respective estimates for 2025 and 2050 as anchor points, and the growth rate between the anchor points for the entire period 2020-2050. The results are shown in Table 9.2 and Figure 9.*2*.

In the figure, we also display the 55th percentile curve from the selected IAMC scenarios with a dashed line. By construction, this will be identical to the central curve in 2025 and 2050, but may deviate in other years. We notice that this 55th percentile curve mostly lies above the central curve, especially in 2035.[40]

Table 9.2: Recommended carbon price range (EUR_{2016}/tCO_2e) for the period 2020-2050.

	2020	2025	2030	2035	2040	2045	2050
Option 1							
Low	42	59	83	116	163	228	319
Central	99	141	199	283	401	568	806
High	186	253	344	467	635	864	1174
Option 2							
Low	116	140	170	206	250	302	366
Central	155	212	289	396	542	741	1014
High	343	433	548	692	875	1106	1398

[39] By anchoring in 2025 instead of 2020, we avoid relying on 2020-prices from the models that are off to a late start (cf. Section 5).

[40] In Appendix D we provide some background information on the model scenarios that lie behind the 55th percentile of the scenario sample.

Should Option 1 or Option 2 be used? Our assessment above may suggest that Option 1 is underestimating the cost of carbon in European countries, which is an argument for recommending Option 2. On the other hand, an argument against Option 2 is that the upward adjustment is somewhat arbitrary (although rather cautious).

Taking into account the two normative issues as well, the cost of carbon in Europe could 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.

We further recommend that the applied carbon prices are to be updated each time there is a major collection of IAM scenarios, likely around major reports from IPCC[41]. This is a strategy to reduce some areas of uncertainty, where possible, by incorporating new and improved estimates and larger samples of scenarios, as they become available. In addition, historic evidence will gradually replace assumptions about the years to come.

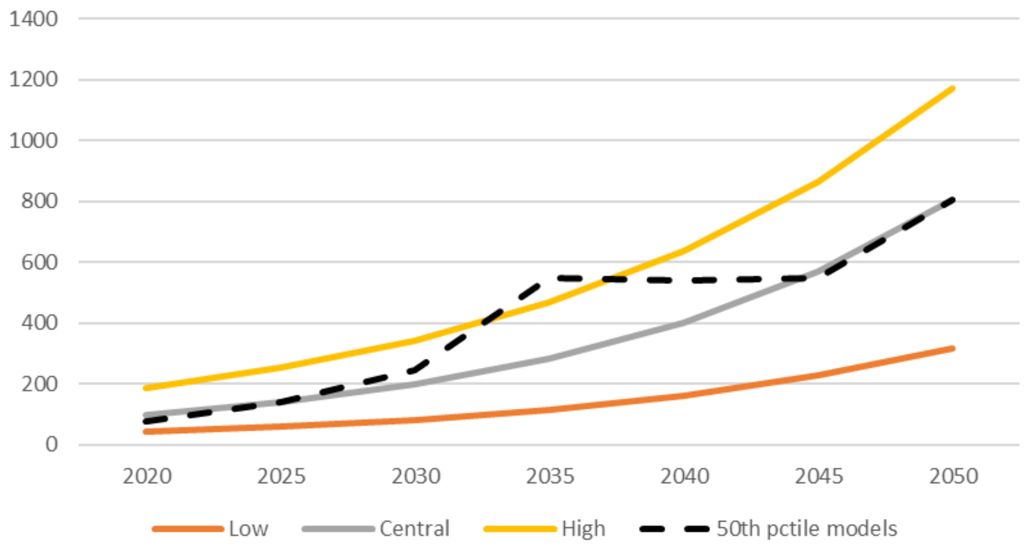

Figure 9.1: Recommended carbon price range (EUR2016/tCO_2e) for the period 2020-2050 – Option 1. The low, central and high price trajectories apply respectively 25th percentile, median, and 75th percentile from the IAMC database scenarios from 2020 to 2050. The years 2025 and 2050 are used as anchor points to create a smooth trajectory with a constant growth rate throughout the period. The dashed line represents the 50th percentile of the model estimates for all 5-year leaps of the period, which contrasts with the smooth central carbon price trajectory.

[41] For example, once the the report *Mitigation of Climate Change* (IPCC, 2022) from the IPCC's Sixth Assessment Report has finished its final revisions, the AR6 Scenario Explorer and Scenarios Database hosted by IIASA could provide an updated basis for a recommended carbon price path.

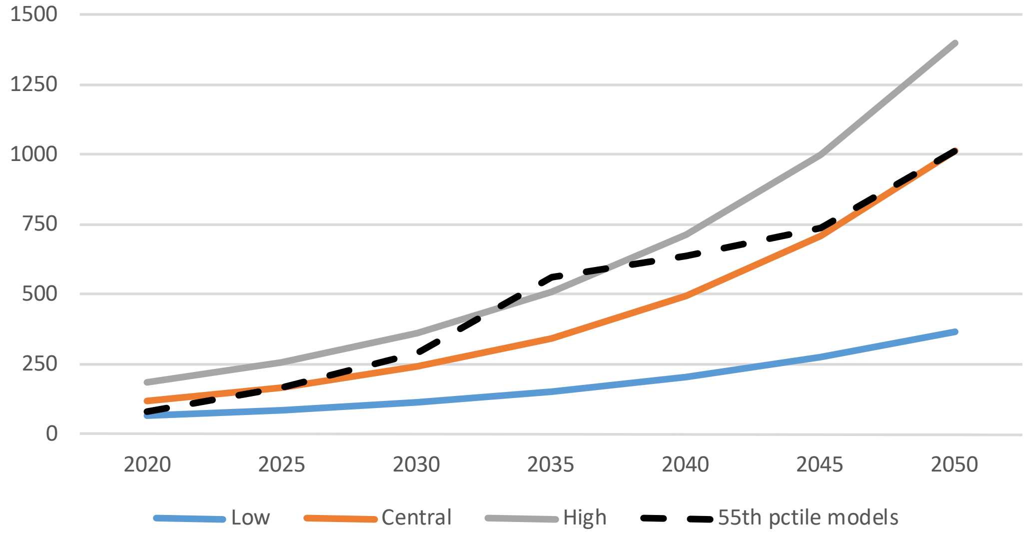

Figure 9.2: Recommended carbon price range (EUR2016/tCO_2e) for the period 2020-2050 – Option 2. The low, central and high price trajectories apply model estimates for 2025 and 2050, and smooth out the trajectory with a constant growth rate in between and before 2025. The dashed line represents the 55th percentile of the model estimates, which contrasts with the smooth central carbon price trajectory.

10 How to include carbon values in cost-benefit analysis (CBA) – general guidance

10.1 Principles

Since GHG emissions lead to higher concentration of GHGs in the atmosphere, which in turn is expected to lead to damaging climate change, it is reasonable to include a valuation of changes in carbon emissions in CBA. As the decision maker should be concerned with the damages of climate change, one could argue that some measure of the damage costs as the per-ton valuation of GHG emission changes should be applied, as it aligns with the theoretical heritage of CBA (O'Mahony, 2018). However, there are numerous aspects like uncertainty and ethical considerations, as touched upon in Section 2, that make the damage cost approach less attractive for use in CBA. Furthermore, the EU governments have pledged commitment to the Paris agreement and its target of limiting global warming to well below 2 degrees and pursue efforts to keep it to 1.5 degrees (1.5˚C), and also to reach net zero GHG emissions by 2050. As discussed above, this makes the use of a shadow price consistent with the climate target most appropriate for CBA. This approach is echoed in numerous studies, such as Meunier and Quinet (2015) and the Norwegian Expert Commission Cost-Benefit Analysis (Hagen et al., 2012).

10.1.1 Accounting principles

In the absence of carbon taxes and permits, it would be straightforward to apply the shadow price of carbon to emissions changes in the CBA. When such policies exist, the analysis will require some more accounting. In our view, the best way to combine good accounting and good analysis is to apply what Minken and Samstad (2005) calls the "the inclusive principle" or what Sugden (1999), as referred to in Department for Transport (2018), calls the "Willingness to Pay Calculus". In the latter report they describe this as a way to arrive at a money measure of the net welfare change for each individual that is brought about by the project under consideration, and then to sum these. When the cost-benefit accounts are presented in this way, there often are items which appear as benefits for one person and equally-valued costs for someone else: such items are transfer payments. Items which do not cancel out in this way are social costs or benefits (sometimes called resource or real resource costs or benefits). The word "social" is used to signify that these are costs or benefits which fall on "society as a whole", meaning the aggregate of all individuals.

It is possible to arrive at the exact same result for "net social benefit" by distinguishing between social costs/benefits and transfer payments from the outset, but only account for the former. One could argue that since transfers between agents cancel out, they are not necessary to include in the later stages of analysis. With regards to this report, it would be the equivalent of ignoring the carbon tax in the sector where the analysis is taking place, as it is only a transfer between users and the government. Some even take the view that it is only the difference between the cost of carbon applied for CBA and the tax that matters, e.g., if the cost of carbon is deemed to be €150 per ton, but the carbon tax is €100 per ton, then only €50 per ton should count as social cost. And if the cost of carbon is completely matched by the carbon tax, i.e. complete internalization, it cancels out, and the complete user cost including taxes is considered social cost. Such a logic has been recommended in Ministry of Finance (2005), and applied in papers like Börjesson, Fung, and Proost (2017). In our view, such a method may blur the analysis of transfers and distributional concerns, cost of public funds, sensitivity analysis and cases with multiple externalities and taxes.

We believe that using the "inclusive principle" in CBA accounting is good practice, and it is particularly useful when doing CBAs on projects that may induce changes in GHG emissions in a sector with carbon permits and/or taxes.

10.2 How to account for the GHGs emitted

A key question, as posed in NOU 2012:16 (2012), is whether the project subject to CBA leads to:

1. An increase in the total volume of GHG emissions globally, and there is no institution that demands those emissions to be cut elsewhere.
2. An increase in GHG emissions that is covered by a binding emissions trading system (ETS).
3. An increase in GHG emissions that is not covered by a binding ETS, but is still covered by a pledged, binding emission target, and therefore needs to be reduced elsewhere at some point.

In the first case, the relevant carbon price is the social cost of carbon, that is, the damage costs of an additional unit of GHG emissions. For a country that has pledged itself to a binding emissions target, this becomes less relevant.

In the second case, the net emissions from the project would be zero (as long as the emissions cap is fixed and binding), but the cost of emission quotas need to be included in the calculation of costs and benefits. The expected market value of emission quotas should be consistent with the future equilibrium situation that is evaluated in the CBA, both in the reference scenario and the project scenarios (whether emissions are regulated by a tax or an ETS with exogenous or endogenous emissions cap).

In the third case, the effect the project has on emissions should be evaluated according to the shadow price of the stated goal, the 1.5˚C target/net-zero goal. This holds whether or not the increased emissions are regulated by a tax on emissions. The underlying reasoning here is that when some emissions increase, other emissions will have to come down to still reach the pledged emissions target. The costs of making these additional emissions reductions are then the real costs of the increased emissions.

In our context, the first case does not seem as relevant as the other two cases, as most European countries have a stated emissions goal (and since nearly all countries in the world have signed the Paris agreement with a stated temperature goal). Thus, it seems reasonable that the carbon values should take this emissions goal into account. Hence, in the following we will assume this to be the case. When we refer to the *cost of carbon*, we thus mean the shadow price of the given emissions constraint, *not* the social cost of carbon (cf. also the discussion above).

As pointed out in the subsection above, the "inclusive principle" is particularly useful when doing CBAs on projects that may induce changes in GHG emissions in sectors with carbon permits and taxes, as it enables clear accounting of transfers and social costs and benefits.

Below we show an example of a project leading to higher emissions of say 10 units, and distinguish between a case where the increased emissions are regulated by either a CO_2 tax or an ETS. We assume here that the CO_2 tax and the ETS price are the same (10 per unit emissions), but that they are lower than the cost of carbon, which is set to 15 per unit emissions (i.e., the shadow price, not the social cost of carbon). We also assume a marginal cost of public funds (MFC) of 20%, i.e. that any change in government revenue will be matched by a change in distortionary taxation, which imposes a change in the deadweight loss the taxation has on society (e.g., the labor market). Many guidelines recommend using an MFC for CBA, e.g., Norway (Norwegian Agency for Public and Financial Management, 2018), Denmark (Transportministeriet, 2015) and Sweden (Trafikverket, 2020). The value in this example corresponds to the value applied in Norwegian CBA.

10.2.1 Accounting with carbon taxes

In Table 10.1 we show the example in the carbon tax case:

Table 10.1: CBA accounting using the "inclusive principle" of an example project in a setting where users are subject to a carbon tax.

	Project users	Government	Other agents in society	Total
Δ Project costs		-700		-700
Δ Gross user benefits	+2000			+2000
Δ User cost ex tax and permits	-1000			-1000
Δ Cost of CO_2 permits (transfer)	N/A			N/A
Δ Cost of abatement in other ETS firms	N/A			N/A
Δ CO_2 taxes paid by users (transfer)	-100	+100		0
Δ Cost of project carbon emissions			-150	-150
Δ Cost of funds			-120	-120
Δ SUM	+900	-600	-270	+30

Notice in the final column that the project brings about costs in the form of project costs, user costs, carbon costs (emissions valued at their shadow price) and the cost of public funds. These costs are weighed against the gross user benefits. In this generic example we have a project that under the current tax regime would bring about a positive social net present value (NPV), as can be seen in the final column, last row. In the last row we also see how costs and benefits are distributed between different groups. In this example we have that project users benefit from the project, while the government (i.e. taxpayers) and "Other parts of society" face a net cost (here in the form of emission costs and the deadweight loss from public funds).

An important point is that the row "Δ CO_2 taxes paid by users" sums up to zero, because it is a transfer between users and the government. It would still have sum up to zero even if the taxes where set optimally, equal to the shadow price of carbon.

If we consider the same project in a different world where carbon taxes are set equal to the shadow price of carbon, the equilibrium would likely be different. This changes both the base scenario and the project scenario in the CBA. It may be that the sector where the project is considered, will be less socially profitable to invest in under optimal carbon pricing. It will depend on how responsive the sector is to the carbon tax. Let us return to our simple example, where the project finds itself in a world where carbon taxes are set equal to 15 (i.e., the recommended shadow price) instead of 10. Under this stricter emissions regime, let us assume that the increase in emissions will be 10% lower, i.e., the emissions increase as a result of the project changes from 10 to 9 units. Compared to the emissions regime in the previous example, this will likely increase the user costs and/or reduce the user benefits. In this example we simply assume that user costs are increased (while benefits stay unchanged). The adjusted example is shown in Table 10.2.

Table 10.2: CBA accounting using the "inclusive principle" of an example project in a setting where users are subject to a carbon tax, with the tax exogenously set at Pigovian level

	Project user	Government	Other agents in society	Total
Δ Project costs		-700		-700
Δ Gross user benefits	+2000			+2000
Δ User cost ex tax and permits	-1010			-1010
Δ Cost of CO_2 permits (transfer)	N/A			N/A
Δ Cost of abatement in other ETS firms	N/A			N/A
Δ CO_2 taxes paid by users (transfer)	-135	+135		0
Δ Cost of project carbon emissions			-135	-135
Δ Cost of funds			-113	-113
Δ SUM	+855	-565	-248	+42

10.2.2 Accounting with a binding emissions trading system

In Table 10.3 we show the same example, except that the tax is replaced by a fixed, binding emissions trading system (ETS).

Table 10.3: CBA accounting using the "inclusive principle" of an example project in a setting where users are subject to a fixed, binding emission trading scheme

	User benefits	Government	Other agents in society	Total
Δ Project costs		-700		-700
Δ Gross user benefits	+2000			+2000
Δ User cost ex tax and permits	-1000			-1000
Δ Cost of CO_2 permits (transfer)	-100		+100	0
Δ Cost of abatement in other ETS firms			-100	-100
Δ CO_2 taxes paid by users (transfer)	N/A	N/A		N/A
Δ Cost of project carbon emissions			0	0
Δ Cost of funds			-140	-140
Δ SUM	+900	-700	-140	+60

It is well-known from basic environmental economics that an emissions tax and an ETS can give exactly the same outcome, if the tax is set equal to the ETS price that follows from a certain emissions quota (or if the quota is set equal to the emissions level that follows from a certain tax level). However, if there is a change in the demand for emissions, e.g., due to a new project, the outcome will differ between a tax and an ETS. In the latter case, total emissions are unchanged, while in the former case emissions will increase or decrease.

Thus, the calculus is different under a an ETS regime than under a carbon tax regime. Since the ETS is assumed to be binding (and we assume no carbon leakage), the emissions from the project will be netted out. This is often referred to as the waterbed effect (e.g., Perino (2018)). Hence, net carbon emissions, and therefore net carbon costs, will be zero – there is no need to reduce emissions elsewhere in the economy (outside the ETS) to be in compliance with the overall emissions target. This can be seen in the row "Δ Cost of project carbon emissions". This also means that it doesn't matter here whether permits are auctioned or given out for free, as the project doesn't affect the number of permits issued.

The permit price is a transfer from the user of the project to some other firm in the ETS that sells it on the market and undertakes costly abatement efforts itself. The cost of this firms' abatement equals the cost of the sold permits. Hence, the permit price reflects the shadow price of carbon in the sector where the project is taking place. Whether the permit system has optimal coverage (i.e. it covers all emission sources) and reflects the shadow price of the economy or not, is exogenous to the project and the analyst. What really matters to the project calculus in this example, is whether the emission cap is binding. If so, the project value is unaffected by the fact that emissions in the economy as a whole is inefficiently regulated. This brings us to the next version of the example.

10.2.3 Accounting with an emission trading system with an endogenous cap

Here is again the same example as in Table 10.4, but now the emissions cap is endogenous, assuming here that the cap increase amounts to 50% of the direct increase in emissions. The increase in the cap is assumed to be sold off by the government at the ongoing permit price to some other firm in the ETS, which then again relieves them of abatement effort.

Table 10.4: CBA accounting using the "inclusive principle" of an example project in a setting where users are subject to an emission trading scheme where the CO_2 cap is endogenous

	User benefits	Government	Other agents in society	Total
Δ Project costs		-700		-700
Δ Gross user benefits	+2000			+2000
Δ User cost ex tax and permits	-1000			-1000
Δ Cost of CO_2 permits (transfer)	-100	+50	+50 (100-50)	0
Δ Cost of abatement in other ETS firms			-50 (50-100)	-50
Δ CO_2 taxes paid by users (transfer)	N/A	N/A		N/A
Δ Cost of project carbon emissions			-75	-75
Δ Cost of funds			-130	-130
Δ SUM	+900	-650	-205	+45

The key change in this version of the example compared to the previous, is that the project actually induces a net increase in emissions, in spite of being a part of an ETS. This is because of the endogenous emission cap. The net increase in emissions is valued at the recommended shadow price of carbon (as in the tax case, except that here emissions increase by 5 instead of 10 units). The purchase of permits still reflects the replacement of activity elsewhere in the part of the economy that is covered by the ETS.

Notice that the rows "Δ Cost of CO_2 permits" and "Δ CO_2 taxes paid by users" always sum up to zero, as they are transfers between different agents. When considering the actual net cost of emissions in the CBA, the rows "Δ Cost of abatement in other ETS firms" and "Δ Cost of project carbon emissions" are the most important (when disregarding cost of funds). We notice that in the tax case, the cost is higher than in the binding ETS case for the same project emissions, as these are valued at the recommended shadow price. In the ETS case the cost is lower, as abatement efforts to make sure that net induced emissions equal zero are reflected in the permit price.

In the ETS case with the endogenous cap, there will be abatement efforts by some other firm in the ETS, valued at the permit price, and also a net increase in emissions due to the endogenous increase in the cap, valued at the recommended shadow price. Then there is also reduced abatement costs as the cap is increased. Hence, this case can be considered as a weighted combination of the tax and ETS cases, where the weights depend on how much the cap adjusts to changes in project emissions. In the extreme case where the cap adjusts 100% to changes in project emissions, we are basically in the tax case.

The implications for CBA of an endogenous ETS cap have been studied by Johansson (2020) and Jorge-Calderón (2021). Johansson (2020) provides a formal analysis of the case where a reduction in emissions within the ETS leads to a future reduction in permits (a punctured waterbed, cf. Perino (2018)). This net reduction in emissions should be valued by households' willingness to pay (WTP) for emission reductions and the effect on profits – minus the permit price, as the permit price reflects the value of displaced production. He argues that households' WTP for emission reduction and changes in aggregate profits through climate related productivity effects is the theoretically correct way of valuing the change in net emissions. In our context, we argue that since reaching 1.5˚C and net zero GHG emissions by 2050 is the overarching goal, the net emissions should be valued at the shadow price of reaching this goal. From an efficiency standpoint, the ETS will ideally over time gain full coverage over all emission sources and coincide with cost-effective attainment of the stated climate target.

10.2.4 Exogenous (often sub-optimal) policies

One has to acknowledge that there easily could be a discrepancy between the carbon price necessary to reach the stated emissions target (e.g., 1.5˚C and net zero GHG emissions), and the carbon prices and coverage that is in place (e.g., in Europe). In most scenarios simulating the 1.5˚C target (or net zero emissions by 2050), it is assumed that all emissions sources face the same emissions price, which is then the shadow price of the emissions target, in other words the *cost of carbon*. Implementing such a carbon price would be the most cost-effective regulation of emissions in the economy (disregarding here other potential market failures). If the implemented carbon prices differ from the cost of carbon (e.g., supported by other policies), the analyst still has to value net changes in emissions according to the recommended carbon price, while at the same time take into account that the equilibrium in the economy is affected by the policies put in place (which may then be sub-optimal). For near-term emissions, current and stated policies are then the most natural to consider. For emissions longer into the future, an alternative may be to consider policies implemented in the study by the European Commission (2018), where they use, among others, the PRIMES model to analyze net zero emissions by 2050. If not specified otherwise, these policies would have to be considered exogenous.

This is a crucial and somewhat difficult issue, which requires more discussion. There are many ways to regulate emissions. Here it is useful to distinguish between a situation with differentiated CO_2 prices between emission sources, and a situation where the CO_2 price is supported by other climate policies.

We first consider differentiated CO_2 prices (and no supportive policies), e.g., between sectors regulated by the ETS and other sectors. In order to reach the target, some prices must then exceed the initial cost of carbon (i.e., the cost of carbon with uniform prices but the same target), while other prices must be lower. The target could be reached, but it would not be at least cost in the economy as a whole. If all CO_2 prices are below the cost of carbon (as in the examples above), the target would not be reached.

Assume e.g. that the ETS price is below, while the tax is above the initial cost of carbon. Everything else being equal, this is obviously inefficient for the economy as a whole, since this leads to unequal marginal abatement costs (MACs) across sectors, which drives up total costs for a given level of abatement. If we in the CBA then apply *actual* MACs instead of the recommended shadow price, the project-induced emissions in the tax case (Table 10.1) will be valued higher than the recommended shadow price of carbon, while in the ETS case it will be lower (and vice versa if the ETS-price is higher than the tax). If the tax is differentiated across non-ETS sectors, the "Δ Cost of project carbon emissions" may no longer be equal to the tax in the affected sector though, as the relevant cost of carbon will depend on where additional emission reductions take place. A natural assumption might be that all tax levels are increased proportionally, in which case the average CO_2 tax would be the appropriate choice for the MAC that determines the cost of carbon. In the long run, however, one might assume that European countries will aim to harmonize CO_2 prices across emission sources, in which case MACs would be the same irrespective of where emissions take place.

Next, we consider implications of supportive policies, and first assume that it is combined with CO_2 taxation, not ETS. Assume that CO_2 taxes are harmonized across emission sources, but supportive policies are used which lead to lower CO_2 taxes than otherwise. As explained in Task 1, even though the CO_2 tax is reduced, the shadow price of the emission constraint is probably not. It is more likely that the overall costs, and possibly also the marginal costs, increase.[42] To ease the discussion below, we consider a specific sector, that is, emissions from road transport. Here CO_2 emissions standards are typically used for vehicles. Strict emissions standards imply that a certain emissions target can be reached at a lower CO_2 tax on fuel. The standard itself, however, comes with a cost, as it increases the costs of constructing the vehicles for a given quality (or possibly higher costs of clean fuels, such as

[42] There are exceptions though, such as if other policies are introduced to correct for other market failures, such as green innovation externalities.

hydrogen). Assume now that a large project leads to higher emissions, implying that further efforts are needed to reduce road transport emissions. If the government is committed to its emissions target, a natural assumption might then be that both the standard and the CO_2 tax will become stricter. The marginal abatement costs (additional costs divided by additional emissions reductions) are then likely bigger than the CO_2 tax, as the costs of stricter standards are hidden when only looking at the CO_2 tax. Although this is a specific example, it illustrates that the appropriate cost of carbon to use in a situation where supportive policies supplement CO_2 taxation will be higher than the CO_2 tax itself.

If supportive policies complement an ETS, however, things are different if both the emissions cap and supportive policies remain fixed. In that case, we are back to the situation in Table 10.3 above, where net change in emissions would be zero. The question is, however, whether it is realistic to assume that both the cap and supportive policies remain fixed. This is especially the case if supportive policies are implemented in order to keep the ETS price at “acceptable” levels. If higher emissions lead to a relaxation of the cap (to avoid an increase in the ETS price), emissions in other sectors would have to come down, in which case we are back to the situation in the previous paragraph. If higher emissions instead lead to more supportive policies (again to avoid higher ETS price), these supportive policies are likely to be more costly than reflected by the ETS price (as explained above). One example here is a mandated share of renewable power, which typically reduces the ETS price. Strengthening the mandate to avoid an increase in the ETS price will likely be quite costly, and the implicit cost of the additional emissions from a project will most likely exceed the ETS price.[43] Hence, in any case the net change in emissions induced by the project should be valued (at least) at the recommended shadow price of carbon unless both the cap and supportive policies remain unchanged.

In the later discussion, we return to these issues and which of the alternatives considered seem most realistic.

[43] For instance, if the RES target is set very high, leading to a low ETS price, increasing the RES target even more to keep the ETS price down would presumably be very costly, and the implicit cost of additional emissions from a project be much higher than the ETS price.

11 Carbon pricing in CBA under current guidelines

In this section we give an overview over current guidelines in different countries and institutions for how to include carbon values in cost-benefit analysis. Most of the guidelines are focused on the transport sector. We briefly document the practice described in these guidelines, and outline the most important underlying principles. We limit ourselves to review only a handful of guidelines (where the authors master the language). We review guidelines from the following countries/institutions:

- UK
- Ireland
- New Zealand
- Sweden
- Norway
- Denmark
- European Investment Bank (EIB)

11.1 UK

In the elaborate guideline framework of Transport Analysis Guidance (TAG), the guidelines for the role of GHG emissions in CBA are given in the TAG UNIT A3 -Environmental Impact Appraisal (Department for Transport, 2022). Summarized, the guidelines state that the analyst is to estimate the impacts that the scheme has on energy consumption and on GHG emissions, and these impacts are to be monetized. The valuation of emissions are based on the estimated abatement cost per ton CO2e needed to achieve the government's emission target (i.e. the shadow price).

The guidelines separate between emission impact in the traded sector (UK ETS) and the non-traded sector. In the non-traded sector, emissions are valued at the estimated marginal abatement costs consistent with the Government's commitments on greenhouse gas emissions. Higher and lower estimated values are provided for sensitivity analysis. Estimated carbon prices up to the year 2100 to for the non-traded sector are provided in Excel workbooks. In the latest update by the Department for Business (2021), they base their carbon price trajectory on the IPCC scenarios consistent with 1.5°C with low overshoot, with 2040 as an anchor point. The price is extrapolated forwards and backwards in time with a real growth rate of 1,5%. Compared to most of the IPCC scenarios, the UK carbon price trajectory starts a lot higher and grows a lot slower. The guidelines assess this to be appropriate with regards to domestic emissions reduction targets, and consistent with the desire to stimulate early action in the clean technology space. The current recommended parameters for analysis are £$_{2020}$248 per tCO_2e in 2022, which grows to £$_{2020}$378 per tCO_2e in 2050. This is the central estimate.

If the scheme affects changes in emissions in the traded sector, for example electricity, these emissions should still be considered and valued during appraisal. This is because even though the UK ETS is an important means to achieve the emissions reduction targets, it is expected that even the covered sectors would need additional measures to reach net-zero, which will be costly. However, the guidelines also state that *appropriate adjustments should be made to account for any existing carbon pricing in the market prices of goods or services*.

11.2 Ireland

According to Department of Transport (2021), the analyst is to use the shadow price of carbon that reflects the government's emission targets, with regards to emissions in the non-ETS sector. The guidelines provide shadow prices for CO_2 from 2019 to 2050, based on modelling done for the National Mitigation Plan (Curtin, Bruin, Hanley, & Gallachóir, 2017). In this carbon price trajectory the price per tCO_2e is $€_{2014}46$ in 2022, and grows to is $€_{2014}265$ in 2050.

Any effect a project may have on CO_2e emissions from organizations/facilities/ installations operating within the EU ETS are not to be included in the quantification of emissions for a project scenario, as this would be considered double counting.

11.3 New Zealand

In the latest guidelines for CBA in the transport sector in New Zealand (Waka Kotahi NZ Transport Agency, 2021b), CO_2 emission valuation for CBAs is based on the estimates from the High-Level Commission on Carbon Prices (Stiglitz et al., 2017), after an assessment documented in waka Kotahi NZ Transport Agency (2021a). The guidelines refer to this as target-consistent shadow price paths for GHG emissions. They provide both low and high price paths. The low path has a price of $NZD_{2020}63$ in 2022 and grows to $NZD_{2020}116$ in 2050. The high path has a price of $NZD_{2020}122$ in 2022 and grows to $NZD_{2020}232$ in 2050.

11.4 Sweden

According to the current guidelines for CBA in the Swedish transport sector Trafikverket (2021), all CO_2 emissions in the domestic transport sector (excluding aviation) are to be valued according to the estimated carbon price that reflect the shadow price of the politically set emissions target. This shadow price is assumed to be reflected by the penalty fee if sellers of gasoline and diesel fail to fulfil the annual reduction quota for emissions from gasoline and diesel fuels in the transport sector, and this fee at most can be SEK 7/kg CO_2e (i.e., 7000 SEK/tCO2e). This forms the basis for the applied carbon price in CBA in the Swedish transport sector, and this price is expected to remain constant (in real terms) throughout the period of analysis. For air travel within the EU ETS, the CO_2 emissions from the fuel is considered to be net zero (i.e. complete waterbed effect). This coincides with recommendations from a report to the Ministry of Enterprise and Innovation (Österström, 2016). However, the guidelines state that the emissions from contrails still needed to be converted to CO_2e and valued accordingly. Trafikverket (2021) recommends a factor of 1.4 (i.e. a 40% addition to the CO_2 emissions from fuel) for domestic flights and a factor of 1.9 for international flights.

11.5 Norway

The Norwegian Ministry of Finance provided (for the first time) guidelines for carbon prices in Norwegian CBA in 2021 (Finansdepartementet, 2021a, 2021b). For emissions not covered by the EU ETS, the valuation follows the stated carbon tax trajectory from the Climate Plan of 2021 (Klima- og Miljødepartementet, 2021), where the tax will reach 2000 NOK_{2020} per tCO_2e in 2030. Between 2030 and 2040 the carbon price is recommended to follow the price path outlined in IEA (2021). From 2040 and onward the carbon price is expected to grow with the real interest rate recommended for Norwegian CBA (4% for the first 40 years, 3% for the next 35 years, and 2% thereafter). This gives a carbon price of NOK_{2022}766 in 2022, that grows to a price of NOK_{2022}2083 in 2050 (the stated carbon tax trajectory in the Climate Plan is higher than the price path from IEA (2021)). All sectors are assumed to follow the same price path principles after 2030, even sectors covered by the EU ETS.

For emissions within the EU ETS, the guidelines assume a full waterbed effect, but the carbon price of an emission permit needs to be included in the analysis. For sectors that are covered by the EU ETS in addition to having a domestic carbon tax, namely petroleum and domestic aviation, both the permit price and the carbon tax needs to be included in the calculation. Emission changes from land-use and forestry are valued at the same principles as emissions covered by the EU ETS.

For sensitivity analysis the guidelines provide a low and high price path. For the low price path they recommend a value of 75% of the EU ETS permit price and then a growth rate of the real interest rate for CBA. For the high price path they recommend the median value of scenarios from the Special Report on Global Warming of 1.5°C (SR15) (IPCC, 2018) that are consistent with the 1.5°C target with low or now overshoot.

11.6 Denmark

In the guidelines for the Danish transport sector (Transportministeriet, 2015), one assumes that all changes in CO_2 emissions from the ETS sector are net zero in the CBA. The guidelines provide projections for both the price of allowances and the shadow price of reaching climate targets in the non-ETS sector. These prices are assumed to be identical for the time being[44]. The real value of the shadow price increases over the 2020s and 2030s and stabilizes after 2040. This gives a carbon price of DKK_{2021} 790 per tCO_2e in 2022 and a corresponding price of DKK_{2021} 1343 in 2050.

11.7 European Investment Bank

In the 2020 version (currently under review) of the European Investment Bank's guidelines for CBA, carbon prices are based on estimates of marginal damage costs (European Investment Bank, 2020b, p. 25). The guidelines provide a central price path and a high price path. The central path entails a price of $€_{2016}$40 in 2020 and $€_{2016}$121 in 2050. With regards to emissions covered by the EU ETS, the guidelines assume a full waterbed effect: *Any emission*

[44] https://www.cta.man.dtu.dk/modelbibliotek/teresa/transportoekonomiske-enhedspriser

that is internalised, such as that proportion of GHG emissions that are paid for through the EU Emissions Trading Scheme, are subtracted from external costs (p. 183).

In a note to the reader the guidelines state (p. 1): *The transformation of the EIB into the EU Climate Bank, as well as research advances in some of the elements of the appraisal require that the guide be revised. Amongst some of the elements requiring revision there are: the cost of carbon, the value of time (VoT) in transport and the value of transport safety.* We therefore expect that the guidelines for applying carbon prices in CBA will be updated in the near future[45].

[45] In Annex 5 of the EIB report "EIB Group Climate Bank Roadmap 2021-2025", the European Investment Bank (2020a), propose to apply a carbon price path roughly consistent with the median price path of the IAMC scenarios applied in IPPC (2018) with low overshoot and little reliance on BECCS, resulting in a price per tCO_2e of $€_{2016}80$ in 2020, which grows to $€_{2016}800$ in 2050.

12 How to include carbon values in CBA for sectors regulated by the EU ETS

Above we discussed in general terms how carbon values should be included for sectors regulated by an emissions trading system. In this section we discuss this in the context of the EU Emissions Trading System (EU ETS), which is regarded as EU's cornerstone climate policy, also covering EEA countries like Norway. In the first subsection, we give a brief overview of the EU ETS. Then we discuss the implications of the Market Stability Reserve (MSR), which has been recently implemented in the EU ETS. Subsequently, we discuss regulatory changes of the EU ETS, including changes of the emissions cap, and implications for the use of carbon values in CBA, before we summarize in the last subsection. The discussion here is relevant for any emissions changes that take place in ETS sectors, whether or not these are direct effects of the project or secondary effects (e.g., a road transport project that affects emissions from aviation and/or electricity generation related to electrification of road transport).

12.1 Briefly about the EU ETS

The EU ETS regulates about half of EU's greenhouse gas emissions (mostly CO_2), including large installations in electricity generation, other energy production, manufacturing industry and aviation. EU ETS was started in 2005, and we are now in the fourth phase (2021-2030). So far, no decision has been made for the years after 2030, but most likely the ETS will continue after 2030.

A crucial part of any ETS is the annual emissions cap, i.e., the annual number of emissions allowances (called EUAs) that are either auctioned or given out for free to regulated installations. From 2013, the annual cap was reduced linearly, with the annual reduction corresponding to 1.74% of the total allocation in 2013. After 2020, the linear reduction rate has been increased to 2.2%, and currently the EU is considering to increase the reduction rate in order to be aligned with the strengthened target for 2030.

Another crucial issue is that emissions allowances can be freely banked and borrowed within each phase, and freely banked from one phase to the next (borrowing from future phases is not allowed). This will tend to smooth the EUA price over time, although history has shown that the price has been varying quite a lot, nevertheless.

Around 60-65% of allowances are auctioned, while the rest is given out for free to the regulated installations. Manufacturing industries receive a large share of free allowances, as many of them are deemed highly exposed to carbon leakage (cf. Section 6), while producers of electricity do not receive any allowances (with some exceptions). Airlines receive some free allowances.

To understand the dynamics of the EU ETS, not only the market dynamics but also the political dynamics, it is useful to briefly consider the historical development of the EUA price and how this has led to regulatory changes in the EU ETS. Figure 12.*1* shows the EUA price from 2008 to May 2022, i.e., from phase 2. The price started at 20-30 Euro per ton in the first half of 2008, until the financial crisis hit the world. Then the EUA price dropped significantly, and as the financial crisis was followed by a long-lasting economic recession in the EU, the EUA price fell further and stayed below 10 Euro continuously in the years 2012-2017. The demand for allowances was lower than the supply (i.e., the emissions cap), even with the low price, and so a huge number of allowances was banked in the market. The EU policy makers introduced various measures to increase the EUA price (first backloading, i.e., postponement of auctioning, and then the first version of the MSR), but without much success. That is, until the MSR was revised in the beginning of 2018.

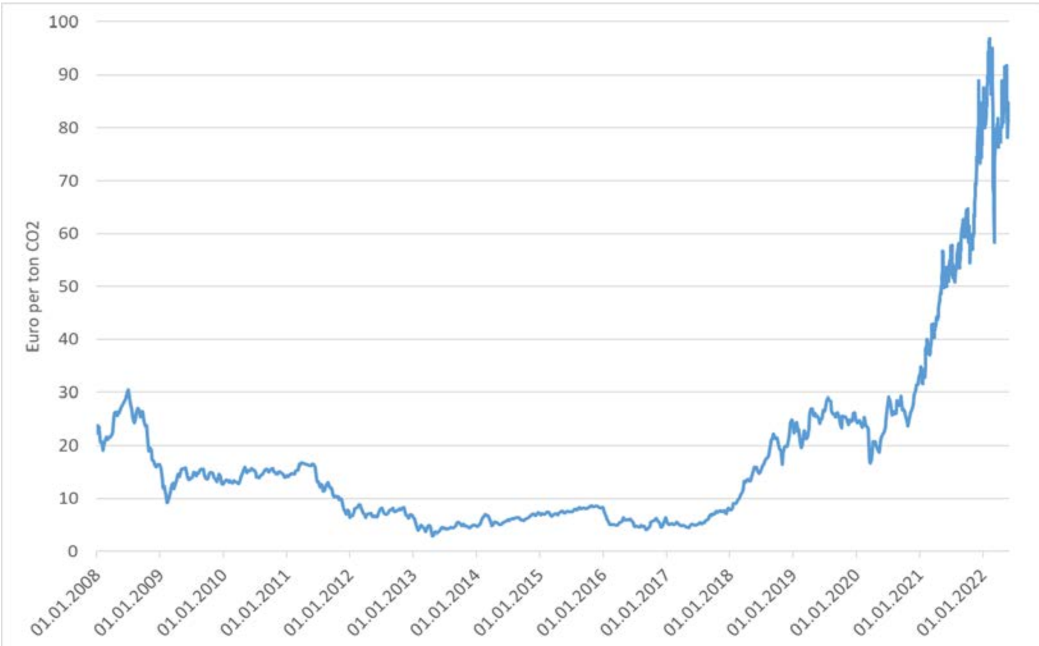

Figure 12.1: EUA prices in the EU ETS from 2008 to May 2022. Euro per ton CO_2.

12.2 Assessment of the Market Stability Reserve (MSR) in the EU ETS

The MSR works as follows (see illustration in Figure 12.*2*): Each year the total number of banked EUAs in the market exceeds an upper threshold of 833 Mt of CO_2, the volume of auctioned EUAs next year is reduced compared to the originally planned volume.[46] The EUAs that are not auctioned are instead moved into the MSR. In the first few years (until 2024), the number of EUAs entering the MSR equals 24% of the banked EUAs. From 2024, the ratio will be reduced to 12%. If banking drops below a lower threshold of 400 Mt CO_2, the volume of auctioned EUAs next year is increased by 100 Mt CO_2, and the size of the MSR is reduced accordingly. These rules were already decided in the first version of the MSR.

In 2018, it was decided that whenever the number of EUAs in the MSR exceeds the number of auctioned EUAs of the previous year, all EUAs above this threshold should be permanently

[46] When we talk about banked allowances, we mean "total number of allowances in circulation (TNAC)", which is the formal term used by the EU. Note that the EU is currently considering smaller changes to the MSR regulations, based on proposals from the European Commission.

canceled. This will start in 2023. Consequently, the long-term cap on emissions is reduced, and will expectedly be reduced by several years of emissions (Refinitiv Carbon, 2019). As the market realized that the long-run supply of EUAs was substantially reduced, the price surged from around 7 Euro in late 2017 to above 20 Euro in the second half of 2018.

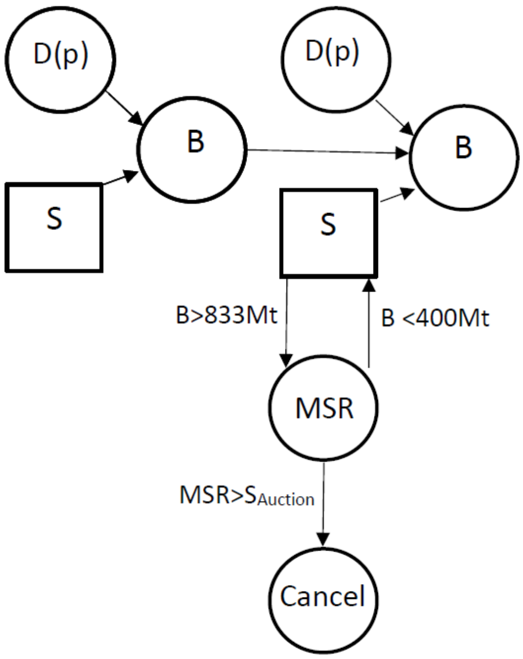

Figure 12.2: Illustration of the MSR. D(p) denotes annual demand for EUAs (i.e., annual emissions), S denotes the annual supply of EUAs, B denotes total banking of EUAs in the market after each year, MSR denotes the number of EUAs in the MSR, and Cancel denotes how many EUAs are canceled. The figure only shows the workings of the MSR for one year – this system will continue into the future unless regulations are changed.

Moreover, the changes to the MSR implies that the cap on emissions is no longer exogenously given – it depends on the outcome of the ETS market. The more banking, the more EUAs are canceled, and the lower becomes the emissions cap.

What are the implications of these new rules? As explained by e.g. Perino (2018), the waterbed referred to in Section 2.2.2 is temporarily punctured in the EU ETS. Not 100% punctured, but partially. This means that if an additional abatement measure is implemented, having a direct effect on emissions this year (or in the next few years), emissions will not simply be reshuffled (as when the waterbed effect is fully operative). Total long-term emissions will decline. The explanation is as follows: An additional abatement measure reducing emissions this year will increase the net supply of EUAs in the market, increasing banking to next year and most likely also to future years. Since the current level of banking is far above the upper threshold (833 Mt), more EUAs will enter into the MSR in coming years, and more EUAs will eventually be canceled. In other words, the long-term emissions cap is reduced. This is illustrated in Figure 12.*3* in an example where it is assumed that some project reduces emissions in 2020 by 100 Mt. Each subsequent year, additional EUAs will enter the MSR (as long as total banking exceeds 833 Mt), and all these additional EUAs will be canceled (from 2023).

How much the cap will be reduced is uncertain. Perino (2018) assesses that one ton of additional emission reduction in 2020 will lead to a net reduction in the long-term cap of 0.4-0.8 ton, while Gerlagh, Heijmans, and Rosendahl (2020) finds the net reduction to be close to one in their simulations. From Figure 12.*3* we see that already after five years, EUAs corresponding to 65% of the emission reduction have been cancelled (assuming here that total banking exceeds 833 Mt at least during this period). Basically, it all comes down to how long banking in the market will exceed the upper threshold of 833 Mt. This partly depends on how emissions will develop in coming years (compared to the annual allocation of EUAs), which again depends on economic activity, supportive policies and technological progress of green technologies. In addition, it depends on expectations in the market about future EUA prices. If future price expectations are high, incentives to bank more EUAs increase (and vice versa).

This mechanism obviously works both ways. That is, if a project leads to higher ETS emissions (e.g., due to more emissions in the electricity sector because of more use of electric vehicles), the long-run emissions will go up.

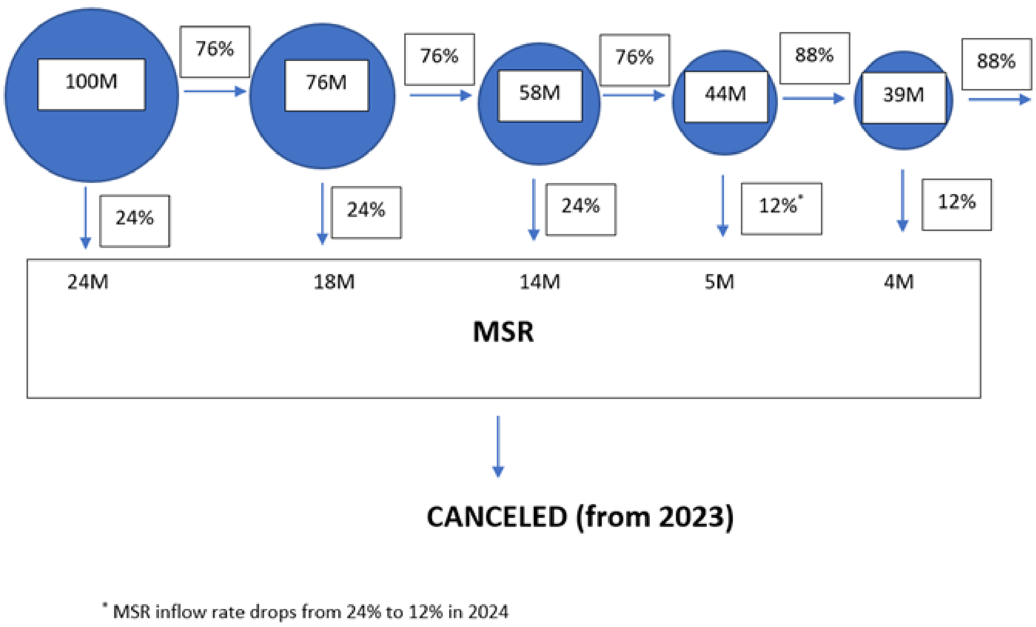

Figure 12.3: Illustration of the effects of reducing ETS emissions by 100 Mt in 2020 (assuming 100M EUAs more banking to 2021 and disregarding effects on the ETS price)

On the other hand, if additional emission reductions take place many years from now, the impacts on the long-term emissions cap are quite different. If these additional emissions reductions come by surprise, i.e., the market does not take this into account in its current expectations, the long-term emissions cap may be unchanged (e.g., if it takes place after the door into the MSR has been closed). However, if the market already now anticipates that additional emission reductions in the future will lead to lower EUA prices in the future, the incentives to bank EUAs are reduced, and the inflow of EUAs into the MSR may drop. If so, cancellation of EUAs will decline, *increasing* the long-term emissions cap. This is discussed and analyzed in Rosendahl (2019) and Gerlagh et al. (2020), referring to this as a green paradox. Again, if we consider a project that is expected to *increase* ETS emissions in the future (e.g., due to more electrification in Non-ETS sectors), the long-run ETS emissions may in fact *drop*.

What are the implications for CBA of investments and other measures that affect emissions regulated by the EU ETS? From the discussion in the previous section, we know that the appropriate carbon value of emissions (reductions) in sectors regulated by an ETS is the ETS price – provided that the emissions cap is fixed. However, as explained above, the emissions cap is no longer fixed in the EU ETS, due to the MSR. In addition comes possible regulatory changes, see next subsection.

Leaving regulatory changes aside, the implications of the MSR for actual net emissions from the project under CBA depend on especially two factors: i) the time profile of changes in emissions due to the project under evaluation, and ii) whether the market anticipates these changes in emissions and as a response adjusts its net banking of EUAs. The closer in time emissions are changed, the more the MSR will be operative, with supply of EUAs adapting to demand. In the extreme, net changes in emissions might be almost equal to the direct effect on emissions. This might be the case for changes in emissions in the nearest future (cf. the results in Gerlagh et al., 2021, mentioned above). In this case, the appropriate carbon value should be the same as for unregulated emissions, i.e., the recommended shadow price of carbon (cf. Section 2.1.3). If instead emissions changes take place in the more distant future, it is less likely that one can rely on the MSR to reduce the actual emissions cap. Then net emissions from the project can be expected to be zero, as the carbon cap can be expected to be fixed and binding, and the ETS price may again be the proper carbon value. That is, unless one takes into account possible regulatory changes of the EU ETS, which we now turn to.

12.3 Discussion of regulatory changes of the EU ETS (endogenous policies)

In Section 2.1.5 we discussed the implications of endogenous climate regulations, especially related to the emissions cap in an ETS. Here we will briefly discuss the relevance of this in the EU.

For this purpose, it is useful to return to the discussion at the end of Section 12.1, where we explained what happened when the EUA price was below 10 Euro for several years. Various measures were implemented with the objective of raising the EUA price. Measures that reduced the short-run cap, but not the long-run cap, didn't have much of an effect, while revising the MSR so that the *long-run* emissions cap was (significantly) reduced led to a strong price increase. Further, there are currently plans in the EU to speed up the decrease in the emissions cap (i.e., increase the annual reduction factor from today's 2.2%, see above) due to the more ambitious climate target for 2030. There have also been discussions about a carbon price floor in the EU ETS (Carbon Pulse, 2020).

Looking beyond 2030, the cap on emissions in the EU ETS is not yet determined, unless one takes it for granted that the annual reduction factor will simply continue until the cap becomes zero. The reduction factor was adjusted from phase 3 (2013-2020) to 4 (2021-2030) to be consistent with the 2030 target, and will be probably be adjusted again due to the stricter 2030 target, and it seems likely that the EU will adjust this factor again if deemed necessary to reach future emissions targets. Moreover, the reduction factor in the EU ETS will also be considered in light of the division of EU's overall emissions budget between ETS and Non-ETS sectors. The more difficult and costly emission reductions in Non-ETS sectors are expected to be, the bigger share of emissions reductions will likely take place in the ETS.[47] There is also a discussion whether to include more sectors into the ETS in the future, in order to harmonize CO_2 prices across sectors.

This discussion clearly suggests that the (effective) emissions cap in the EU ETS is not unaffected by the EUA price, (updated) emissions targets nor cost comparison with Non-ETS sectors. It is of course much more difficult to pin down an exact relationship between e.g. the EUA price and changes in the long-run cap. Still, it seems natural to assume that lower (expected) emissions (of some size) within the EU ETS eventually will lead to lower emissions cap.

12.4 Conclusions for including carbon values in CBA for sectors regulated by the EU ETS

From the general discussion in Section 10 and the discussion of the EU ETS in Section 12.1-12.3, our recommendation would be to apply the *recommended cost of carbon* also for valuing changes in emissions regulated by the EU ETS when performing CBA. Additional emissions reductions in the short run will effectively reduce the long-run emissions cap automatically 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 automatic impact on the long-run emissions cap via the MSR, but increases the likelihood of more stringent emissions cap via regulatory changes. Although these impacts are difficult to quantify, there are other good arguments for applying the same cost of carbon across emission sources. From the discussion in Section 10.2.3 (see also the following Section 13), we have that for emissions *not* regulated by an ETS (either unregulated or regulated by tax or other measures) one should use the *recommended cost of carbon* when valuing emissions changes in CBA. Our recommendation implies that the emissions from projects in the ETS sector are not assumed to be netted out, but counted like emissions not regulated by the ETS and valuing them according to the same cost of carbon. The paid ETS price can then simply be viewed as a transfer between permit holders.

Our recommendation is somewhat different than what is currently the practice in many European countries, cf. Section 11, where the (projected) EUA price is often used. One reason for this may be that the new rules of the MSR was established in 2018, and hence has not been taken into account in many EU/EEA countries. A second reason may be that the typical starting point for a single country is to consider domestic welfare effects. Moreover, EU policies may be considered exogenous to a single EU/EEA country, at least when considering smaller member states. For EU/EEA as a whole, however, it is more reasonable to consider EU/EEA's total welfare and treat EU/EEA policies as endogenous.[48]

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[47] Cf. e.g. the stronger emission reduction for ETS than Non-ETS in 2030.

[48] This is quite similar logic as in a market with one big and many small producers (dominant producer model), where the big producer considers the price as endogenous while small producers consider the price exogenous (e.g. the oil market with OPEC and Non-OPEC is often modeled in this way).

13 How to include carbon values in CBA for non-ETS sectors

In this section we consider emissions not regulated by the ETS, and implications for the use of carbon values in CBA. The discussion here is relevant for any emissions changes that take place in Non-ETS sectors, whether or not these are direct effects of the project or secondary effects (e.g., a new airport affecting also emissions from road transport).

For sectors not regulated by the ETS, a change in emissions due to a specific project will also lead to net changes in emissions. Hence, to still meet the emissions target, other emissions will have to adjust. The appropriate carbon value to use in CBA will then in principle depend on the marginal abatement costs of these other emissions (i.e., the shadow price). We argued in Section 10.2 that if Non-ETS sectors face only CO_2 taxes (and no other supportive policies), the most natural choice of carbon value would then be the average CO_2 tax. If supportive policies are also implemented, which is much more likely in the context of the Non-ETS sectors, the appropriate carbon value exceeds the average CO_2 tax as the supportive policies mask the real costs of abatement. The marginal abatement costs of reaching the emission target will then likely be higher than if the same emission reductions were reached via CO_2 pricing only.

In the longer term, it seems reasonable to assume that the stringency of the emissions targets in the ETS and Non-ETS will be more or less harmonized, meaning that the shadow price of emissions will be fairly similar. If so, a natural choice of carbon value for emission in Non-ETS sectors would again be the (shadow) *cost of carbon* in the EU/EEA.

In the short term (until 2030), one might argue that the real shadow prices should reflect the Non-ETS targets for the years 2021-30. If so, a question is whether the carbon value should differ among EU/EEA countries, as each country has its own Non-ETS target. On the other hand, trade in “Non-ETS credits” is allowed, although it is unclear to what extent such trade will take place. If the Non-ETS shadow price of a country is *lower* than the recommended cost of carbon, our recommendation would be to use the latter. This reason is that whereas not reaching the 2030 target would seem unacceptable, overcompliance would not - except that it comes with a cost. Following the reasoning above, however, overcompliance can make it easier to reach more long-term targets, making sure that the country is on track to reach the net zero emissions target in 2050.

To summarize, our recommendation would be to use the recommended cost of carbon for all emissions in Non-ETS sectors, but possibly consider higher carbon values 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*. It is beyond the scope of this report to assess whether that is the case or not.

14 How to include carbon values in CBA abroad

Some projects may affect emissions abroad, either indirectly through carbon leakage from domestic activities or directly through financing projects abroad. Carbon leakage refers to the possibility that climate policies in e.g. the EU may lead to higher emissions outside the EU, e.g., if emissions-intensive and trade-exposed industries relocate out of the EU. Emissions targets typically refer to domestic emissions, not emissions embodied in imported goods. Still, countries are often concerned about these emissions, too, which is e.g. evidenced by the allocation rules in the EU ETS (cf. Section 12.1).

When it comes to carbon leakage, there is a large literature on this topic which we will not go into (see e.g., Böhringer, Fischer, & Rosendahl, 2014; Böhringer, Rosendahl, & Storrøsten, 2017; Martin, Muûls, De Preux, & Wagner, 2014; Z. Zhang, 2012) The general recommendation from this literature is *not* to reduce the CO_2 price in sectors exposed to leakage, but rather to implement supplemental policies such as output-based allocation or (even more effective) border carbon adjustments such as carbon tariffs. However, when a project indirectly leads to higher or lower emissions abroad, one could still consider whether these changes in foreign emissions should be valued. A natural question to ask then is whether the domestic country's primary target is the *global* target of keeping global warming below 1.5 degrees, or the *domestic* target of reaching net zero emissions by 2050. If the domestic target is the primary target, changes in foreign emissions should not be valued in a CBA. If the global target is the primary target, and the latter target is an operative target that follows from the former, changes in foreign emissions should in principle be valued similarly as changes in domestic emissions (see however the discussion about differentiated carbon prices below). We believe that the latter interpretation is the most relevant one for most countries (i.e., the 1.5ºC target). A country may still consider own emissions somewhat more important than foreign emissions, however, at least in cases where foreign emissions change only indirectly as a response to domestic activities.

When it comes to financing projects abroad, the reasoning is quite similar to the one in the previous paragraph. The effects on emissions are now more directly, however, in which case one could argue that the responsibility for these emissions are bigger than when emissions only change indirectly due to domestic activities. This may suggest that the appropriate carbon value on changes in emissions abroad should be the same as domestically, as the CO_2 prices we derived above were mainly based on scenarios where CO_2 prices were implemented globally. The recommended cost of carbon is consistent with reaching the 1.5ºC target globally in the most cost-effective way estimated possible. Hence, there would be a need for arguments besides efficiency to deviate from the principle of applying the same value, as such deviation could be a subtle driver towards carbon leakage and choosing less carbon efficient solutions within projects in some areas compared to others.

On the other hand, we also raised the question whether from a global welfare perspective carbon prices should be differentiated between rich and poor countries, as argued by e.g. Stiglitz et al. (2017). If so, carbon values within Europe should be higher than otherwise, while carbon values in (poor) developing countries should be lower. How much higher and lower is difficult to say, and this is in any case a normative question (cf. our discussion above).

One could here also ask whether there are better ways of improving welfare in poor countries than by using lower carbon values in these countries than in richer countries. It is however beyond the scope of this report to enter into such a discussion.

To summarize, our recommendation would be to generally use the same carbon value for emissions abroad as domestically, but possibly consider lower carbon values for emissions in (poor) developing countries. Decision-makers that provide CBA guidelines will then have to consider if this is likely to foster excessive investment in high-emitting projects in poor countries.

15 How to include carbon values in CBA for emissions with an offsetting mechanism

Some emissions are neither regulated by an ETS nor a tax, but is required to acquire offsets to cover (parts of) their emissions. This is e.g. relevant for international aviation, such as flights between EU/EEA countries and Non-EU/EEA destinations. Greenhouse gas emissions from these activities are not part of EU's (or other countries') official emissions, and so far not regulated by the EU ETS.[49]

An offsetting mechanism typically means that a company must buy emissions offsets or credits for every ton of emissions it has, possibly above a specified emission level. These credits are sold by other companies (or countries) who have reduced emissions in some other countries (typically developing countries). These emission reductions have been verified by some third-party. The most well-known example is the Clean Development Mechanism (CDM) established under the Kyoto protocol. In principle, an offsetting mechanism means that increased emissions by an airline or shipping company due to increased activity are fully offset by reduced emissions elsewhere in the world – hence, global emissions remain unchanged. From this perspective, one could argue that there are no climate costs from these activity changes, and hence the carbon value used should be set equal to the offset price (similar to an ETS with a fixed cap).

This simple reasoning may not be appropriate though, and several issues have to be discussed.

First, as mentioned before, European countries (and the EU) have targets of net zero GHG emissions by 2050, and as mentioned in the previous section we consider this an operative target for reaching the primary target of keeping global warming below 1.5°C. A natural question to ask here is whether the net zero emissions target also applies to emissions from international transport between EU/EEA and Non-EU/EEA destinations. If so, this may be an argument for using the established cost of carbon instead of the offset price as the relevant carbon value, as increased emissions from this transport will not be offset by emission reductions within the EU/EEA (including here international transport between EU/EEA and Non-EU/EEA countries).

Second, there has been much criticism against the CDM, which is the most well-known offset mechanism (e.g., Rosendahl and Strand (2009); Schneider (2011); J. Zhang and Wang (2011)). The main criticism is related to the issue of additionality (Cames et al., 2016). That is, how can one be sure that the project that is reducing emissions would not have taken place anyway, i.e., without payment from the buyer of CDM credits? This counterfactual situation is inherently difficult to know, especially for projects that involves energy savings or increased production of renewables, which might be profitable on its own. As a

[49] Emissions from international sea transport are also not covered by any countries' official emissions. An offset mechanism is not planned for international shipping, however (as far as we know), where the focus is more on targets for reducing emissions and emissions intensities.
https://www.climatechangenews.com/2020/02/11/shipping-raise-ambition-2030-climate-target-study-shows/

consequence, the EU first abandoned some types of CDM projects, and then decided to not use CDM or other Non-EU offsets after 2020. The price of CDM credits has been extremely low the last years, as there is a huge oversupply of such credits. Hence, it seems unlikely that buying CDM credits today will bring about additional emissions reductions. A new offset mechanism may become established under the Paris agreement, but so far this has not been established.

When it comes to emissions from international aviation, the UN's International Civil Aviation Organisation (ICAO) has developed a market-based offset system called CORSIA (Timperley, 2019). The purpose of this system is that the *growth* in international aviation emissions above 2020 levels should be offset by emission reductions elsewhere.[50] The scheme is not mandatory until 2027. Discussions are ongoing about what kind of credits should be eligible as offsets, with some countries wanting to use CDM credits (typically countries with large unused supply of such credits). There has been much criticism against the environmental integrity of CORSIA, see e.g. Larsson, Elofsson, Sterner, and Åkerman (2019).

One criticism against both CORSIA and offset mechanisms in general is that it can weaken national climate pledges by the donor countries offering offset credits. Emission credits sold to an airline cannot also be counted as a contribution from the donor country. Thus, as pointed out by Larsson et al. (2019), it may be "tempting for countries to sell credits to airlines instead of using emissions reductions to achieve their own NDC since the former provides additional income". If so, the emissions reduction may look additional at the micro level, but still be non-additional at the macro level.

To sum up, there are several problematic issues with respect to offsets, especially in the context of aviation and CORSIA. Thus, the simple reasoning mentioned above, suggesting to use the offset price as the carbon value for these emissions, may not be appropriate. As it is in general advantageous to apply the same cost of carbon across emission sources, our recommendation would therefore be to apply the established cost of carbon also for emissions that are regulated by an offsetting mechanism.

[50] Because of the Corona virus, 2020 will not be used as baseline after all, see https://www.euractiv.com/section/aviation/news/airlines-granted-huge-emissions-reprieve-by-un-compromise/

16 Summary and recommendations for the use of carbon values in CBAs

16.1 Discussion

In Section 10 we discussed general principles on how to include carbon values in CBA, distinguishing in particular between project emissions regulated by an ETS and project emissions regulated by a tax. Unregulated emissions should be treated in the same way as emissions regulated by a tax. We argued that using the "inclusive principle" in CBA accounting is good practice, as it distinguishes clearly between transfers and real costs. We also showed several examples.

When considering the actual net cost of emissions in the CBA, we pointed to the rows "Δ Cost of abatement in other ETS firms" and "Δ Cost of project carbon emissions" in the tables as the most important. We explained that 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, the established *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, we are in a situation in between 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 fixed), we are for practical purposes in the tax case. We further explained that if carbon prices are differentiated and/or supported by other climate policies, the recommendation would 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.

After briefly reviewing current guidelines in selected countries (Section 11), we went on to discuss how to use carbon values in sectors regulated by the EU ETS (Section 12), in Non-ETS sectors (Section 13), and abroad (Section 14). When it comes to the EU ETS, we discussed the implications of the Market Stability Reserve (MSR), which implies that the emissions cap is endogenous, as well as regulatory changes in response to e.g. lower than expected/desired ETS prices. We argued that considering the emissions cap in the EU ETS as fixed may seem a bit naïve, at least from the perspective of EU/EEA as a whole. 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 increases the likelihood of more stringent emissions cap via regulatory changes. We admit, however, that these impacts are difficult to quantify.

For emissions in Non-ETS sectors, the general principles referred to above can more easily be applied. One possible exception, however, relates to short-term emissions, as there are specific Non-ETS targets for each EU/EEA country for the years 2021-2030. The shadow price of reaching these targets may differ across countries, and may also differ from the shadow price of the long-term target.

For emissions abroad, a cost-effective approach would suggest that the same CO_2 prices are used abroad as domestically, as foreign emissions have the same climate impacts as emissions at home. There are two potential arguments against, however. One is that the 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. The other is that from a welfare perspective one could argue that poor countries should have lower CO_2 prices than richer countries. However, this is a normative issue that we leave to the final decision makers for CBA guidelines.

16.2 Conclusion and recommendation

Based on the discussion above, our recommendation is the following:

- The established *cost of carbon* should be applied throughout the economy, i.e., independent of whether the project emissions are regulated by the EU ETS, part of Non-ETS sectors, or regulated by an offset mechanism.
- Higher carbon values may be used in the short run (until 2030) in Non-ETS sectors if the shadow prices that follow from the existing Non-ETS target exceed the established *cost of carbon*.
- The established *cost of carbon* should also be used for emissions from international transport and in projects abroad, 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, at least throughout the domestic economy. This carbon value will then always be consistent with the best estimate for reaching the 1.5°C target at least cost, and encourages consistency and simplicity to the CBA work. 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 many 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 construction phase). We think these recommendations are applicable also for the updating of CBA guidelines in other countries.

References

Acemoglu, D., Aghion, P., Bursztyn, L., & Hemous, D. (2012). The environment and directed technical change. *American Economic Review, 102*(1), 131-166.

Arneth, A., Barbosa, H., Benton, T., Calvin, K., Calvo, E., Connors, S., . . . van Diemen, R. (2019). IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems. In: Technical report, Intergovernmental Panel on Climate Change.

Budinis, S., Krevor, S., Mac Dowell, N., Brandon, N., & Hawkes, A. (2018). An assessment of CCS costs, barriers and potential. *Energy strategy reviews, 22*, 61-81.

Byers, E., Krey, V., Kriegler, E., Riahi, K., Schaeffer, R., & et al. (2022). *AR6 Scenarios Database hosted by IIASA, release 1.0*. Retrieved from: https://data.ene.iiasa.ac.at/ar6

Böhringer, C., Fischer, C., & Rosendahl, K. E. (2014). Cost-effective unilateral climate policy design: Size matters. *Journal of Environmental Economics and Management, 67*(3), 318-339.

Böhringer, C., & Rosendahl, K. E. (2011). Greening electricity more than necessary: on the cost implications of overlapping regulation in EU climate policy.

Böhringer, C., Rosendahl, K. E., & Storrøsten, H. B. (2017). Robust policies to mitigate carbon leakage. *Journal of Public Economics, 149*, 35-46.

Börjesson, M., Fung, C. M., & Proost, S. (2017). Optimal prices and frequencies for buses in Stockholm. *Economics of Transportation, 9*, 20-36.

Cames, M., Harthan, R. O., Füssler, J., Lazarus, M., Lee, C. M., Erickson, P., & Spalding-Fecher, R. (2016). How additional is the clean development mechanism. *Analysis of application of current tools and proposed alternatives. Oeko-Institut EV CLlMA. B, 3*.

Carbon Pulse. (2020). European Commission to reconsider EU ETS floor price as part of wider reforms -senior official. Retrieved from https://carbon-pulse.com/101617/

Curtin, J., Bruin, K. d., Hanley, E., & Gallachóir, B. Ó. (2017). *Energy Modelling to Inform the National Mitigation Plan*. Retrieved from Ireland: https://www.dccae.gov.ie/documents/ESRI%20Energy%20Modelling%20Paper%20May%202017.pdf

Department for Business, E. I. S. (2021). *Valuation of greenhouse gas emissions: for policy appraisal and evaluation*. Retrieved from https://www.gov.uk/government/publications/valuing-greenhouse-gas-emissions-in-policy-appraisal/valuation-of-greenhouse-gas-emissions-for-policy-appraisal-and-evaluation

Department for Transport. (2018). *TAG unit A1.1, Cost Benefit Analysis*. London Retrieved from https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/712699/tag-unit-a1.1-cost-benefit-analysis-may-18.pdf

Department for Transport. (2022). *TAG UNIT A3 - Environmental Impact Appraisal*. Retrieved from https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/825064/tag-unit-a3-environmental-impact-appraisal.pdf

Department of Transport. (2021). *Common Appraisal Framework For Transport Projects And Programmes*. Ireland Retrieved from https://www.gov.ie/en/organisation-information/800ea3-common-appraisal-framework/

Emmerling, J., Drouet, L., van der Wijst, K.-I., Van Vuuren, D., Bosetti, V., & Tavoni, M. (2019). The role of the discount rate for emission pathways and negative emissions. *Environmental research letters, 14*(10), 104008.

European Commission. (2018). A clean planet for all. A European strategic long-term vision for a prosperous, modern, competitive and climate neutral economy. *COM (2018) 773 final*.

European Investment Bank. (2020a). *Climate Bank Roadmap 2021-2025*. Retrieved from https://www.eib.org/attachments/thematic/eib_group_climate_bank_roadmap_en.pdf

European Investment Bank. (2020b). *The Economic Appraisal of Investment Projects at the EIB*. Retrieved from https://www.eib.org/attachments/thematic/economic_appraisal_of_investment_projects_en.pdf

Finansdepartementet. (2021a). *Hvordan ta hensyn til klimagassutslipp i samfunnsøkonomiske analyser*. Retrieved from https://www.regjeringen.no/no/tema/okonomi-og-budsjett/statlig-okonomistyring/hvordan-ta-hensyn-til-klimagassutslipp-i-samfunnsokonomiske-analyser/id2863676/

Finansdepartementet. (2021b). *Karbonprisbaner for bruk i samfunnsøkonomiske analyser*. Retrieved from https://www.regjeringen.no/no/tema/okonomi-og-budsjett/statlig-okonomistyring/karbonprisbaner-for-bruk-i-samfunnsokonomiske-analyser/id2878113/

France Stratégie. (2019). *The Value For Climate Action - A Shadow Price Of Carbon For Evaluation Of Investments And Public Policies*. Retrieved from https://www.strategie.gouv.fr/sites/strategie.gouv.fr/files/atoms/files/fs-the-value-for-climate-action-final-web.pdf

Fricko, O., Havlik, P., Rogelj, J., Klimont, Z., Gusti, M., Johnson, N., . . . Amann, M. (2017). The marker quantification of the Shared Socioeconomic Pathway 2: A middle-of-the-road scenario for the 21st century. *Global Environmental Change, 42*, 251-267.

Fujimori, S., Masui, T., & Matsuoka, Y. (2014). Development of a global computable general equilibrium model coupled with detailed energy end-use technology. *Applied Energy, 128*, 296-306.

Gerlagh, R., Heijmans, R., & Rosendahl, K. E. (2020). Endogenous Emission Caps Always Induce a Green Paradox. *NMBU School of Economics and Business Working Paper No. 4/2020*.

Greenstone, M., Kopits, E., & Wolverton, A. (2013). Developing a social cost of carbon for US regulatory analysis: A methodology and interpretation. *Review of Environmental Economics and Policy, 7*(1), 23-46.

Grubler, A., Wilson, C., Bento, N., Boza-Kiss, B., Krey, V., McCollum, D. L., . . . De Stercke, S. (2018). A low energy demand scenario for meeting the 1.5 C target and sustainable development goals without negative emission technologies. *Nature energy, 3*(6), 515-527.

Guivarch, C., & Rogelj, J. (2017). Carbon price variations in 2 C scenarios explored.

Hagen, K. P., Berntsen, S., Bye, B., Hultkrantz, L., Nyborg, K., Pedersen, K. R., . . . Åvitsland, G. (2012). Cost-benefit analysis. *Official Norwegian Reports NOU, 16*.

Hausfather, Z. (2018). Explainer: How 'Shared Socioeconomic Pathways' explore future climate change. *Carbon Brief.* Retrieved from https://www.carbonbrief.org/explainer-how-shared-socioeconomic-pathways-explore-future-climate-change

Huppmann, D., Kriegler, E., Krey, V., Riahi, K., Rogelj, J., Rose, S. K., . . . Zhang, R. (2018). IAMC 1.5°C Scenario Explorer and Data hosted by IIASA (Publication no. 10.22022/SR15/08-2018.15429). from Integrated Assessment Modeling Consortium & International Institute for Applied Systems Analysis https://data.ene.iiasa.ac.at/iamc-sr15-explorer

Huppmann, D., Kriegler, E., Mundaca, L., Smith, C., Rogelj, J., & Séférian, R. (2018). 2. SM Mitigation pathways compatible with 1.5 C in the context of sustainable development–Supplementary Material. *Supplemntary material to SR15 IPCC Report*.

Huppmann, D., Rogelj, J., Kriegler, E., Krey, V., & Riahi, K. (2018). A new scenario resource for integrated 1.5° C research. *Nature Climate Change, 8*(12), 1027-1030.

IEA. (2019). *Global EV Outlook 2019*. Retrieved from IEA, Paris: www.iea.org/publications/reports/globalevoutlook2019/

IEA. (2021). *World Energy Outlook 2021*. Retrieved from https://iea.blob.core.windows.net/assets/4ed140c1-c3f3-4fd9-acae-789a4e14a23c/WorldEnergyOutlook2021.pdf

IPCC. (2018). *Global Warming of 1.5 °C*. Retrieved from http://www.ipcc.ch/report/sr15/

IPCC. (2022). *Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Retrieved from Cambridge University Press, Cambridge, UK and New York, NY, USA:

Johansson, P.-O. (2020). The 2018 Reform of EU ETS: Consequences for Project Appraisal. *CERE Working Paper, 2020:11*.

Jorge-Calderón, D. (2021). *Aviation investment: economic appraisal for airports, air traffic management, airlines and aeronautics [Forthcoming]* (2nd ed.): Routledge.

Klima- og Miljødepartementet. (2021). *Klimaplan for 2021-2030*. Oslo Retrieved from https://www.regjeringen.no/no/dokumenter/meld.-st.-13-20202021/id2827405/

Krey, V., Guo, F., Kolp, P., Zhou, W., Schaeffer, R., Awasthy, A., . . . Fujimori, S. (2019). Looking under the hood: A comparison of techno-economic assumptions across national and global integrated assessment models. *Energy, 172*, 1254-1267.

Kriegler, E., Petermann, N., Krey, V., Schwanitz, V. J., Luderer, G., Ashina, S., . . . Méjean, A. (2015). Diagnostic indicators for integrated assessment models of climate policy. *Technological Forecasting and Social Change, 90*, 45-61.

Larsson, J., Elofsson, A., Sterner, T., & Åkerman, J. (2019). International and national climate policies for aviation: a review. *Climate Policy, 19*(6), 787-799.

Marcucci, A., Panos, E., Kypreos, S., & Fragkos, P. (2019). Probabilistic assessment of realizing the 1.5° C climate target. *Applied Energy, 239*, 239-251.

Martin, R., Muûls, M., De Preux, L. B., & Wagner, U. J. (2014). Industry compensation under relocation risk: A firm-level analysis of the EU emissions trading scheme. *American Economic Review, 104*(8), 2482-2508.

McCollum, D. L., Zhou, W., Bertram, C., De Boer, H.-S., Bosetti, V., Busch, S., . . . Fay, M. (2018). Energy investment needs for fulfilling the Paris Agreement and achieving the Sustainable Development Goals. *Nature energy, 3*(7), 589-599.

Méjean, A., Guivarch, C., Lefèvre, J., & Hamdi-Cherif, M. (2019). The transition in energy demand sectors to limit global warming to 1.5 C. *Energy Efficiency, 12*(2), 441-462.

Meunier, D., & Quinet, E. (2015). Valuing greenhouse gases emissions and uncertainty in transport cost benefit analysis. *Transp Res Procedia, 8*, 80-88.

Ministry of Finance. (2005). *Veileder i samfunnsøkonomiske analyser [Guidelines for Cost-Benefit Analysis]*. Norway. Retrieved from https://www.regjeringen.no/globalassets/upload/kilde/fin/reg/2005/0029/ddd/pdfv/266324-veileder_i_samfunnsok_analyse_trykket.pdf

Minken, H., & Samstad, H. (2005). *Nyttekostnadsanalyser i transportsektoren: Rammeverk for beregningene*: Transportøkonomisk institutt.

Nordhaus, W. (2014). Estimates of the social cost of carbon: concepts and results from the DICE-2013R model and alternative approaches. *Journal of the Association of Environmental and Resource Economists, 1*(1/2), 273-312.

Norwegian Agency for Public and Financial Management. (2018). *Veileder i samfunnsøkonomiske analyser [Guidelines for Cost-Benefit Analysis]*. Oslo, Norway. Retrieved from https://dfo.no/filer/Fagomr%C3%A5der/Utredninger/Veileder-i-samfunnsokonomiske-analyser.pdf

NOU 2012:16. (2012). *Samfunnsøkonomiske analyser*. Oslo: Departementenes servicesenter

O'Mahony, T. (2018). *Appraisal in transition: 21st century challenges and updating Cost-Benefit Analysis in Ireland*. Retrieved from https://www.researchgate.net/publication/328383318_Appraisal_in_transition_21st_century_challenges_and_updating_Cost-Benefit_Analysis_in_Ireland

O'Neill, B. C., Kriegler, E., Ebi, K. L., Kemp-Benedict, E., Riahi, K., Rothman, D. S., . . . Kok, K. (2017). The roads ahead: Narratives for shared socioeconomic pathways describing world futures in the 21st century. *Global Environmental Change, 42*, 169-180.

Perino, G. (2018). New EU ETS Phase 4 rules temporarily puncture waterbed. *Nature Climate Change, 8*(4), 262-264.

Pindyck, R. S. (2017). Coase Lecture—Taxes, Targets and the Social Cost of Carbon. *Economica, 84*(335), 345-364.

Refinitiv Carbon. (2019). *EUA price forecast. The European carbon market is finally fit for purpose*. Retrieved from Oslo:

Reilly, J., Paltsev, S., Strzepek, K., Selin, N. E., Cai, Y., Nam, K.-M., . . . Webster, M. (2013). Valuing climate impacts in integrated assessment models: the MIT IGSM. *Climatic change, 117*(3), 561-573.

Riahi, K., Van Vuuren, D. P., Kriegler, E., Edmonds, J., O'neill, B. C., Fujimori, S., . . . Fricko, O. (2017). The shared socioeconomic pathways and their energy, land use, and greenhouse gas emissions implications: an overview. *Global Environmental Change, 42*, 153-168.

Rogelj, J., Popp, A., Calvin, K. V., Luderer, G., Emmerling, J., Gernaat, D., . . . Marangoni, G. (2018). Scenarios towards limiting global mean temperature increase below 1.5 C. *Nature Climate Change, 8*(4), 325.

Rosendahl, K. E. (2019). EU ETS and the waterbed effect. *Nature Climate Change, 9*(10), 734-735.

Rosendahl, K. E., & Strand, J. (2009). *Simple Model Frameworks For Explaining Inefficiency Of The Clean Development Mechanism: Simple Model Frameworks For Explaining Inefficiency Of The Clean Development Mechanism*: The World Bank.

Schneider, L. R. (2011). Perverse incentives under the CDM: an evaluation of HFC-23 destruction projects. *Climate Policy, 11*(2), 851-864.

Stiglitz, J. E., Stern, N., Duan, M., Edenhofer, O., Giraud, G., Heal, G. M., . . . Pangestu, M. (2017). Report of the high-level commission on carbon prices.

Sugden. (1999). *Review of cost/benefit analysis of transport projects*. Retrieved from See Appendix A of TAG Unit A1.1: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/712699/tag-unit-a1.1-cost-benefit-analysis-may-18.pdf

Timperley, J. (2019). *Corsia: The UN's plan to 'offset' growth in aviation emissions after 2020, Carbon Brief 4 February 2019*. Retrieved from https://www.carbonbrief.org/corsia-un-plan-to-offset-growth-in-aviation-emissions-after-2020

Trafikverket. (2020). *Analysmetod och samhällsekonomiska kalkylvärden för transportsektorn: ASEK 7.0: Kapitel 4 Kalkylmodeller för samhällsekonomisk analys (CBA) – struktur och innehåll*. Sweden. Retrieved from https://www.trafikverket.se/contentassets/4b1c1005597d47bda386d81dd3444b24/asek-7.0--2020/04_kalkylens_innehall_a70.pdf

Trafikverket. (2021). *Analysmetod och samhällsekonomiska kalkylvärden för transportsektorn: ASEK 7.0: Kapitel 12 Samhällsekonomisk kostnad för klimateffekter*. Retrieved from https://bransch.trafikverket.se/contentassets/4b1c1005597d47bda386d81dd3444b24/asek-2021/12_klimateffekter_a70.pdf

Transportministeriet. (2015). *Manual for samfundsøkonomisk analyse på transportområdet – Anvendt metode og praksis i Transportministeriet*. Copenhagen

Van Vuuren, D. P., Stehfest, E., Gernaat, D. E., Van Den Berg, M., Bijl, D. L., De Boer, H. S., . . . Harmsen, M. (2018). Alternative pathways to the 1.5 C target reduce the need for negative emission technologies. *Nature Climate Change, 8*(5), 391-397.

waka Kotahi NZ Transport Agency. (2021a). *Economic Valuation Of Greenhouse Gas Emissions: A technical paper related to the Monetised benefits and costs manual's updated section 3.4 Impact of greenhouse gas emissions*. Retrieved from https://www.nzta.govt.nz/assets/resources/Monetised-benefits-and-costs-manual-technical-notes/Technical-report-Economic-evaluation-of-GHG-emissions-FINAL.pdf

Waka Kotahi NZ Transport Agency. (2021b). *Monetised Benefits And Costs Manual*.

Weyant, J. (2017). Some contributions of integrated assessment models of global climate change. *Review of Environmental Economics and Policy, 11*(1), 115-137.

Zhang, J., & Wang, C. (2011). Co-benefits and additionality of the clean development mechanism: An empirical analysis. *Journal of Environmental Economics and Management, 62*(2), 140-154.

Zhang, Z. (2012). Competitiveness and leakage concerns and border carbon adjustments.

Österström, J. (2016). Luftfartens marginalkostnader: en delrapport inom Samkost 2. In: Statens väg- och transportforskningsinstitut.

Aamaas, B., Peters, G., Wei, T., & Kor, J. I. (2019). What relevant information do the integrated assessment models and scenarios from the 1.5 C special report provide for Norway? *CICERO Report*.

Appendix A: Shared Socioeconomic pathways

Each of the carbon price trajectories investigated in this report is the result of a model trying to solve for the carbon budget constraint in a given future scenario. By scenario, we apply the definition from Aamaas et al. (2019): A plausible description of how the future may develop based on a coherent and internally consistent set of assumptions about key driving forces (e.g., rate of technological change, population growth, GDP growth) and relationships. Note that scenarios are neither predictions nor forecasts, but are used to provide a view of the implications of developments and actions.

Major differences in scenario assumptions should give different carbon price trajectories. In some cases, the same scenario is applied to different models, and the carbon prices are widely different. The trajectories are different because the various models depict the workings of the world in widely different ways, which we will get back to in the next section.

Scenarios form an essential part of climate change research and assessment. They help us to understand long-term consequences of near-term decisions, and enable researchers to explore different possible futures in the context of fundamental future uncertainties (Riahi et al., 2017). And when different research communities use a common set of scenario assumptions, it becomes a lot easier to compare and combine their research. In the last decade the climate change research community have developed the five Shared Socioeconomic Pathways (SSPs), which work as common scenario descriptions that can be applied to the models. The SSPs have different narratives that describe the underlying logic for each SSP, and they provide storylines that cover more than the variables that are included in the formal models. An in-depth description of the models can be found in O'Neill et al. (2017). In Table A.1 we give the summary of narratives from Riahi et al. (2017).

Table A.1: Narratives for the five SSPs

SSP1	**Sustainability – Taking the Green Road (Low challenges to mitigation and adaptation)**
	The world shifts gradually, but pervasively, toward a more sustainable path, emphasizing more inclusive development that respects perceived environmental boundaries. Management of the global commons slowly improves, educational and health investments accelerate the demographic transition, and the emphasis on economic growth shifts toward a broader emphasis on human well-being. Driven by an increasing commitment to achieving development goals, inequality is reduced both across and within countries. Consumption is oriented toward low material growth and lower resource and energy intensity.
SSP2	**Middle of the Road (Medium challenges to mitigation and adaptation)**
	The world follows a path in which social, economic, and technological trends do not shift markedly from historical patterns. Development and income growth proceeds unevenly, with some countries making relatively good progress while others fall short of expectations. Global and national institutions work toward but make slow progress in achieving sustainable development goals. Environmental systems experience degradation, although there are some improvements and overall the intensity of resource and energy use declines. Global population growth is moderate and levels off in the second half of the century. Income inequality persists or improves only slowly and challenges to reducing vulnerability to societal and environmental changes remain.
SSP3	**Regional Rivalry – A Rocky Road (High challenges to mitigation and adaptation)**
	A resurgent nationalism, concerns about competitiveness and security, and regional conflicts push countries to increasingly focus on domestic or, at most, regional issues. Policies shift over time to become increasingly oriented toward national and regional security issues. Countries focus on achieving energy and food security goals within their own regions at the expense of broader-based development. Investments in education and technological development decline. Economic development is slow, consumption is material-intensive, and inequalities persist or worsen over time. Population growth is low in industrialized and high in developing countries. A low international priority for addressing environmental concerns leads to strong environmental degradation in some regions.
SSP4	**Inequality – A Road Divided (Low challenges to mitigation, high challenges to adaptation)**
	Highly unequal investments in human capital, combined with increasing disparities in economic opportunity and political power, lead to increasing inequalities and stratification both across and within countries. Over time, a gap widens between an internationally-connected society that contributes to knowledge- and capital-intensive sectors of the global economy, and a fragmented collection of lower-income, poorly educated societies that work in a labor intensive, low-tech economy. Social cohesion degrades and conflict and unrest become increasingly common. Technology development is high in the high-tech economy and sectors. The globally connected energy sector diversifies, with investments in both carbon-intensive fuels like coal and unconventional oil, but also low-carbon energy sources. Environmental policies focus on local issues around middle and high income areas.
SSP5	**Fossil-fueled Development – Taking the Highway (High challenges to mitigation, low challenges to adaptation)**
	This world places increasing faith in competitive markets, innovation and participatory societies to produce rapid technological progress and development of human capital as the path to sustainable development. Global markets are increasingly integrated. There are also strong investments in health, education, and institutions to enhance human and social capital. At the same time, 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. All these factors lead to rapid growth of the global economy, while global population peaks and declines in the 21st century. Local environmental problems like air pollution are successfully managed. There is faith in the ability to effectively manage social and ecological systems, including by geo-engineering if necessary.

When these storylines are broken down into concrete variables, the main difference between the SSPs comes from differences in global GDP and population growth, urbanization, access to education, the availability of resources, technology developments, and drivers of demand (e.g., lifestyle changes).

While multiple groups of researchers created estimates of these key variables that were consistent with the storylines, single projections were chosen as representative for each SSP to ensure consistency across the modelling efforts of different researchers (Hausfather, 2018). To illustrate the differences, we show the projections for the SSPs for both populations and GDP globally.

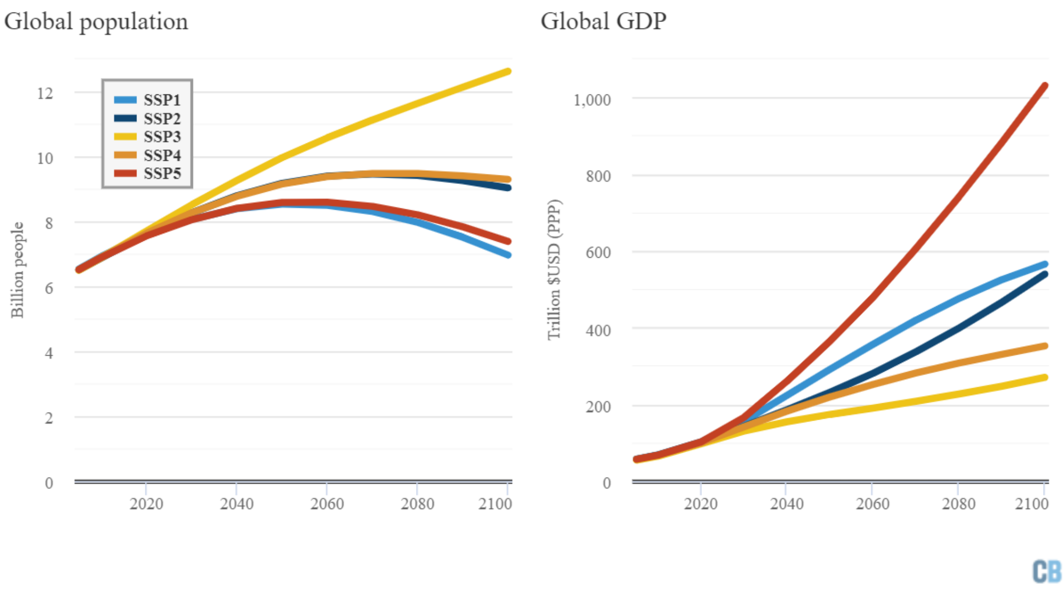

Figure A.1: Global population (left) in billions and global gross domestic product (right) in trillion US dollars on a purchasing power parity (PPP) basis. Figures from Hausfather (2018).

Six of the integrated assessment models (IAMs) we briefly presented in section 6 were used to translate the socioeconomic conditions of the SSPs into estimates of future energy use characteristics and GHG emissions. The models AIM-CGE, GCAM, IMAGE, MESSAGE-GLOBIOM, REMIND-MAgPIE, and WITCH-GLOBIOM ran in total of 24 baseline scenarios for different SSPs, though not all models ran all SSPs. For each SSP a model was chosen as a "marker", in order to make the scenarios easier to compare and work with. For example, researchers would look at the IMAGE model outputs as a marker for SSP1, while the MESSAGE model would serve as a marker for SSP2. The GHG emissions from the IAMs were translated into atmospheric concentrations and temperature rises in the climate model MAGICC. The CO_2 emissions and global mean temperature in the baseline scenarios are shown in Figure A.2.

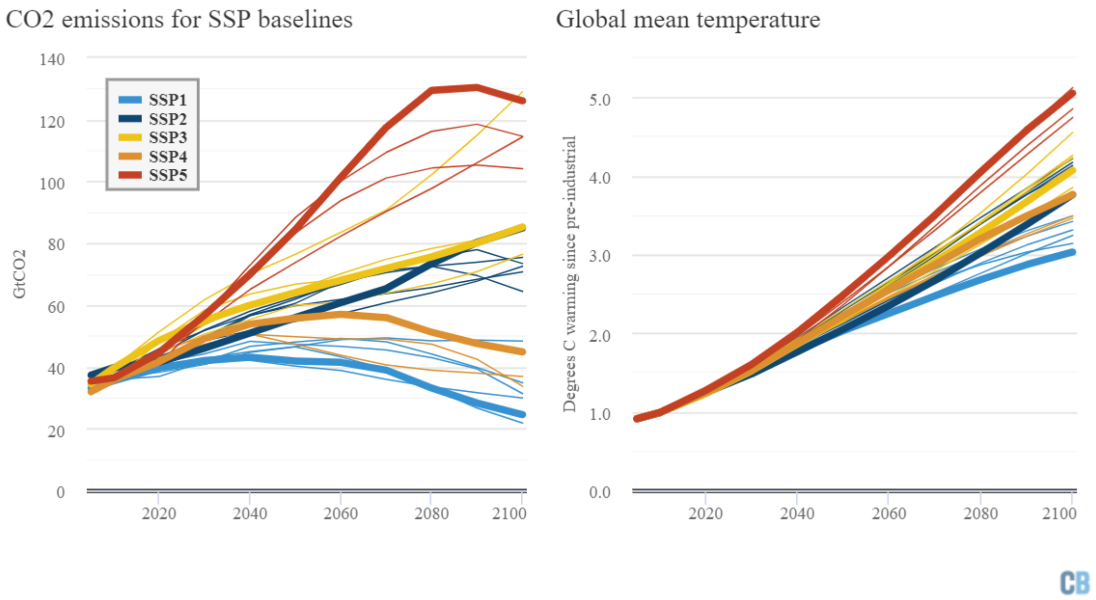

Figure A.2: CO_2 emissions (left) in gigatonnes ($GtCO_2$) and global mean surface temperature change relative to pre-industrial levels (right) in ˚C across all models and SSPs for baseline no-climate-policy scenarios. The "marker" model for each SSP is shown by a thicker line, while all other model runs for that SSP have thin lines. Figures from Hausfather (2018).

It is clear in Figure A.2 that no SSP has a baseline where the goals of the Paris agreement are met, meaning that climate policy with costly abatement measures are necessary. The higher emissions in the baseline, the more difficult and costly the necessary abatement measures will be, reflecting a higher carbon price. This difficulty is reflected in how some models are unable to arrive at a solution that is consistent with the 1.5˚C target. Figure A.3 from Rogelj et al. (2018) shows in the bottom row that reaching the target of 1.9 W m^{-2} in radiative forcing (which corresponds to the 1.5˚C target) was found infeasible for several models SSP2-SSP5. And several models did not even implement SSP3-SSP5 assumptions. No model has been able to solve the 1.5˚C target under SSP3 conditions.

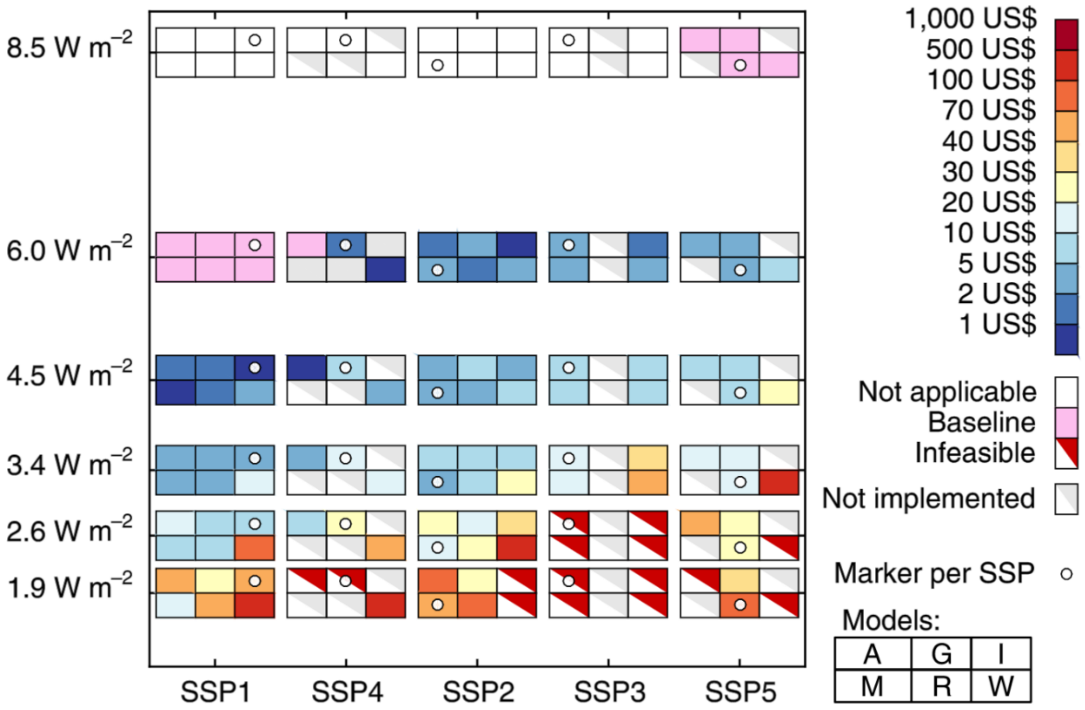

Figure A.3: Variation of carbon prices over SSP and radiative forcing target space. Values are shown as average global average carbon prices over the 2020–2100 period discounted to 2010 with a 5% discount rate. Mitigation challenges are assumed to increase from left to right across the SSPs (that is, SSP1, SSP4, SSP2, SSP3, SSP5). Each box represents one model–SSP– radiative forcing target combination. A, AIM/CGE; G, GCAM4; I, IMAGE; M, MESSAGE-GLOBIOM; R, REMIND-MAgPIE; W, WITCH-GLOBIOM. All scenarios with a carbon price greater than 0 (that is, all but the baselines) have been designed to reach one of the radiative forcing targets on the vertical axis. Models for which no baseline data are indicated have baselines that result in an end-of-century radiative forcing between 6.0 and 8.5 W m^{-2}.

Appendix B: Scenarios with high overshoot

In Table B.1 we display the available scenarios from the IAMC database where the 1.5˚C target is fulfilled, but with a high probability of overshooting. This ensemble of scenarios is included in the first round of assessing relevant carbon prices for CBA, but is excluded in the second round, as the high probability of overshooting, makes it incompatible with the EU net-zero targets. As the target is less stringent than for the scenarios with low or no overshooting, the range of carbon prices is lower. For the 34 scenarios with high overshoot the range is USD 113-3725, compared to a range of USD 126-13400 for the 40 scenarios with low or no overshoot.

Table B.1: Ensemble of scenarios from the IAMC database consistent with the 1.5 ˚C target with high overshoot. Carbon prices in USD_{2010}

Model/Scenario	Model Core	Category	2020	2030	2040	2050
AIM/CGE 2.1|EMF33_WB2C_cost100	AIM/CGE	1.5C high overshoot	3.2	145	399	391
GCAM 4.2|SSP2-19	GCAM	1.5C high overshoot	13.0	70	172	280
GCAM 4.2|SSP5-19	GCAM	1.5C high overshoot	13.0	83	186	303
IMAGE 3.0.1|CD-LINKS_NPi2020_400	IMAGE	1.5C high overshoot	0.0	453	906	1042
IMAGE 3.0.1|IMA15-LoNCO_2	IMAGE	1.5C high overshoot	82.7	673	967	1042
IMAGE 3.0.1|IMA15-RenElec	IMAGE	1.5C high overshoot	82.7	673	967	1042
MESSAGE-GLOBIOM 1.0|ADVANCE_2030_Price1.5C	MESSAGE	1.5C high overshoot	0.0	280	456	744
MESSAGE-GLOBIOM 1.0|EMF33_WB2C_cost100	MESSAGE	1.5C high overshoot	0.2	45	73	119
MESSAGE-GLOBIOM 1.0|EMF33_WB2C_full	MESSAGE	1.5C high overshoot	0.2	43	70	115
MESSAGE-GLOBIOM 1.0|EMF33_WB2C_limbio	MESSAGE	1.5C high overshoot	0.2	73	118	192
MESSAGE-GLOBIOM 1.0|EMF33_WB2C_nofuel	MESSAGE	1.5C high overshoot	0.2	48	78	126
MESSAGEix-GLOBIOM 1.0|CD-LINKS_NPi2020_400	MESSAGE	1.5C high overshoot	0.2	110	179	291
POLES ADVANCE|ADVANCE_2020_WB2C	POLES	1.5C high overshoot	2.7	68	248	428
POLES ADVANCE|ADVANCE_2030_1.5C-2100	POLES	1.5C high overshoot	2.7	38	1700	3725
POLES ADVANCE|ADVANCE_2030_Price1.5C	POLES	1.5C high overshoot	2.7	38	1155	2250
POLES ADVANCE|ADVANCE_2030_WB2C	POLES	1.5C high overshoot	2.7	38	274	532
POLES CD-LINKS|CD-LINKS_NPi2020_400	POLES	1.5C high overshoot	0.7	153	543	1248
REMIND 1.7|ADVANCE_2020_1.5C-2100	REMIND	1.5C high overshoot	1.8	119	195	317
REMIND 1.7|ADVANCE_2030_1.5C-2100	REMIND	1.5C high overshoot	1.8	15	262	427
REMIND 1.7|ADVANCE_2030_Price1.5C	REMIND	1.5C high overshoot	1.8	15	195	317
REMIND 1.7|CEMICS-1.5-CDR20	REMIND	1.5C high overshoot	1.8	102	187	305

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Model/Scenario	Model Core	Category	2020	2030	2040	2050
REMIND-MAgPIE 1.5|SSP1-19	REMIND	1.5C high overshoot	8.1	151	246	400
REMIND-MAgPIE 1.5|SSP2-19	REMIND	1.5C high overshoot	8.1	196	636	1033
REMIND-MAgPIE 1.5|SSP5-19	REMIND	1.5C high overshoot	8.1	106	384	691
REMIND-MAgPIE 1.7-3.0|CD-LINKS_NPi2020_400	REMIND	1.5C high overshoot	1.8	117	190	310
REMIND-MAgPIE 1.7-3.0|EMF33_1.5C_cost100	REMIND	1.5C high overshoot	9.0	131	214	347
REMIND-MAgPIE 1.7-3.0|EMF33_1.5C_full	REMIND	1.5C high overshoot	9.0	113	186	302
REMIND-MAgPIE 1.7-3.0|EMF33_1.5C_nofuel	REMIND	1.5C high overshoot	9.0	147	240	390
REMIND-MAgPIE 1.7-3.0|PEP_1p5C_full_NDC	REMIND	1.5C high overshoot	1.8	14	236	456
REMIND-MAgPIE 1.7-3.0|PEP_1p5C_full_eff	REMIND	1.5C high overshoot	3.1	94	185	301
REMIND-MAgPIE 1.7-3.0|PEP_1p5C_full_goodpractice	REMIND	1.5C high overshoot	3.1	24	216	407
REMIND-MAgPIE 1.7-3.0|PEP_1p5C_full_netzero	REMIND	1.5C high overshoot	3.1	29	196	362
REMIND-MAgPIE 1.7-3.0|SMP_2C_lifesty	REMIND	1.5C high overshoot	26.1	43	69	113
REMIND-Maggie 1.7-3.0|SMP_2C_regul	REMIND	1.5C high overshoot	39.1	64	104	169

Appendix C: Carbon price tables

In the following tables we display the descriptive statistics for carbon prices from the relevant ensemble of scenarios. The corresponding table for 2050 was shown in Section 7 (Table 7.1).

Table C.1: Descriptive statistics from the ensemble of carbon prices for the year 2020, from starting sample (left), to applicable and consistent sample (right). Prices in 2016-Euros.

Prices in 2020	Original sample	Remove studies with high overshoot	Remove studies with unsustainable BECCS	Remove studies with more than 10x increase 2020 to 2030
N	80	46	17	6
Min price	0	0	1	45
25th pctile price	2	2	2	57
Median price	8	16	5	78
75th pctile price	57	82	50	82
Max price	171	171	101	101
Average price	30	42	27	73

The 55th percentile (cf. recommendations in section 9) for the 17 carbon prices that are consistent with low or now overshoot, and do not rely on unsustainable BECCS, is 9 Euros in 2020. For the 6 remaining carbon prices after removing studies with more than 10x increase from 2020 to 2030, the 55th percentile is 80 Euros.

Table C.2: Descriptive statistics from the ensemble of carbon prices for the year 2025, from starting sample (left), to applicable and consistent sample (right). Prices in 2016-Euros.

Prices in 2025	Original sample	Remove studies with high overshoot	Remove studies with unsustainable BECCS
N	84	50	20
Min price	13	38	38
25th pctile price	49	94	59
Median price	99	144	141
75th pctile price	185	253	253
Max price	3012	3012	3012
Average price	178	253	293

The 55th percentile price for the 20 carbon prices that are consistent with low or now overshoot, and do not rely on unsustainable BECCS, is 166 Euros in 2025. This is about 18% higher than the median price.

Table C.3: Descriptive statistics from the ensemble of carbon prices for the year 2030, from starting sample (left), to applicable and consistent sample (right). Prices in 2016-Euros.

Prices in 2030	Original sample	Remove studies with high overshoot	Remove studies with unsustainable BECCS
N	84	50	20
Min price	14	57	69
25th pctile price	87	178	131
Median price	178	225	244
75th pctile price	363	625	476
Max price	6023	6023	6023
Average price	346	491	583

The 55th percentile price for the 20 carbon prices that are consistent with low or now overshoot, and do not rely on unsustainable BECCS, is 289 Euros in 2030. This is about 18% higher than the median price.

Table C.4: Descriptive statistics from the ensemble of carbon prices for the year 2040, from starting sample (left), to applicable and consistent sample (right). Prices in 2016-Euros.

Prices in 2040	Original sample	Remove studies with high overshoot	Remove studies with unsustainable BECCS
N	84	50	20
Min price	69	92	93
25th pctile price	194	291	285
Median price	326	548	542
75th pctile price	898	962	962
Max price	12046	12046	12046
Average price	737	991	1235

The 55th percentile price for the 20 carbon prices that are consistent with low or now overshoot, and do not rely on unsustainable BECCS, is 638 Euros in 2040. This is about 18% higher than the median price.

Appendix D: Key characteristics of the modeling underpinning the central trajectory

The 55th percentile carbon price in the chosen sample from the IAMC database consists of the average of the following two scenarios:

(i) AIM/CGE 2.1|CD-LINKS_NPi2020_400
(ii) IMAGE 3.0.1|IMA15-LiStCh

The first of these scenarios is documented in McCollum et al. (2018), while the latter is documented in Van Vuuren et al. (2018).

These scenarios have some key commonalities. They are both in the category of achieving the 1.5ºC target, but with low overshoot. They also both have SSP2 ("Middle of the Road" – see Appendix A) as the baseline scenario assumption.

Comparing these scenarios in section 6.4, we see that they are quite different with regards to energy production and energy mix. Scenario (i) has more than 30% higher production than (ii), and (i) is far more reliant on renewables and biomass. Scenario (i) also has a higher usage of CCS, while scenario (ii) has a higher use of afforestation.

McCollum et al. (2018) is an extensive study with multiple scenarios from multiple models, so there are not many details specifically on scenario (i). The authors note that AIM/CGE is one of the models that exhibit the largest increase in supply-side investments in the 2C and 1.5C pathways (along with REMIND-MAgPIE) and also among the ones with the most rapid upscaling of renewable electricity capacity, principally solar photovoltaic and wind. This, by extension, has implications for increased electricity transmission and distribution (T&D) and storage investments. Figure D.1, which is taken from Figure 2 in McCollum et al. (2018), gives an illustration of this. We have drawn an arrow pointing at scenario AIM/CGE 2.1|CD-LINKS_NPi2020_400.

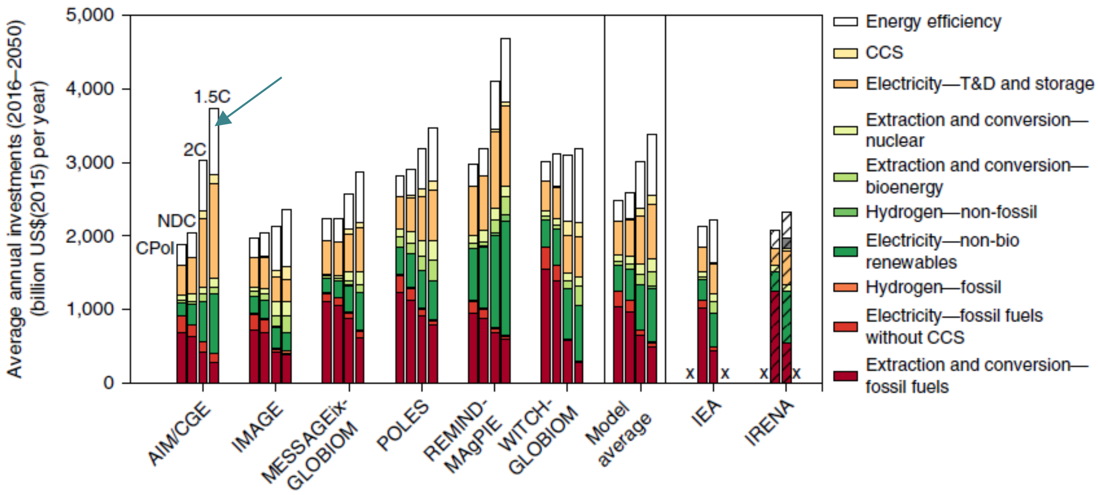

Figure D.1: Projected global-average annual energy investments by category from 2016 to 2050 according to different models. From Figure 2 in McCollum et al. (2018)

Scenario IMAGE 3.0.1|IMA15-LiStCh from Van Vuuren et al. (2018) is a scenario where they explore the possibilities for large-scale lifestyle changes (LiStCh) as an alternative to relying on negative-emission technology. This scenario, a version of SSP2, has the following key assumptions:

> *Consumers change their habits towards a lifestyle that leads to lower GHG emissions. This includes a less meat-intensive diet (conforming to health recommendations), less CO_2-intensive transport modes (following the current modal split in Japan), less intensive use of heating and cooling (change of 1C in heating and cooling reference levels) and a reduction in the use of several domestic appliances (Van Vuuren et al., 2018).*

In addition, the aforementioned study of Krey et al. (2019) provides some description of key cost assumptions for the IMAGE 3.0 model. For the interested reader of this report, we provide in Table D.1 the model assumptions for capital costs and operation and maintenance costs for key technologies in the EU, as they are presented in Krey et al. (2019).

Table D.1: Key baseline cost assumption in model IMAGE 3.0. Taken from Appendix 3 in Krey et al. (2019).

VARIABLE	UNIT	2010	2015	2020	2025	2030	2035	2040	2045	2050
Capital Cost|Electricity|Biomass|1	US$2010/kWe	2290.1	2286.3	2259.4	2243.1	2224.8	2204.7	2208.5	2210.7	2211.1
Capital Cost|Electricity|Biomass|2	US$2010/kWe	3022.8	2993.0	2953.0	2872.1	2788.6	2703.1	2615.7	2526.2	2434.7
Capital Cost|Electricity|Coal|IGCC	US$2010/kWe	2231.5	2273.7	2309.1	2276.6	2239.7	2199.3	2155.5	2108.2	2057.2
Capital Cost|Electricity|Coal|PC	US$2010/kWe	1704.5	1748.6	1785.5	1814.1	1839.4	1862.2	1882.3	1899.3	1913.0
Capital Cost|Electricity|CSP	US$2010/kWe	9281.3	4634.2	4351.5	4067.9	3746.4	3497.7	3292.1	3159.3	3042.6
Capital Cost|Electricity|Gas|CC	US$2010/kWe	830.9	851.2	868.3	881.5	893.1	903.7	912.9	920.8	927.1
Capital Cost|Electricity|Gas|CT	US$2010/kWe	453.1	459.6	465.0	469.2	473.0	476.3	479.3	481.8	483.8
Capital Cost|Electricity|Hydro	US$2010/kWe	2195.0	2271.0	2277.5	2495.9	2602.0	2711.3	2814.1	2843.5	2869.9
Capital Cost|Electricity|Nuclear	US$2010/kWe	5022.0	5175.9	5319.5	5407.1	5465.1	5505.9	5529.8	5548.2	5554.0
Capital Cost|Electricity|PV	US$2010/kWe	3535.1	1525.2	1351.0	1273.6	1201.1	1127.4	1063.1	1032.9	1015.3
Capital Cost|Electricity|Wind|Offshore	US$2010/kWe	5861.2	4087.5	3658.4	3350.0	3058.3	2875.4	2786.1	2771.3	2741.6
OM Cost|Fixed|Electricity|Biomass|1	US$2010/kWe/yr	93.4	94.3	95.1	95.8	96.3	96.8	97.3	97.7	98.0
OM Cost|Fixed|Electricity|Biomass|2	US$2010/kWe/yr	103.9	104.7	105.4	105.9	106.3	106.8	107.1	107.5	107.7
OM Cost|Fixed|Electricity|Coal|IGCC	US$2010/kWe/yr	22.6	23.0	23.3	23.6	23.9	24.1	24.3	24.4	24.6
OM Cost|Fixed|Electricity|Coal|PC	US$2010/kWe/yr	20.0	20.5	21.0	21.3	21.6	21.9	22.1	22.3	22.5
OM Cost|Fixed|Electricity|CSP	US$2010/kWe/yr	39.6	40.4	41.0	41.5	42.0	42.4	42.8	43.1	43.3
OM Cost|Fixed|Electricity|Gas|CC	US$2010/kWe/yr	5.6	5.8	5.9	6.0	6.0	6.1	6.2	6.2	6.3
OM Cost|Fixed|Electricity|Gas|CT	US$2010/kWe/yr	5.1	5.2	5.2	5.3	5.3	5.4	5.4	5.4	5.5
OM Cost|Fixed|Electricity|Hydro	US$2010/kWe/yr	13.8	14.0	14.2	14.4	14.5	14.6	14.7	14.8	14.8
OM Cost|Fixed|Electricity|Nuclear	US$2010/kWe/yr	88.4	91.7	94.5	96.7	98.6	100.3	101.8	103.1	104.1
OM Cost|Fixed|Electricity|PV	US$2010/kWe/yr	43.0	42.4	41.0	39.4	37.7	36.0	34.3	32.6	30.8
OM Cost|Fixed|Electricity|Wind|Offshore	US$2010/kWe/yr	101.1	101.9	102.6	103.1	103.6	104.0	104.3	104.6	104.9
OM Cost|Fixed|Electricity|Wind|Onshore	US$2010/kWe/yr	57.1	57.8	58.5	59.0	59.4	59.9	60.2	60.5	60.8

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