The Simple Integrated Assessment Model

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Part 3. The Social Cost of Carbon and Marginal Abatement Costs

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1. Introduction

The price of something, anything, is meant to include not only the profit the seller of that thing expects to make, but also all the costs of producing that thing. However, many situations arise where some of the costs of producing that thing are not either visible or incurred by the seller. Instead, they are borne by wider society, or some sub-set of it. Economists call these hidden costs 'externalities', i.e. they appear external to the system producing, pricing, selling and hence benefiting from this process. Climate change has been viewed as the biggest and most important externality ever identified.

The externality of climate change arises from the fact that the making or use of that thing you are selling or using is associated with some greenhouse gas emissions, which are released into a well-mixed atmosphere, which in turn results in climate impacts (mainly costs) on wider society, both now and in centuries to come. That it has external costs in the now to wider society makes the release of those greenhouse gasses a tragedy-of-the-commons issue[1], with the commons being the atmospheric stock of greenhouse gasses and the climate head space linked to this. That external costs are also spread over significant time horizons because of the persistence of say CO_2 in the atmosphere, and this creates a tragedy-of-the-horizons dimension to the externality, where one generation is robbing future generations of their climate head space[2].

If climate change is an externality, then clearly one solution is to attempt to internalise it i.e. to make sure the climate costs of anything are included into the price of everything. For that we need to know how much each tonne of carbon costs the global economy, both now and over some time frame (horizon) going forward, and then make sure that cost is woven into the price of everything. This is the next big battleground in the climate space, even though it has been a big part of climate analysis for the last 30 years or more.

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[1] https://www.pnas.org/content/114/1/7

[2] https://www.bankofengland.co.uk/speech/2015/breaking-the-tragedy-of-the-horizon-climate-change-and-financial-stability

There are three ways of pricing carbon. The first is cap and trade, as exemplified by the European Emissions Trading Scheme. Here there is no explicit attempt to derive a price. Instead, a regulator (in this case the European Union) sets a cap on emissions in a sector (predominately the power sector and heavy industry), and then sells permits to emit CO_2 in line with that cap. The market then iterates to a price that emitters in that sector are willing to pay to either emit by purchasing permits from those granted them operating below quota, or to avoid this cost by reducing their emissions. This approach has generally led to very low carbon prices, principally because the regulators were too generous on the number of permits issued in any given year (a case of oversupply).

The second approach is to base the price on the cost of avoiding a tonne of carbon. This is known as the Marginal Abatement Cost (MAC), and this is the approach currently favoured by the UK and EU[3]. Here, all options for reducing emissions of a given process are ranked by price and cumulative emissions, and the cheapest X tonnes are selected to achieve the necessary emissions reduction. The total carbon saved divided by the cost of the portfolio of activities that made this saving is the MAC. This has to be done relative to some Business-As-Usual (BAU) counterfactual, where some other possibly cheaper technologies could have been bought that didn't reduce emissions. The UK and EU rightly prefer the MAC approach over its Social Cost of Carbon (SCC) counterpart because it is driven by technology prices, which are somewhat known, and carbon budgets, which can be fixed by policy decisions, thus avoiding having to specify and estimate highly uncertain climate damages as you have to in the SCC approach.

This brings us on to the most contentious and yet important carbon valuation, the Social Cost of Carbon (SCC). SCC is the preferred approach for costing carbon in the US and derives directly from IAMs like DICE. Indeed, DICE was specifically designed to estimate SCC and hence the size of an appropriate carbon tax to internalise climate damage externalities in the price of all goods and services. The concept of SCC is simple, even if the execution is less so. If I add one tonne of carbon to the atmosphere how much does that cost the global economy? For that we need to know how much warming that one tonne causes, something we have discussed at length in Part 1; Section 3.6 of SIAM, and how much damage that elicits, something we covered in Part 1; Section 3.7 of SIAM.

In Section 2 we will estimate the SCC using the SIAM framework. In Section 3 we will estimate something close to the MAC, again using SIAM.

2. The Social Cost of Carbon (SCC)

As discussed above, the SCC is the climate cost attached to emitting one tonne of carbon. This is going to be about adding up all future economic losses associated with that tonne of carbon and time discounting them in some way (or maybe not). A carbon tax is the most obvious manifestation of the SCC cost, and as argued for in SIAM, such a tax is probably the only way you can firewall the Low Carbon Economy (LCE) from providing returns that would otherwise fuel growth of the High Carbon Economy (HCE).

Because we are trying to evaluate future costs, we will use standard economic practice of translating these into Net Present Value (NPV) through the highly contentious act of discounting future returns, which is probably the most problematic aspect of Integrated Assessment Models (IAMs). Discounting is where you say that income (or expenditure) in the future is worth less when viewed from the present. If I gave you a choice of having £10 now or

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[3] https://www.lse.ac.uk/GranthamInstitute/wp-content/uploads/2019/05/GRI_POLICY-REPORT_How-to-price-carbon-to-reach-net-zero-emissions-in-the-UK.pdf

£10 this time next year I bet you you would take the £10 now unless you want to use me as a zero interest bank. What if I offered you £10 now and £15 this time next year? No? So you can see that £10 now is, in all likelihood, worth more to you now than £10 in the future. This is called your time preference and we all do it to varying degrees depending on our personal circumstances. The main debate between Nordhaus and Stern was what discount rate to assume for climate losses? Nordhaus assumed a social discount rate of 3 % yr^{-1} in line with many economic observations and, as a result, DICE quickly discounts the effects of future climate damages. Stern on the other hand in the Stern Report assumes extremely low discount rates on future damages of the order of 0.1 % yr^{-1} because he assumes you cannot treat climate change like normal economic phenomena given it represents an intergenerational and existential threat. As much as I lean toward Stern' view, 0.1 % yr^{-1} is a somewhat arbitrary assumption. You will get to play with the discount rate to decide for yourselves what to do. This will highlight that it's a choice we make in our analysis, not the 'fact' that it is invariably presented as.

In addition to having to set a discount rate, you are also going to have to decide a time frame over which you are doing your adding up to get the NPV. Again, the orthodox thing to do would be to do this over the next 30 years. However, a significant amount of the climate change effects from our tonne of carbon will happen well beyond that time frame, suggesting we need to significantly extend our 'time horizons' to embrace intergenerational timescales in order to try and avoid intergenerational transfers of climate debt. Again, this time frame is a choice we make as analysts, not a fact, and you will get to choose your time frame for your analysis to explore me verses we-terialist perspectives of the SCC.

Hopefully what follows will echo and build on your experiences in SIAM. It is certainly a lot simpler than what you did in the DECARBONISATION and ADAPTATION scenarios and so should now be well within your reach. More importantly, think about each step as you execute it. There is a lot of rich learning to be had in this exercise.

S2.1. Insert a blank worksheet in your SIAM model and label it Social Cost of Carbon. Add the following column headings: YEAR, EMISSIONS, CUMULATIVE EMISSIONS, TEMP. CHANGE, ADDITIONAL DECAY, CAPITAL, CAPITAL LOSSES, DISCOUNT FACTOR, DISCOUNTED CAPITAL LOSSES, NET PRESENT VALUE. Below each, put in the relevant units as per SIAM, other than emissions and cumulative emissions will be in tC (rather than GtC), and the CAPITAL will be in $ (rather than T$).

S2.2. Fill down the YEAR from 2020 to 2100.

S2.3. Emit one tonne of carbon to the atmosphere.

S2.4. Formally calculate cumulative emissions from this for the next 80 years to 2100. I appreciate that is rather trivial for the case where you are adding just one tonne in 2020, but later you may well want to use this framework to work out climate costs of specific proposals where you input a series of emissions over a project lifetime.

S2.5. Now translate these cumulative emissions into global temperature changes 2020 to 2100 just like you did in SIAM i.e. using the transient climate response to cumulative emissions approach where you simply multiply these cumulative emissions by the climate sensitivity in SIAM. Remember we are in tC, not GtC! You may also want to update your climate sensitivity in light of our previous discussions where I estimated total anthropogenic emissions to 2020 at 613 GtC, derived from the atmospheric CO_2 concentration record[4]. Don't

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[4] (410 - 280)2.123/0.45 = 613 GtC. 410 ppmv is the current [CO2], 280 ppmv is the pre-industrial value from

be put off by the fact that this is a tiny amount of warming. It is associated with just one tonne of carbon after all.

S2.6. As you can predict, this temperature change is going to increase the decay rate of productive capital. Given we are above the 1 °C threshold globally, all we need to capture this effect is to know by how much this decay rate has increased following our addition of one tonne of carbon. This is because our entire analysis is going to estimate the effects of one *additional* tonne of carbon post 2020. From Section 3.7 of Part 1 of SIAM we can represent this additional decay as,

$$\Delta d = s_d \Delta T \qquad (1).$$

S2.7. If equation (1) tells you what proportion of global capital you are going to lose each year as a result of your one additional tonne of carbon emitted in 2020, then the amount of capital we lose is

$$\Delta K = \Delta d K \qquad (2).$$

where K is total capital in any given year. We can take that from our SIAM scenarios, and I suggest you use the DECARBONISATION scenario for this.

It is valuable to pause here and think about what the loss of capital, ΔK, represents. Imagine you emit a tonne of carbon from flying to New York on a field trip. This mixes into the atmosphere, warms the entire planet (albeit by regionally differing amounts), which increases the decay rate of productive structures GLOBALLY. Through the loss of those structures your decision to fly induced, all future productive returns associated with those structures were also lost. It turns out that capital is, by definition, the time discounted value of all future returns from an investment, and hence this loss of capital is the full cost of the decision to fly.

This perspective of climate costs contrasts with the alternative income-based view of climate costs traditionally implemented in IAMs. Here, climate costs are simply deducted from GDP or income, reflecting the belief that climate costs can be paid for within year and have no lasting legacy effects. In some sense that is true. If my house floods I repair it using income. But this ignores all the future returns I lost from the things that had to be replaced which were far from end of life.

There is one other mode of climate cost we are possibly ignoring here, and that is effects on productivity. Rather than removing capital or deducting from income, perhaps climate change reduces productivity. So a flood prevents me from going to work, but once the flood is gone the road is open again and I can go to work. We do not include both income and productivity related climate costs here, but instead lump all costs onto capital and that should be kept in mind here on. However, the more important thing to appreciate is that we (me) are emitting a tonne of carbon, but it is the GLOBAL economy that is carrying the cost.

Head the next column CAPITAL and populate it 2020 to 2100 by linking to the SIAM DECARBONISATION scenario. Now predict the climate losses by multiplying the change in decay by the CAPITAL. Almost miraculously you should see that a tiny change in the decay rate of the economy when multiplied by a huge capital value gives a few dollars of loss per year associated with the one tonne of carbon added. Note also this effect persists because CO_2 is

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ice core data. 2.123 converts ppmv to GtC in the atmosphere. 0.45 is the airborne fraction, i.e. the fraction of anthropogenic emissions that stay in the atmosphere, the other 55% being taken up by the oceans and the terrestrial biosphere.

conserved in the atmosphere[5].

S2.8. We now need to add up these climate losses associated with our tonne of carbon. Ask yourself how long into the future you want to do that? Also recall that CBA expects you to include time preference effects. Let us start here by calculating the discount factor resulting from this time preference. In 2020 make this 1 (i.e. no discounting). Then in subsequent years discount this at 3 %/yr to 2100 (adding this factor to the SIAM PARAMETER table). Again, you can play with that discount rate later once we are up and running. Hopefully you should see that $1 in 2020 is only worth 9 cents in 2100. This is nothing to do with inflation given all our dollars are 'constant' in value.

Now multiply your climate loss of capital by your discount factor to get your time discounted climate cost, 2020 to 2100.

S2.9. Finally, we are ready to add up these costs to get our NPV. I suggest you initially do this for 2020 to 2050 (i.e. the orthodox CBA evaluation window), and also 2020 to 2100 (i.e. an intergenerational window). This cost is per one tonne of carbon and hence is, by definition, the Social Cost of Carbon! Currently it is in units of $/tC, whereas it is common to report it in $/t$CO_2$. Why not express it in both units.

I get that for a 3 %/yr discount rate with costs aggregated over 30 years, the SCC is 617 $/tC, or 168 $/t$CO_2$. That is closer to the Stern Review estimate, even though we are time discounting heavily, and about four times bigger than what you get from DICE. If we discount and add up in a way similar to Stern (0.1 %/yr discount rate over 80 years) the SCC rises to 1458 $/t$CO_2$. Ask yourself if that is ethically responsible? If it is, what do you think a world that evolved under that carbon price would be like?

The principle reason for this difference in the SCC estimates from SIAM compared to orthodox IAMs is that we are taking climate damages as the loss of capital, as opposed to the loss of income. The truth is in all likelihood some combination of the two. But let's reflect back on these SCC estimates. If that return flight to New York was one tonne of carbon, then even an orthodox approach to valuing the future would justify adding ~$600 to the ticket price to compensate the global economy for the economic losses this imposed. That would approximately double the ticket price. In addition to reflecting on how that would modify flight purchasing practices, this necessarily leads us to reflect on what we do with this additional money if a ticket were bought. It certainly belongs to those who experienced any losses as a result of our decision to fly, but obviously we can never identify who they are specifically. This suggests the need to put the money into a huge climate compensation scheme[6].

3. The Marginal Abatement Cost (MAC)

Although incredibly illuminating, you can now see the problems surrounding estimating the SCC. This is why both the EU and the UK elected to go with MAC instead. Here we are interested in the cost of trying to avoid emitting a tonne of carbon, which is a technical issue dependent on the cost of the technology you use to do that relative to the cost of the

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[5] We haven't dwelt on the dynamics of the other greenhouse gases. Methane for example is not conserved in the atmosphere, but rather has a residence time of about a decade, being scavenge rather effectively by the OH radical. As a result, although methane is very potent radiatively (as many like to highlight), it is not very persistent in comparison to CO_2.

[6] See Article 9 in the Paris Agreement: https://unfccc.int/files/meetings/paris_nov_2015/application/pdf/paris_agreement_english_.pdf

alternatives. In practice this is done by deciding how much carbon you want to 'save', and then lining up the cheapest set of options that meet that saving to form a marginal abatement curve. The MAC is then the ratio of costs to tonnes of carbon abated[7].

We are going to estimate it slightly differently using SIAM, but the philosophy is the same. In Part 2 Section 3.3 we raised the spectre that perhaps LCE investments were less productive than their BAU counterparts. By way of a reminder, there are two principle reason for this. Firstly, LCE technologies are still somewhat immature, and hence we don't know how to build, implement and use them as productively as we might. In contrast, we have over three hundred years of experience with carbon-based technologies. Secondly, although there is much to deride about fossil fuels, we must respect just how energy dense they are, which makes extracting useful work from them all the more attractive. In contrast, renewables are, by definition, diffuse.

Let's imagine a choice between investing one additional dollar in the BAU and one in the LCE economy. All else being equal, we might expect the returns produced by the BAU investment will be a little higher than the LCE all else being equal. So, in effect, the LCE choice represents a loss for the investor in the short to medium term. However, that is being offset by carbon savings relative to BAU. In short, here MAC is the ratio of those investment losses to those carbon gains, all else being equal.

S3.1. Insert a blank worksheet in your SIAM model and label it Marginal Abatement Cost. Add the following column headings: YEAR, BAU CAPITAL, BAU GWP, EMISSIONS, LCE CAPITAL, LCE GWP, ABATEMENT COST, DISCOUNT FACTOR, DISCOUNTED ABATEMENT COST, MAC. Below each, put in the relevant units with all value expressed in $ (not T$), and emissions in tC (not GtC).

S3.2. Fill down the YEAR from 2020 to 2100.

S3.3. Invest one dollar of capital in both the BAU and the LCE in 2020 and generate the corresponding GWP using the BAU and LCE productivities as derived in your SIAM parameter table.

S3.4. Calculate the 2020 carbon intensity from the BAU scenario and use this to calculate the 2020 emissions from your one dollar's worth of BAU GWP. Careful with your units! Now calculate the 2020 ABATEMENT COST as BAUGWP - LCEGWP. Again, this is how much money an investor is 'losing' as a result of choosing LCE over BAU.

S3.5. To populate your 2021 values, first depreciate your 1 dollar capital investment in the BAU and and LCE using the baseline capital depreciation rate of 3 %/yr. Note, there is no further investment in the BAU or LCE economy after 2020 here and we are deliberately not including climate damages. When you have completed the 2021 row, you should now be able to drag this all down to 2100 and see your BAU and LCE dollars decay exponentially at 3 %/yr.

A3.6. The ABATEMENT COST is spread over time, and as a result we can imagine discounting could be important. Include a DISCOUNT FACTOR column with a 3 %/yr discount rate as per the SCC worksheet, and apply this to the ABATEMENT COST to get your DISCOUNTED ABATEMENT COST. You can now add these up and divide it by the sum of the carbon savings associated with the LCE investment relative to its BAU counterpart. I get that a 3 %/yr discount rate added up over 30 years gives a MAC price of 244 $/tC, or 66 $/t$CO_2$. This is

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[7] http://www.lse.ac.uk/GranthamInstitute/wp-content/uploads/2019/05/GRI_POLICY-REPORT_How-to-price-carbon-to-reach-net-zero-emissions-in-the-UK.pdf

remarkably similar to cross sector MAC prices used in UK Government policy making[8].

What determines MAC here is the difference in productivity of the BAU and LCE capital investments. If you make the two types of capital equally productive then clearly there is no cost of decarbonising and the investor can choose either without penalty. As we explored in Part 2, you can imagine that having deployed less productive LCE investments the drop in productivity would drive endogenous innovation in order to attempt to redress the associated drop in growth, and as we saw in the ADAPTATION scenario this has a profound effect on carbon prices going forward, making them drop dramatically.

4. The Summit

If you have started from base camp at the beginning of SIAM Part 1, and have climbed every inch to this point all I can say is well done you! I really hope you found it worth it. I can't imagine you didn't learn something on the way, even if it was perseverance alone. If you have any feedback for future climbers then please mail me (a.jarvis@lancs.ac.uk) with it and I will be sure to pass it on, modifying this text accordingly.

Climb down safely.

5. Acknowledgements

SIAM has evolved over the past four years as a teaching aid for a 3rd year undergraduate module called Climate and Society. Like me, the students have little or no economics training, and this current draft owes a lot to our slowly resolving ignorance. This 2020/21 revision has also benefited significantly from an ESRC-NISER funded project - Timescales and Investment Dynamics in the Economy (TIDE).

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[8] https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/794737/valuation-of-energy-use-and-greenhouse-gas-emissions-for-appraisal-2018.pdf