A Simple Integrated Assessment Model (SIAM)

Andrew Jarvis, Lancaster Environment Centre, Lancaster University.

Contents

Part 2. Model Building and Scenario Analysis

1. Introduction

In PART 1 we laid out the Model Description for SIAM. In PART 2 we will now implement the model in Excel and run three scenarios. Specifically, we will see what happens under a BAU regime where the effects of climate change are left unmanaged (the BAU scenario). Once you have become familiar with this, we will then use this framework to explore attempting to avoid dangerous climate change through investing in an alternative low carbon economy (the DECARBONISATION scenario). This will lead us to using SIAM to estimate the cost of carbon. Finally, we will explore adapting to climate change through innovating on productivity (the ADAPTATION scenario).

As stated in PART 1, model building in Excel is not for everyone. But let's not lose sight of the objective and motivation here, which is to educate ourselves in the practices of Integrated Assessment Model (IAM) construction, use and misuse, as well as becoming more intimately associated with the systemic characteristics of climate change. Figure 1 again provides the structure we are working with, so all the time you can reflect back on the mechanisms we are attempting to describe.

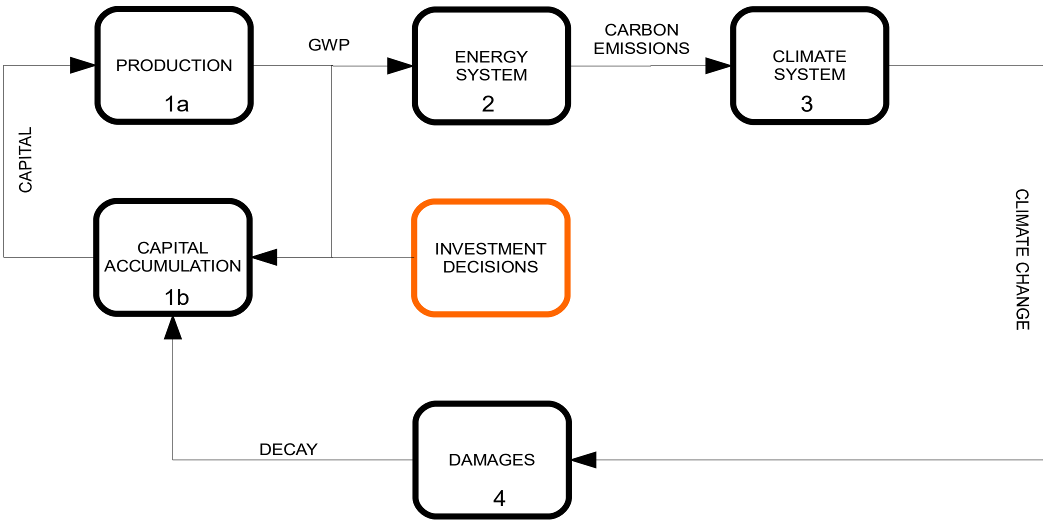

Figure 1. A schematic diagram of the Simple Integrated Assessment Model (SIAM). Numbers denote which equations apply (see accompanying text below).

2. The Business-As-Usual Scenario

In four equations (1-4 - see PART 1: Model Description) we have all the steps we need to specify a description of the global economy and how this might respond to the climate change it induces through the release of greenhouse gases (specifically CO_2). Revisit Figure 1 to convince yourself we are in good shape and that you understand the overall picture.

Other than the one or two tech-heads amongst you, you may view the task ahead as a challenge. However, if we break it down into its component parts and take it one Step (**S**) at a time it is much easier than you might imagine. I am hoping that not only will you acquire some very useful Excel skills in undertaking the task, you will also gain some deep insights into what goes on in the murky world of climate and economic modelling so that when you see published modelling results, or hear experts talk about a price for carbon, you can start to form informed judgements of your own.

If you don't want to have the DIY IAM experience then you can download a complete model, SIAM_full.xls[1], which houses all three scenarios. For those building their own model this finished model will provide a useful check.

S.2.1 Open up Excel and save the fresh file somewhere with an appropriate name (e.g. mySAM_v1.xls). You do not want to lose your work so remember to keep saving periodically. Now rename the worksheet 'BAU'. This is to distinguish it from the 'DECARBNISATION' and 'ADAPTATION' scenarios which we will investigate in sections 3.0 and 4.0.

S.2.2 Here on it is important that you work methodically and keep your workings neat and tidy. If you don't you will easily become confused and unable to spot where you have gone wrong. Again, please consult the completed model regularly if you need to. I am going to assume you can refer to this worked example to check you have implemented the instruction accurately.

S.2.3 Your model is composed of two things, parameters (things that don't change over time) and variables (things that do change over time). As a result, it is good to set out your spreadsheet along these lines. So label the first 8 columns 'VARIABLES' and mark this section off by shading the 9th column. Then label the next 4 columns 'PARAMETERS'.

S.2.4. Label up the 8 variables columns 'YEAR', 'CAPITAL', 'GWP', 'EMISSIONS', 'CUMULATIVE EMISSIONS', 'TEMPERATURE CHANGE', 'DECAY RATE', and finally 'GWP GROWTH RATE'. Units are a big deal here so label them clearly under each column label. Make sure you become familiar with them and can convert between them if necessary. They are themselves a useful currency in all climate discussions.

S.2.5 Table 1 below shows all the parameter values you will need, at least to start off. Populate your PARAMETERS table in your worksheet to match the first three columns. **Please note that, wherever possible, I present parameter values as percentages to help communication. However, you must use their natural unit equivalents unless you tell Excel otherwise.**

S.2.6 We will start our simulation in 1980 because the current trends from which we are extrapolating start around here. I have provided data for you under the 'DATA' tab in the worked example so you can go back and look at how well your model hindcasts in your own time. We will end our simulations in 2100 because that is where most IPCC analyses end. So put 1980 as the initial value in the YEAR column and then create a series under this from 1981-2100. Please do this the long winded way of adding 1 to the previous year so that you get the idea of basing the current value on the previous value.

---

1 https://modules.lancaster.ac.uk/course/view.php?id=31678

Table 1. SIAM starting parameter values and equations

	VALUE	UNITS	EQUATION
K(1980); 1980 total capital value	450	T$	
A; Total factor productivity	6	%/yr	$y=AK$ (1a)
Emissions sensitivity to GWP	0.7	-	$u=0.7\,y^{0.6}$ (2)
Ratio of emissions to GWP growth	0.6	-	$u=0.7\,y^{0.6}$ (2)
Land Use Change emissions	1.5	GtC/yr	
$\sum u$(1980); 1980 cumulative emissions	250	GtC	
Climate sensitivity	1.1/600	°C/GtC	$\Delta T=(1.1/600)\Sigma u$ (3)
Base decay rate of capital	3	%/yr	$d=max(3,3+s_d(\Delta T-1))$ (4)
s_d; Decay sensitivity to GMSTC	1.0	%/yr/°C	$d=max(3,3+s_d(\Delta T-1))$ (4)

Table 2. SIAM starting variables and equations

	VALUE	UNITS	EQUATION
y; Gross World Product (GWP)	variable	T$/yr	$y=AK$ (1a)
K; Total capital	variable	T$	$K(t)=K(t-1)+y(t-1)-d\,K(t-1)$ (1b)
u; Emissions rate	variable	GtC/yr	$u=0.7\,y^{0.6}$ (2)
$\sum u$; Cumulative emissions	variable	GtC	$\Sigma u(t)=\Sigma u(t-1)+u(t-1)$
ΔT; Global Mean Surface Temperature Change (GMSTC)	variable	°C	$\Delta T=(1.1/600)\Sigma u$ (3)
d; Capital decay rate	variable	%/yr	$d=max(3,3+s_d(\Delta T-1))$ (4)
r; GWP relative growth rate	variable	%/yr	$r(t-1)=(y(t)-y(t-1))/y(t-1)$

S.2.7 We are now going to complete the 1980 values for all our VARIABLES. The 1980 value of CAPITAL and CUMULATIVE EMISSIONS (we call these the initial conditions) are given in Table 1. Refer to the cells in Table 1 to populate these values in your VARIABLES columns. Now use equation (1a) to produce the 1980 value for GWP; equation (2) to produce the 1980 value of EMISSIONS; equation (3) to produce the 1980 value of TEMPERATURE CHANGE; and equation (4) to produce the 1980 value of CAPITAL DECAY RATE. Again, check against the worked example to make sure you have got all this right if you need to.

S.2.8 Now move to the 1981 row (only!) of the VARIABLES and, using equation (1b), specify the 1981 value for CAPITAL, carefully referring to the 1980 values of CAPITAL, GWP and CAPITAL DECAY RATE as appropriate.

S.2.9 Now fill across the remaining missing 1981 values of the VARIABLES by dragging down the 1980 values. When you do this you will see something is wrong. The problem is that the PARAMETERS in the associated equations also incremented. We don't want this, we want them to remained fixed on the values in the PARAMETERS section. To stop Excel incrementing the parameters you need to add the $ symbol before the column and row index for each parameter in each equation. This needs to happen to ALL the the parameters used in equations throughout the model, so go back and add the $ symbol where appropriate.

You also need to define the 1981 CUMULATIVE EMISSIONS, which simply requires you add the 1981 EMISSIONS and the land use change emissions to last years value.

S.2.10 It would be soul destroying if we had to keep going through this process each year from 1982-2100. Fortunately, the next 118 years are very simple. Highlight the 1981 row of VARIABLES and drag this down to year 2020. It should fill down automatically now and, providing you haven't got any bugs in your worksheet, everything should work! Again, compare with the worked example to make sure it's all working correctly if you need to. A good tip is to set all VARIABLES to 2 decimal places so that you are not overwhelmed by a sea of numbers. If it all appears to be working, continue dragging down to 2100. Look at the 2020 values of everything and check it makes sense by comparing it with the DATA. For example, how much has it warmed (it should be ~1.2 ˚C)? And what is the current annual carbon emission rate (it should be ~10 GtC/yr)? And what is the current annual GWP (it should be ~85 T$/yr)? Hopefully you should be gaining some idea of what these numbers should be, which is valuable.

S.2.11 It is going to pay to make some graphs to visualise what is going on. Insert a new worksheet and name it say PLOTS. On this sheet insert an x-y graph and set the YEAR as the horizontal axis and GWP on the vertical. Even though you have included climate damages in your simulation it is hard to see that much has changed/is changing going forward. Your figure gives the impression GWP is still growing strongly after all. Indeed, Nordhaus and others would argue that, because we are all five times richer on average in 2100, any climate damages we have seen are more than offset by this increase in absolute wealth. However, as we covered in PART 1, current economies are not interested in absolute wealth, but rather in relative measures and relative growth rates in particular.

S.2.12 Populate the GWP GROWTH RATE column using the expression given in Table 2. On a separate figure plot the GWP GROWTH RATE. Do the same for TEMPERATURE CHANGE and EMISSIONS. Have a think about what you are looking at. Feel free to add/plot other

VARIABLES too to help you if you want. It is important to understand what is now happening in this BAU scenario. The BAU scenario produces results at the 'bad' end of the IPCC SSP BAU scenarios because the endogenous decarbonisation of the energy sector is much less optimistic than what is assumed in the IPCC-SSPs, as is the climate sensitivity. Add the data provided in the DATA worksheet to all four of your plots and judge for yourself if what you are looking at is credible. It looks like it is and even if it is on the bad end of the possible spectrum, this is a good thing to look at if you are precautionary over climate change.

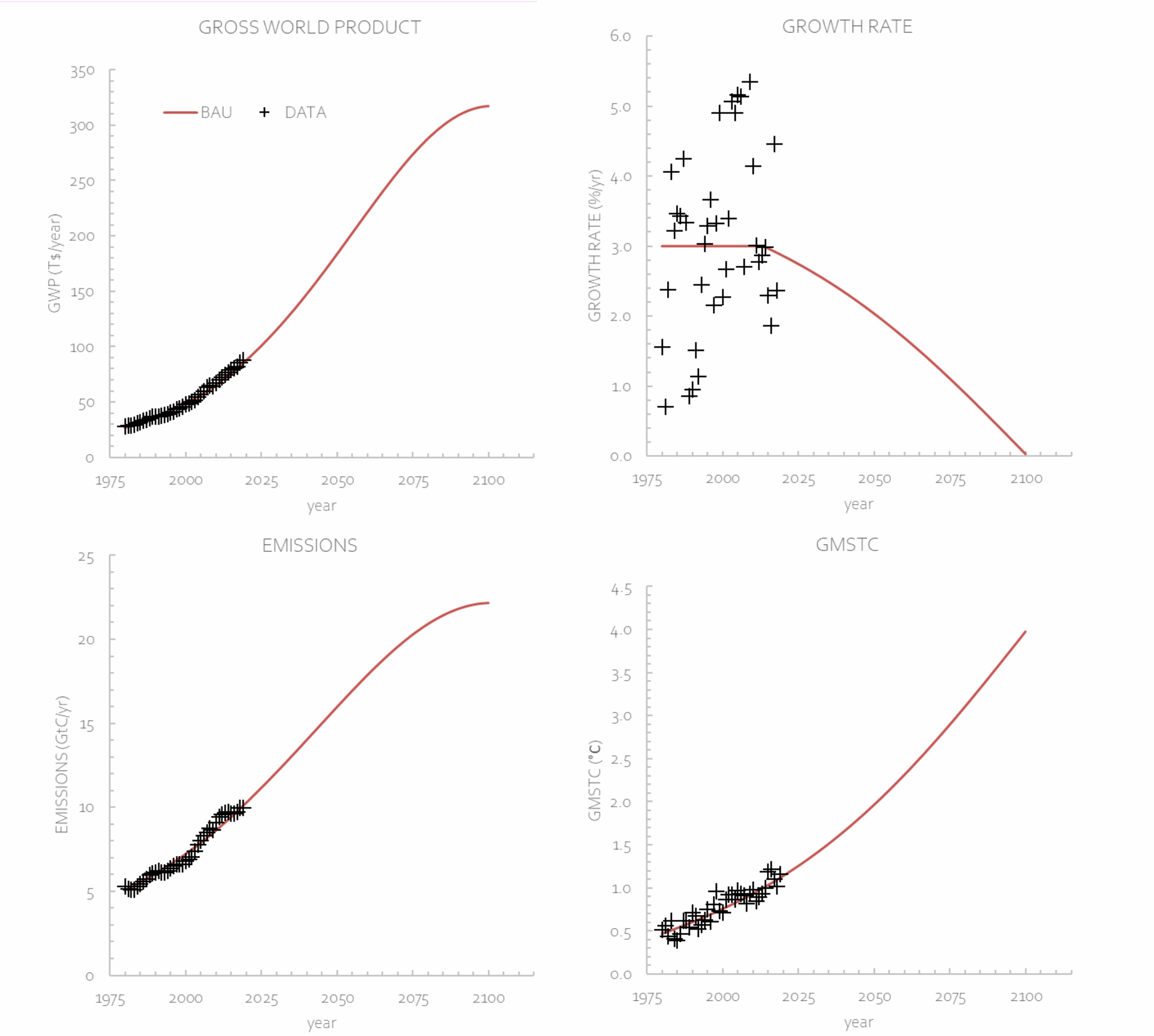

Figure 2. SIAM output for the BAU scenario

S.2.13 As you can see from Figure 2, the effects of climate change above 1 ˚C have significantly slowed the growth in the world economy below 3 %/yr in this BAU scenario. This may not look too dramatic, we are still growing in 2100 after all (just!). However, we are actually looking at the early stages of the climate-induced collapse of this version of the global economy. If you want to find out what happened next to this world economy carry forward your simulation another 50 years and take a look. Specifically, growth goes to zero around 2100 when GMSTC hits 4 ˚C. Above this level of climate change, climate induced losses in infrastructure are greater than rates of infrastructure creation and repair and, therefore, the economy starts to contract with negative growth rates and, therefore, full on depression. This is a terminal state and eventually the global economy wastes away to nothing as climate damages wipe out all infrastructure gradually. I am not saying this will happen (see the next two scenarios), but it is what happens if you extrapolate the Burke et al., damages and assume there is no additional adaptive/mitigative action implemented over and above what happens currently. Clearly such a state would precipitate a lot of adaptive/mitigative actions which would seek to oppose these effects.

S.2.14 Take stock of what we've done. Think about the relationship between the real world and the very simple (and yet I would argue meaningful) simulation we have performed. If it helps, you can see how this impacts on average per capita incomes by dividing GWP by the UN population data provided on the DATA tab. Having just allowed the global economy destroy itself, in the next section we try to 'save' the economy by transitioning to a zero carbon economy.

3.0 The Decarbonisation Scenario

In this section we are now going to try to avoid dangerous interference with the climate system in line with the Paris Agreement. In essence a 'decision maker' is introduced who is able to look ahead (using a climate-society model) to see what climate damages could unfold and then use this information to take steps which avoid any unwanted effects of climate change. Here 'damages' and 'wanted' are very loaded terms because one is immediately provoked to ask from whose perspective?

3.1 The Low Carbon Economy (LCE)

In the economic framework we have set out already, raising energy efficiency is equivalent to increasing productivity, A, which as you can see from equation (1c) raises the growth rate of the economy. This is known as Jevon' Paradox, or rebound and backfire, a feature of the economy that is too often ignored in climate economics, especially at the global scale. If you are interested in looking further into this then Brookes[2] explores this in more detail. Because of this, I contest that the only sensible way to avoid dangerous climate change is to accelerate the rate of decarbonisation of the global economy and this is what we explore here. Later we will explore the effects of raising energy efficiency and hence productivity when we look at the ADAPTATION scenario.

The lever the decision maker can pull in our decarbonisation scenario is to decide how much of the proceeds of from the current High Carbon Economy (HCE) to invest in growing a Low Carbon Economy (LCE)[3]. This new LCE uses energy in exactly the same way the current HCE system does, other than its energy flows are carbon free, although the LCE is slightly less productive than the HCE. The emergence of truly scalable, subsidy-free PV industry alongside the general electrification of many activities within the economy suggests the LCE is

2 Brookes L (2000). Energy efficiency fallacies revisited. Ecological Economics, 28, 355-366 and .

3 We are actually going to grow a zero-carbon economy but I retain the 'high' and 'low' framing as the reader should be familiar with that.

approaching the productivity of the HCE, but the fact that this transition is still seen as having a significant cost barrier implies the LCE is necessarily less productive than the HCE, at least in the short to medium term. We will look at this in more detail shortly. In addition to being operated on nuclear and renewables and the associated electrification of infrastructure and activities, the LCE could also be seen as changes in land use practices, dietary habits, or even the limited development of emissions offsetting technologies, which is certainly a less productive investment.

Although there are low carbon energy sources available presently, the current economy is largely driven (~80 %) by the use of carbon-based sources, with nuclear and renewables comprising the remainder of the global energy portfolio. As a result, it is legitimate to see the new LCE as starting from a low base and growing alongside its HCE counterpart. Here we are going to assume that, although they are mixed together currently, the split of the economy in 2020 reflects the split in the primary energy portfolio i.e. 80 % HCE:20 % LCE.

If we have y dollars to invest each year in capital creation, we are going to invest some fraction of this in the LCE and the remainder in the HCE. In this particular scenario we are going to be ambitious and invest all available GWP into the LCE. This will result in the rapid expansion of LCE whilst the remaining HCE is left to waste away naturally at rate d. This is equivalent to the ~35 year turning circle of the global economy we discussed earlier, where the secular turnover of the economy is not tampered with beyond simply halting all future HCE investment. Contrast this with the situation where, in addition to only investing in the LCE, we actively decommission elements of the HCE. This would be akin to additional measures needed to achieve the 20 year turning circle called for by the IPCC to keep under 1.5 ºC, and the fraction of the HCE actively decommissioned would be referred to as 'stranded asset'[4].

For 100 % LCE investment we are preventing any returns from LCE investments leaking into HCE growth. In reality it appears impossible to physically firewall the returns of one economy from the other like we are doing here, they are by necessity an integrated whole. However, if you don’t there would be nothing to stop the proceeds from the LCE being re-invested in the HCE. Indeed, currently both renewables (and nuclear) co-evolve with fossil fuel energy use, with the proceeds of each promoting the use of the other. This is why the current PV ‘revolution’ is only adding to the global energy portfolio rather than displacing fossil fuels. Therefore, fire-walling the LCE as we are here marks another radical transition in the global economy. I believe this firewall could only be supported by costing carbon emissions at source because it deters re-investment in the HCE at source. We will explore what this cost should be.

3.2 2020

We will be making our LCE investment decisions from 2020 onwards. The reason for this is that this is the implementation date for the UNFCCC Durban Platform and the associated Paris Agreement that was settled in December 2015. Of course, we could start taking action later (otherwise referred to as delayed action), which is often advisable when we are unclear about the relationship between our actions and their consequences. This is true for climate decision

4 Stranding capital means preventing its future use and hence forgoing the returns it was otherwise expected to yield. This is not the same as divestment, which means selling off that capital to someone else to collect the returns from. Although you may feel off the hook divesting from something, the climate system may not be.

making given the very significant uncertainties associated with each of the steps set out in Figure 1. However, there are also very strong arguments for not delaying action, principally because there is so much inertia in both the economy and the climate system, and the risk of inaction could be catastrophic as we saw in the BAU scenario. Even if we stopped building new fossil fuel dependent infrastructure today, it would take more than 35 years for this infrastructure to disappear from the economy. Added to this, the lag between emissions and their impact on climate has timescales range from decades to millennia. The precautionary principle would suggest that early action should take precedence over delayed action when avoiding dangerous climate change although, until Paris, delayed action was very much what was being implemented and looks likely to still be the case in the main. You will see these issues in the scenarios we are about to explore.

3.3 Growing the LCE, degrowing the HCE

What follows is challenging but revealing, so I encourage you to wrestle with it. The very act of partitioning the global economy like this builds a very strong sense of the nature of the global decarbonisation process. We are going to explore a scenario where the world ceases to invest in the HCE post-2020, instead ploughing all GWP into growing the LCE. As a result, the HCE will dwindle away over the coming decades and the returns it produces will be used uniquely to replace the HCE with an equivalent LCE. I am not saying this is a realistic scenario, it is of course very optimistic. But we will see this is now close to what needs to happen if we are to keep GMSTC below 2 °C without having to rely heavily on either carbon removal technologies or stranding assets. Instead it is about all new investment going exclusively into making only LCE capital. The critical thing to appreciate here is that we are going to prevent all investment in the development of new fossil fuel reserves and related downstream capital, instead diverting this investment into growing the LCE. This is equivalent to leaving all the undiscovered fossil fuel in the ground as opposed to leaving all fossil fuels in the ground.

Here on I will not be able to spell every little step out for you and will deliberately leave you to work out some intermediate steps given having made it this far you are clearly able to. Solving and filling in the gaps like this will really cement the learning for you, trust me. It is as if the climb up the mountain is about to become a little more challenging, but still within your reach.

S.3.1 It will help you to study the DECARBONISATION scenario I have produced at this point to get an overview of its structure. Also please keep referring back to this model if you get stuck. You will see that in 2020 we have created two economies; one HCE and one LCE, along with the total global economy which is simply the sum of the two. Prior to 2020 we assume we have followed the BAU pathway and so we begin our scenario in 2020 using the BAU 2020 values as our initial conditions.

Set the start year to 2020 running through to 2100 on a new DECARBONISATION worksheet. The set out the HCE and LCE as two columns each for CAPITAL and GWP. Then set out the TOTAL ECONOMY adjacent to this comprised of EMISSIONS, CUMULATIVE EMISSIONS, TEMPERATURE CHANGE, DECAY RATE, TOTAL GWP and TOTAL GWP GROWTH RATE.

S.3.2 Add the 2020 value for TOTAL CAPITAL, $K(2020)$, to your parameter table taking it from the BAU scenario. Then populate the corresponding HCE and LCE cells assuming 80 % of the 2020 total capital is HCE asset and 20 % LCE asset reflecting the current split of global primary energy use.

We also assume that the A = 6 %/yr of the combined HCE+LCE economy breaks down as follows

$$A_{HCE}=\frac{A}{0.8+0.2h} \qquad (5a)^{5}$$

$$A_{LCE}=h\,A_{HCE} \qquad (5b)$$

where h is how productive LCE investments are compared to HCE. Green economy advocates often believe the productivity of the LCE is greater than that of the HCE (i.e. h > 1). However, renewables are, by their very nature, less energy dense than fossil fuels, although they do benefit from the direct production of very useful (high exergy) electricity. If it turns out that the productivity of the LCE is less than that of the HCE then our investments will be less productive than we had hoped for, which has very important consequences. If we look at the Energy Return On Investment (EROI[6]) of high carbon v low carbon energy portfolios as shown in Table 3, then we might assume the LCE is somewhere between 5 - 10 % less productive than the HCE. Although small, this difference in productivity is the main roadblock to the universal investment in the LCE as you are about to see, through imposing short to medium term additional costs on the global economy. However, we will also shortly see that these costs reap a very healthy return providing we take a longer intergenerational perspective. Finally, we will also see what happens if there is innovation on the LCE productivity. We will assume h = 95 % reflecting the fact that there has likely been some innovation and learning by doing since the data in Table 3 were produced.

Compute values for A_{HCE} and A_{LCE} in your parameter table using equation (5) and populate the 2020 values for the HCE, LCE and TOTAL GWP.

S.3.3 We need to change the way emissions are produced. Equation (2), which represented the way emissions were related to GWP under BAU, no longer holds because the progressive decarbonisation it implies is now captured by the growth of the LCE, which is going to change dramatically post 2020. Instead we need to know the carbon intensity of HCE GWP in 2020, which we assume holds for the rest of the lifetime of the HCE such that,

$$u_{HCE}=\frac{u(2020)}{y_{HCE}(2020)}\,y_{HCE} \qquad (6).$$

Calculate the 2020 HCE carbon intensity as $u(2020)/y_{HCE}(2020)$ in your parameter table and then use this and equation (6) to calculate the 2020 emissions rate for your DECARBONISATION scenario. As you can probably guess, because we are no longer going to invest in HCE capital, this capital will dwindle away and along with it so will HCE GWP and hence the emissions.

5 Have a go at deriving this for yourself.

6 https://en.wikipedia.org/wiki/Energy_return_on_investment

Table 3. The Energy Return On Investment (EROI) for useful energy of a range of energy sources. Usefulness takes account of the fact that combustibles are only ~40 % efficient at doing useful work with the remaining ~60 % being lost as useless heat (unless you develop combined heat and power systems). In comparison, wind, solar, hydro produce electricity directly which is ~80 % efficient at doing useful work. As you can see, the effect of full decarbonisation of the global energy portfolio in this scenario is for the useful EROI to fall by 9 %. This data is from 2010 and the EROI of renewables has improved since. As a result, we will assume a zero carbon energy portfolio is 5% less productive in 2020 than its high carbon counterpart.

Source	Usefulness	EROI		High carbon		Low carbon	
		μ	σ	Contrib. (%)	Useful EROI	Contrib. (%)	Useful EROI
Coal	40.00	44.37	66.30	28.72	5.10	0.00	0.00
Oil	45.00	16.33	7.72	31.46	2.31	0.00	0.00
Gas	50.00	17.14	24.93	21.33	1.83	0.00	0.00
Nuclear	80.00	14.05	20.97	4.75	0.53	4.75	0.53
Hydro	80.00	84.07	82.29	2.40	1.61	2.40	1.61
Biofuels A	30.00	27.37	15.53	10.12	0.83	0.00	0.00
Biofuels B	80.00	14.35	7.43	0.00	0.00	10.12	0.15
Wind	80.00	12.00	11.58	0.41	0.07	27.58	4.56
Solar PV	40.00	9.89	12.20	0.82	0.06	55.15	4.36
TOTALS					12.4 ± 8.6		11.2 ± 5.4
RATIO							0.91

S.3.4 You can now specify the CUMULATIVE EMISSIONS, TEMPERTURE CHANGE, and CAPITAL DECAY RATE variables of the TOTAL ECONOMY for 2020.

S.3.5 We now introduce how CAPITAL grows/shrinks in the HCE and LCE post 2020. Put simply, we are going to invest all TOTAL GWP in the LCE post 2020, and nothing in the HCE. As a result, our capital decays in the HCE according to

$$K_{HCE}(t)=K_{HCE}(t-1)-d\,K_{HCE}(t-1) \qquad (6a)$$

and accumulates in the LCE according to,

$$K_{LCE}(t)=K_{LCE}(t-1)+y(t-1)-d\,K_{LCE}(t-1) \qquad (6b).$$

Perhaps it would be good to revisit Section **3.3 Capital** in the PART 1 to remind yourselves of how this works because this is absolutely critical to understanding the low carbon transition. Use these two equations to populate the corresponding 2021 CAPITAL values for the HCE and LCE. You should now be able to populate all 2021 values.

S.3.6 Once you have set up 2021 properly for all variables, fill down the HCE, LCE and TOTAL economies to 2100. Again, check against the full model provided if you feel you need to. Add the DECARBONISATION TOTAL GWP, EMISSIONS, GMSTC and GROWTH RATE to your BAU plots. Hopefully this looks something like my Figure 3 below. I want to use this to consider costs of decarbonisation, but before we do lets reassure ourselves things are as expected. Note that emissions decay away slowly over the rest of the century as HCE capital depreciates at its planned rate. As a result, cumulative emissions and hence GMSTC tend to a constant, which for the latter is reassuringly below 2 ˚C, but not necessarily "well below 2 ˚C" as asked for by the Paris process. This suggests that <2 ˚C looks achievable within the turning circle of the current economy if we stop all HCE investments in 2020, whereas 1.5 ˚C target appears to require some other radical intervention. Again, this could be either early decommissioning of HCE capital (the stranded asset problem), or geoenigneering, so no wonder these are hot topics currently.

Note how, although reducing growth in the short run due to the drop in productivity, decarbonisation rescues growth in the medium to long run when compared to BAU through avoiding climate damages (Figure 2). This raises a very important issue. The Paris process is not necessarily about changing the economy, but rather could be seen as an attempt to try and keep the economy going in its current form as much as possible. That certainly is how much of the proposals currently on the table should be interpreted. This is also reflected in the way IAMs are configured to minimise socioeconomic disturbance. If so, all the other issues associated with the economy's current configuration, including inequality and ecological destruction, could be left unaddressed. That somehow feels like a missed opportunity to address the systemic risks presented by the prevailing me-terialist agenda.

It is interesting to explore the effects of delaying radical action beyond 2020. How about trying starting the radical decarbonisation investments in 2025? You will find that you will have exceeded the Paris carbon budget significantly even in this short time frame. This is because you have both 5 years more growth to account for, so the HCE is 16 % bigger, and you have used up 5 more years worth of your carbon budget. Although covid-19 hasn't helped, the radical actions post-2020 called for by the Paris Agreement have not been enacted.

S.3.7 Once you are convinced you have SIAM running properly for this DECARBONISATION scenario we need to explore costs. Insert a new worksheet and call it AGGREGATE COST OF CARBON. After having added YEAR as the first column and populated it 2020 to 2100, label the next column 'COSTS' with units of T$/yr. There are numerous ways of defining costs, but an obvious one is the difference between the dollar output of the BAU and DECARBONISATION scenarios. This cost is a mixture of both short to medium term loss of income from reductions in productivity set against any long term loss of income from climate damages. As a result, it is a hybrid of the Social Cost of Carbon (SCC) and Marginal Abatement Cost (MAC) we will explore in Part 3. Calculate this annual cost by subtracting the DECARBONISATION GWP from its BAU counterpart.

The dynamics associated with the turnover of capital and the way GMSTC responds to cumulative emissions means we need to look at cumulative costs because a cost in any one year is not tied directly to the carbon savings in the same year. So next to the COSTS column create a CUMULATIVE COSTS column from it. As shown in Figure 3, this is revealing. These cumulative costs rise to a maximum in around 40 years until the DECARBONISED economy overtakes its BAU counterpart. Again, this is because the productivity drop associated with transitioning to the LCE is near immediate, whereas the climate savings take many decades to materialise. It is because of this investors are put off from such a radical transition, even though after 2075 the LCE investment is fully paid off. Only an intergenerational investor would find such a proposition attractive. Currently capital is designed to last ~35 years on average, reflecting the fact that investors predominately want all their returns within their working lifetime; the me-terialism economy as discussed earlier. This shows us keeping well below 2 °C appears to demand we-terialist investment practices.

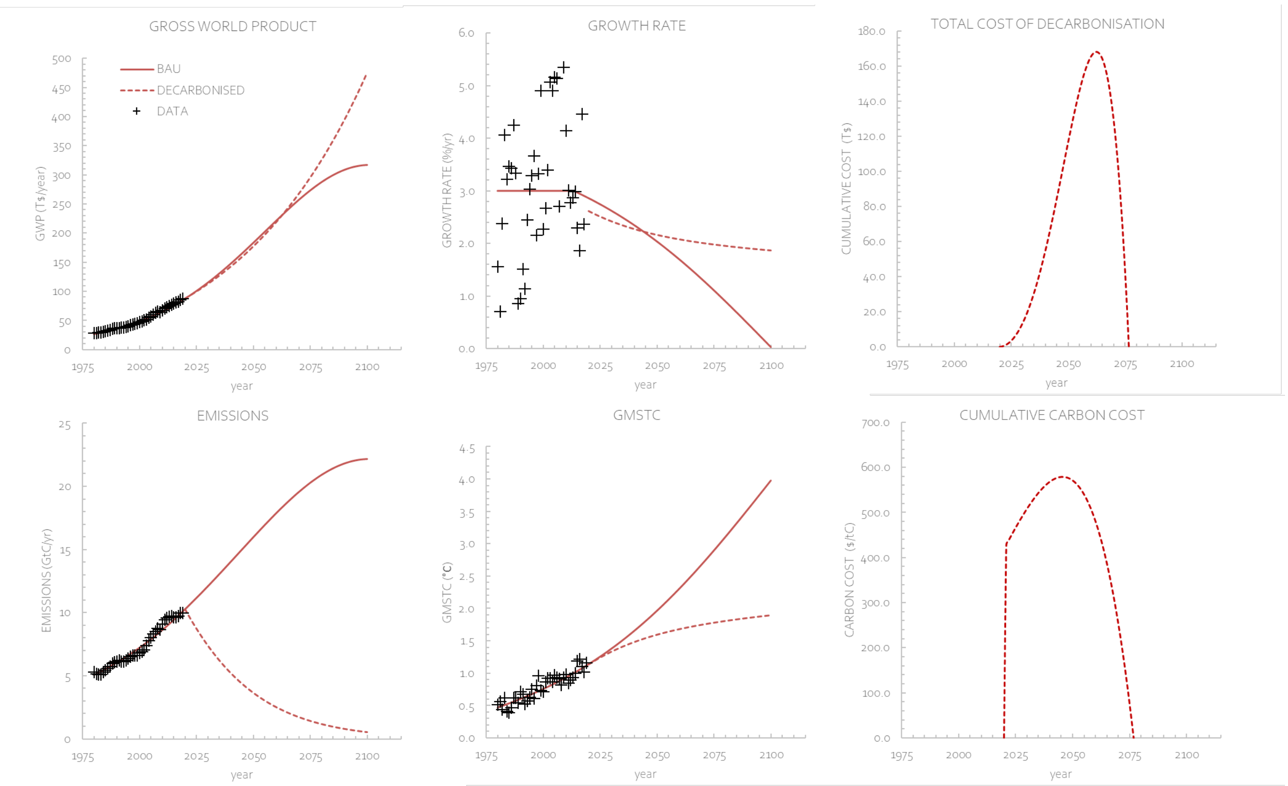

Figure 3. SIAM output for the BAU and DECARBONISATION scenarios

S.3.8. Repeat 3.7 for carbon savings. Then divide your GWP costs by these carbon savings and you will produce an estimate for the implied cost of each tonne of carbon saved. Because our costs include both productivity loss and climate damages this carbon cost needs to be called the AGGREGATE COST OF CARBON (ACC). This then marks it out from the SOCIAL COST OF CARBON (SCC) and the MARGINAL ABATEMENT COST (MAC)[7], both of which are critical metrics in climate negotiations and decision making. We will estimate the SCC and MAC later in Part 3, but for now Figure 3 shows the ACC is big, starting at around 400 $/tC and rising quickly to 600 $/tC by 2050. If true this indicates we need to pay a lot more for our emissions than we currently do[8].

---

7 The Social Cost of Carbon is principally associated with the climate damages of one tonne of carbon, whereas the Marginal Abatement Cost can be seen as the additional cost of a low carbon investment relative to its high carbon counterpart, and hence aligns with productivity costs. The US have preferred the SCC approach led by Nordhaus, whereas the EU have preferred the MAC approach given climate damages are so difficult to forecast.

8 Both MAC and SCC estimates range from 30 to 300 $/tC so our ACC estimate is certainly at the upper end of this range if not significantly above it.

4. The Adaptation Scenario

Perhaps the defining attribute of our economy is that it is wildly adaptive. By this I mean that when presented with a problem you can bet that the economy will try and solve or evolve around it so that it can continue on its way. We tend to call this innovation, but it actually takes on many forms. For example, for climate change it can be using air conditioning to lower mortality rates. However you choose to see adaptive measures, we invariably come back to the central mission of adaptation though, and that is the protection and enhancement of existing elements of society and the economy that flows from this. So raising the levee protects the town centre allowing it to continue to function, and this is little different from inventing a more efficient truck allowing you to transport stuff further thus widening the market.

A recent paper by Cumming and von Cramon-Taubadel[9] uses Burke' damage function to naively speculated that society would simply accept the impact of climate losses on the economy in much the same way your BAU simulation did. As a result, they foresaw a 'helpful' negative feedback of the climate on the economy, slowing growth and hence the pace and magnitude of climate change. Not only would we expect society to fight this, it is likely that emissions would further increase per unit GWP spent on repairing damages given these would be emergency expenditures.

There is much that can and is said about adaptation, and the IPCC dedicate the most space to this critically important topic in their Assessment Report process[10]. It certainly is the most complex of the climate change processes, mirroring many facets of biological evolution. However, take a closer look at adaptation and we invariably find it is responsive, and by this I mean it is the reaction to problems. Yes we often talk about planned adaptation when thinking about climate change, but closer inspection of that also reveals it is invariably precipitated by the emergence of previously unforeseen risks. The reason for this is obvious. Adaptation is about accommodating unforeseen change, and the economy is not unique in this regard, with biology and ecology wrestling the same difficulties when attempting to survive and thrive in an uncertain, highly variable environment.

Although we call decarbonisation 'climate mitigation', it too could be viewed as an adaptive response to an emerging risk. It is interesting in this respect that we are only now actually talking about real actions to reduce emissions once real climate damages have started to bite. But it is useful to think about other adaptations the global economy will undergo in our scenarios and one obvious one is the role innovation plays in raising the productivity of capital structures. The entire industrial and post-industrial era can be viewed through this lens, with the subsequent changes in productivity marking out the march of technology as an adaptive response to a changing world, a world changed by that very process. This is a further reason why all adaptation is endogenous.

In the BAU and DECARBONISATION scenarios we saw the growth rate of the economy drop because of both climate damages and the productivity difference between the HCE and LCE. The one thing we can be sure of is that the economy would not tolerate this, with this experienced loss precipitating innovations in order to try and restore growth. This is precisely what enhanced energy efficiency is, the changing of the way capital behaves to extract more

9 Cumming A and von Cramon-Taubadel S (2018) PNAS, 38, 9533–9538.

10 https://www.ipcc.ch/report/sixth-assessment-report-working-group-ii/

useful work from any given flow of primary energy in response to a drop in that efficiency. This extends well beyond our traditional view of energy, right through to more productive modes of working in an office, or more productive agricultural practices. When the economy underperforms, pressure mounts to raise productivity, whether that underperformance is as a result of climate or any other obstacle, and underperformance for at least the last three hundred years has amounted to drops in growth. I say this not to celebrate this adaptive capacity, although you have to admit there is something truly awesome in its creative power, but rather to alert us to the difficulty we face if we believe we need to stand in its way. For now I will only try and describe it in a simple SIAM-like way so that you can see its effects for yourself. We can then discuss them along with the adaptive process itself.

What I have described above as adaptation is something akin to goal-seeking behaviour[11], and not only can we implement this in SIAM, in doing so it should teach us something profound about economic adaptation of all forms. The way I have described adaptation above implies an objective, either stated explicitly, or, in the case of the global economy, implicitly. In the case of the history of the economy this target appears to be maintaining positive growth rates. Again, feel free to disagree with that objective, I do, but at least appreciate this is the status quo we have to build from even if we desire change. Next, we need to articulate how one behaves to achieve an objective and it turns out there is a canonical description of this that engineers, nature and society 'discovered' completely independently of each other. It is called the integral-of-error response by engineers and it goes like this. If you are where you want to be, carry on doing what you did, else adjust what you are doing depending on how far you are from where you want to be. Try applying that algorithm to a goal you might have and you will see it is incredibly powerful, providing you adjust your position by a sensible amount each time you review and revise your situation.

Let's apply this adaptation algorithm to adjusting the productivity of capital structures, A, as we believe the economy currently does with the goal of achieving 3 %/yr growth.

$$A(t)=A(t-1)+s_A(3-r(t-1)) \qquad (7).$$

Remember r is the GWP relative growth rate such that $r(t\text{-}1)$ is last years GWP growth rate. s_A is the sensitivity of changes in A for every 1 %/yr you are from the goal of 3 %/yr growth. We could digress at this point to have a lengthy debate about intentionality and agency. Are these actions deliberate and is the 3 %/yr intended? The answer is both yes and no. Central Banks really do employ things like this to adjust interest rates, they are called reaction functions. And governments really do now get elected with particular growth rate mandates. But this behaviour can just as easily emerge from the soup of interactions in complex systems[12] and in the body we call this homeostasis[13].

Not only can you now implement this in SIAM to see the effects of adaptation on growth and

11 Unfortunately there isn't a literature that draws together all the biology, control theory, economics, psychology, artificial intelligence material relevant to goal seeking, in an accessible way at least. Perhaps a good place to start is here. https://en.wikipedia.org/wiki/Negative_feedback.

12 https://en.wikipedia.org/wiki/Daisyworld

13 https://en.wikipedia.org/wiki/Homeostasis

climate change, you can now start to think about what other forms of goal seeking the economy could explore that would represent a 'better' goal to achieve. To get you started perhaps the goal should be a particular low level of inequality? What would the economy adapt to achieve that goal?

Before implementing this adaptive behaviour lets try and think about what is adapting with respect to productivity, A. In the real world this is obviously about technological sophistication, or the making of specific capital structures more efficient (think Passivhaus, or Nissan Leaf, or the internet-of-things). But increasing productivity could also be equivalent to innovating on say the amount of stuff (capital) that is sat around doing nothing, or its employment rate. For example, cars sat on drives going nowhere (think Uber), or houses sat empty (think AirBnB). Obviously there is an upper limit on this too when capital is fully employed. Although we don't include this here, you can also think of adaptations which make productive structures more secure in the face of climate change, thereby opposing the climate induced increases in decay (think storm or flood proofing housing). Also keep in mind that all these productivity improvements are not cost free.

S.4.1 Have a go at implementing equation (7) yourself by adapting your DECARBONISATION scenario. Simply create a copy of the DECARBONISATION scenario worksheet and rename it DECARBONISATION+ADAPTATION. Then insert a new VARIABLE column and name it ADAPTED PRODUCTIVITY. Specify this PRODUCTIVITY using equation (7) assuming s_A = 5 %/yr and make your GWP depend on this variable productivity. Then compare the result with your DECARBONISATION scenario. What do you notice as being different, and why?

From Figure 4 we see adapting productivity makes the economy grow far more than it would do otherwise because the effects of climate damages are now being actively opposed by raising productivity. Again, we could imagine this increasing inequality and biodiversity loss, so we must think carefully about whether the innovation driving this process is the good thing it is invariably portrayed as, even by those who might not be traditionally associated with orthodox economics. For example, practically all the 'green' movement literature believes technological innovation and the associated improvements in energy efficiency are de facto good things, just like the economic orthodoxy does. The difference between the two is simply that the 'greens' naively believe this leads to reduced exploitation of nature, whereas the economic orthodoxy selfishly believe nature is ours for the taking.

One good thing that certainly happened is that the cost barrier to decarbonisation is greatly reduced by this adaptation because it has largely eliminated the productivity gap between the HCE and LCE (Figure 4). This cost barrier is currently a critical focus for R&D for Paris and the LCE. In this scenario the low carbon transition now becomes cost effective within 20 years, which is well within reach of orthodox investment practices. Contrast this with the DECARBONISATION only scenario where LCE investments didn't break for over 50 years, requiring the we-terialist investor. Is that good? I'm not sure.

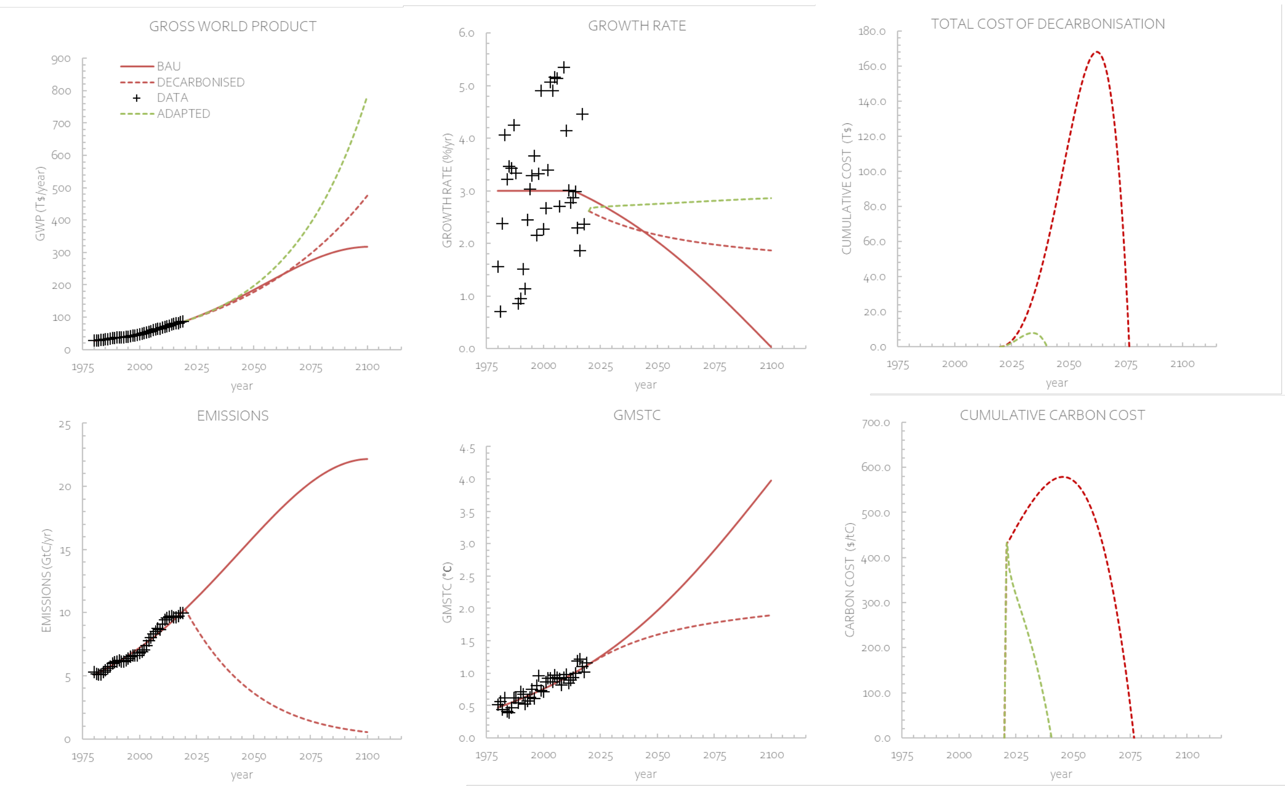

Figure 4. SIAM output for the BAU, DECARBONISATION and DECARBONISATION + ADAPTATION scenarios.

Let's finish by reflecting on how SIAM has evolved. Notice that we have now explicitly introduced purpose and decisions into our analysis – the management of growth under climate change. As with decarbonisation, these turn SIAM from being simply 'descriptive' (i.e. describing the interplay between climate and society) to being 'normative' (i.e. prescribing norms that we wish to impose on the analysis). Although apparently subtle, this is a very important distinction. Currently the norms are largely orthodox growth orientated ones, although throughout I have been provoking you to look sideways at the alternatives as they arose.

5. Summary

We have reached the first summit and need to rest and reflect on the journey up the mountain. We built the core of our model from the conceptual framework lain out in the Model Description, and I thoroughly recommend you go back and re-read PART 1 to cement that learning. We then used Excel to construct a BAU scenario, which we saw led to a ~4 °C world by 2100. We then introduced a DECARBONISATION scenario centred on complete termination of investments in the high carbon economy, with all GWP being channelled into its low carbon counterpart. From this we see that behaviour like this, radical though it is, only just met the terms of the Paris Agreement, and if we delay taking radical action beyond 2020 this is off the table without equivalently radical geoengineering or asset stranding to accompany it. Finally, we added some adaptation on the productivity of capital in order to attempt to maintain growth and found this DECARBONISATION+ADAPTATION scenario led to a much bigger economy while also significantly reducing the size and time frame of the cost barrier to decarbonisation.

In Part 3 we strike out for the top, estimating the Social Cost of Carbon and the Marginal Abatement Cost.

6. Acknowledgements

SIAM has evolved over the past six 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).