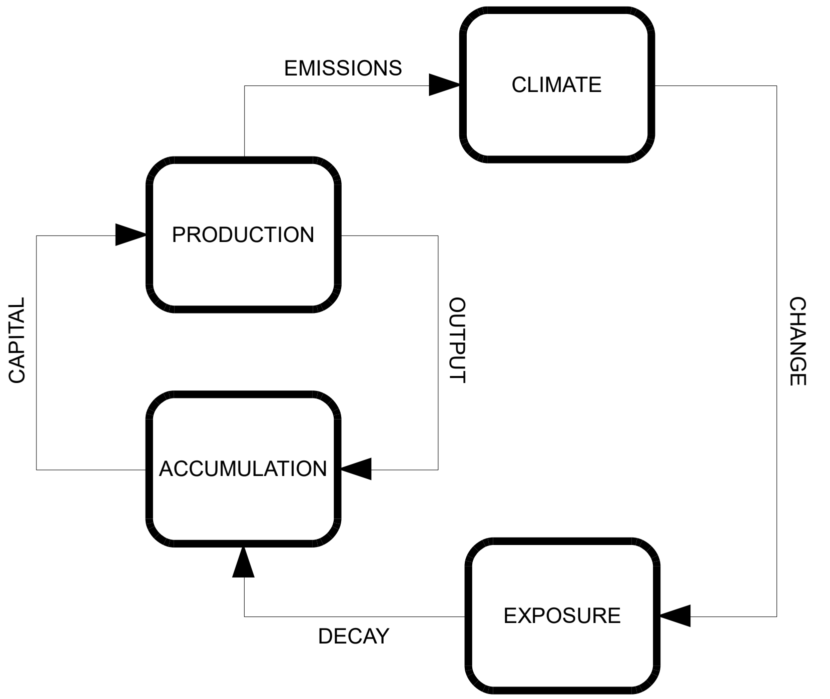
A Simple Integrated Assessment Model
SIAM 2.0



Andrew Jarvis

A Simple Integrated Assessment Model (SIAM) 2.0

PART 1 - Model description

PART 2. Model Building and Scenarios

PART 1 - Model description

1. Introduction

It goes without saying that a useful grasp of the issues surrounding climate change is built on understanding the workings of both the climate system and the economy, and how they interact. My aim here is broaden access to that understanding so that more of us can discuss, negotiate and hopefully act on critically important details that often sit hidden within the domain of the 'climate expert'. No doubt there are many ways I could approach this, but I have chosen to focus on something called Integrated Assessment Models (IAMs). My reason for focusing here is that, despite their very significant failings, IAMs have become the most politically powerful decision support frameworks currently in play in the climate change space simply because they draw together our understanding of climate and economy. As a result, given climate change is one of the biggest issues facing contemporary society, the impetus for wanting to know what an IAM is and to appreciate how they work and are used and abused should be obvious.

This is not the first attempt to communicate the detail of an IAM to a wider audience. Nordhaus and Boyer's seminal book 'Warming the World'[1] was not only one of the first such attempts, the Dynamic Integrated Climate-Economy (DICE) model it reports remains a benchmark to this day and in part earned Nordhaus the 2018 Nobel Memorial Prize for Economics. However, despite being a wild oversimplification by today's IAM standards, unfortunately DICE and its relatives are still too complicated to be communicable to people with no formal training in either climate science or economics. Perhaps this suggests the field is best left to the experts as some experts argue - I don't buy this. Not only do I believe it is important to try and lay bare some of the entrails of IAMs because they have become so influential, experience with teaching this material for the last decade has led me to believe it is possible to do this in a way that is scientifically defensible yet accessible to a surprisingly wide range of people. The trick will be to know where and how to take the necessary shortcuts with a view to making the analysis as simple as possible, but no simpler. It often feels in doing so I'm rowing in the opposite direction to everyone else in the IAM community given they appear to want to make their models look more and more like the real world. For me that path leads to perplexity and confusion because the whole point of a model is that it is not the real world, but rather an accessible map of it and by definition maps are simplifications of the world they seek to represent.

In taking this journey hopefully the learning will be two-fold. First and most important I want you to gain some insight into the growth dynamics of the global economy and how climate plays into this. Only when we appreciate this can we start to conceive of credible ways of addressing this central issue. Related to this, I want you to appreciate the temporal/intergenerational nature of the climate change problem and how current investment practices fail to address this. Secondly, because you get to experience the process of IAM construction from the ground up I am hoping this gives you a more intimate understanding of the interactions between climate and the economy so that you feel empowered to engage in meaningful debate with anyone on interesting and important issues from across the climate-economy spectrum. This might range from mainstream economists at one extreme, through engineers, climate scientists and policy makers, and finally the unorthodox economists and sustainability scientists attempting to straddle this spectrum and

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1 http://www.econ.yale.edu/~nordhaus/homepage/homepage/documents/DICE_Manual_100413r1.pdf

the activists seeking system change. I also need to come clean and say this is a learning journey for me too, one that has been hugely beneficial for my research. Unfortunately, there are moments where I forget my mission to teach and wander off in pursuit of personal insights. I'm hoping you both forgive me and bear with me when I occasionally lapse in this way.

At the risk of stating the obvious, numbers are an inevitable and important component of our climate dialogue and an area I have invested significantly in when preparing this exercise. Firstly, I have tried to keep the number of numbers to an absolute minimum, although I'm sure there is further room for improvement. Secondly, I have tried to make the numbers I use look graspable, memorable, and yet appropriately accurate, rounding them off as best I can to leave their essence. Again, I sometimes fail on this, but in the main I am hoping you find the investment I have made walks a good line between accuracy, precision and parsimony. If I do get this right in places, you should find these numbers are approaching stylised facts about either the climate system or the economy, and if they are, they should be powerful reference points to anchor your climate-related discussions. I am also rounding things off as a way of acknowledging how the considerable uncertainties we face in our analysis affects the precision with which we can use quantities.

The approach I have taken when writing this parallels Nordhaus and Boyer in that it is really a tutorial in IAM construction in spreadsheets like Excel[2]. I am not a spreadsheet nerd, but they are a modelling lingua franca and my aim is to reach the widest possible audience. I am a fan of leading people through the actual model building though, rather than simply providing a a finished product for you to simply press buttons in. This is because, like so many things, the deep learning is in the assembly process much more than it is in the end-use. Please do not be put off by the idea of constructing your own IAM. I have led many who would self-identify as modelling/math-phobic through a range of model building exercises. They invariably declare fear and trepidation from the outset when stood at the bottom of the mountain, but all invariably make it to the summit one way or another if they want to, and value both the journey and the view from the top. The model itself is about as simple as you can possibly conceive in this space (hence the name Simple Integrated Assessment Model - SIAM) whilst hopefully retaining some theoretical and empirical credibility, and we will take small steps. The aim is to educate and illuminate, not to obscure and confuse. That said, as with all mountain climbing, in addition to having the right equipment it requires some application. The climbing will also get progressively harder as your fitness and skill improve.

The reading and doing is arranged as follows. Here in PART 1 we will be introducing what an IAM is and then going through the SIAM model structure and the thinking behind it. This is broken down into five discrete compartments mirroring the model structure shown in Figure 1. In PART 2 we build this model bit by bit, and once built we will use it to explore four canonical scenarios through to the end of this century – Business-As-Usual (BAU), decarbonisation, adaptation and energy efficiency. We end by calculating the cost to the global economy of emitting one tonne of carbon.

For those who do not wish to climb the mountain but would rather enjoy the view from some other vantage point, then I'm hoping this will still be an interesting read where you get to peer into the IAM mindset. I'm also hoping you will engage with issues that strike at the very core

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2 Although other spreadsheets are available, I've opted for Excel simply because of its ubiquity. I've tested the model in freeware like OpenOffice-Calc too, but can't guarantee it is fully portable. That said, I make no use of anything beyond simple cell-by-cell calculations so there shouldn't be a problem.

of the current economic calculus and how it rubs up against the climate change problem. I have tried to make your reading a little richer by occasionally flagging what I believe are relevant and interesting threads to pick up on, but this is far from exhaustive and much of the time I do not give credit to those who built the foundations I stand my construction on. My thinking here was that easily explodes into having to signpost everything, and I wanted to keep the story somewhat self-contained for the reader.

2. What is Integrated Assessment?

The roots of IAMs can be traced back to at least the MIT World3 model that was used as the basis for the ground-breaking and highly influential Limits to Growth book[3]. World3 was the forerunner of using global scale models to alert society to the risks of over exploitation of environmental resources and carrying capacities, a tradition on which IAMs are or should be built. IAMs provide a means of exploring how one might think about trading the economic and social benefits of using fossil fuels (or other activities having a climate impact) against the net loss this use imposes on current and future generations, both human and non-human, through the effects of climate change. This is done by combining two different modelling paradigms; macro-economics and climate systems, to form an integrated climate-economy system view.

The structure of IAMs is simple. The economy with its inputs and outputs interacts with the climate with its inputs and outputs via climate-society feedbacks (Figure 1). What Nordhaus did which was different to the World3 framework was to ask the following question: If using fossil fuels are both good and bad, how much fossil fuel should we use and when to get the 'right' trade-off between these goods and bads? Nordhaus is an orthodox economist working at Yale and so it is no surprise he frames this as an orthodox macroeconomic problem, where 'right' is defined as maximising something related to consumption over some time frame. We will pick up this topic in Section 3.2. The framework implies a rational central planner attempting to judge what is best at the global scale for all concerned and controlling things through a carbon tax. I am not expecting you to agree with this framing, I certainly don't as you will see. The important thing is that you understand this framing so that you can critique its strengths and weaknesses and discuss the alternatives where necessary. This is what we will be trying to do here, in addition to developing some of those alternatives.

3. The Simple Integrated Assessment Model (SIAM)

Recent developments in the field have meant that we can specify a simple yet credible IAM (the Simple Integrated Assessment Model - SIAM) that can be described and implemented in a spreadsheet in a limited number of clear steps. When I say credible, perhaps we need to spell out who might think it is. SIAM is not part of the current IAM community, and many experts would argue it is not credible. However, we have an increasing number of published papers that have grown out of this framework which support large parts of the radical simplifications we are about to make. We will be flagging these en route in an attempt to build some credibility with you the reader.

I think we also need to let you know where SIAM sits in relation to the IAM community. Firstly, in attempting to bring radical simplification to the field we are rowing in the opposite

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3 https://www.donellameadows.org/wp-content/userfiles/Limits-to-Growth-digital-scan-version.pdf

direction to it as we touched on earlier. Secondly, there is a growing sense both in the IAM community and wider society that we must also now row away from the economic mainstream, although much of that community are still camped very close to it while wider society is currently fully immersed. Sections 3.1 to 3.4 provide an account of the global economy that reflects some elements of mainstream economic thinking. I think it is important you see this both because elements of that account provide a useful description of the status quo and hence why climate change is a wicked problem, and because I think it is useful to try and understand the economist's mindset given they have the ear of power. That said, the orthodox economist would, in all likelihood, take great offence over my account given it is so simple and harks back to a pre-world war view. They might also take issue with my drawing on a field known as ecological economics, which views the economy as a metabolic process akin to a biologist's view of energy flows in the body or an ecologist's view of the energetics of an ecosystem. Although this may be an unfamiliar account of the economy for you, I am hoping it goes some way to demystifying some important economic concepts and behaviours. This will largely manifest in me interchanging GDP with useful work, and capital with productive structure. I've agonised over whether this helps or hinders the reader and concluded it is likely empowering to have this additional perspective. The ecological framing certainly helps my mission on radical simplification.

An important thing to keep in view throughout my account is whether I am describing or prescribing something. Too often when I believe I am describing something about either climate or the economy my audience thinks I am prescribing things for it. Take growth for example, which I appreciate is politically charged. We are going to derive a model of the economy that grows simply because that is what the economy has and does do (i.e. it's a description), not because I want it to (i.e. a prescription). This particularly applies to PART 1 which forms the model description. In PART 2 when we look at future scenarios we will get a little more prescriby, and I have worked hard to produce a framework that is flexible enough to explore a wide array of differing futures. My plea here is that you keep asking yourself, 'is Jarvis prescribing or describing?' before you dismiss the narrative.

Our analysis will be global for two reasons. Firstly, the climate system receiving greenhouse gas emissions has no regard for nation or the individual given the atmosphere is so well mixed. Secondly, in the 21st century the global economy is just that – global – marshalling flows of materials, energy, information and people across scales ranging from meters to thousands of kilometres. Trade is global. Institutions and companies are global. The legal and illegal structures guiding the economy are global. It is also the definition of a complex system, the networked interactions of the now ~8 billion people and the structures they create, not to mention nature and the natural world it is all situated within. This global perspective will help in the radical simplification we will be making, but it will also skate over the huge inequities lying just beneath the surface. Although we won't be attempting to capture these quantitatively, we will point to them where possible and encourage some qualitative consideration so that you can use your global results to unpack in your heads the implications for the people and places you believe need thinking about. Hopefully you don't find this approach too depersonalised or monolithic.

The key to not losing yourself in the detail of what follows is to have a map in mind as you work your way through the various steps. Study Figure 1 carefully and try and memorise its components and how they are arranged and connected relative to one another (if you are familiar with the climate change debate then hopefully this will broadly parallel your existing thinking). You should then be able to see where the specific components plug into this overall framework as you go. Maths is a necessary evil in this operation because we need to translate our conceptual picture of the world into an operational model that we can use to extract the numbers we need to put things like the Paris Agreement and net-zero into context. I have made every effort to make this aspect as simple, transparent and accessible as possible, again with a view to widening access to these important concepts. You won't have to do any maths yourself, just don't be put off when you see some, and believe that you have the ability to translate it into a spreadsheet, because you absolutely do. Each step is itself relatively straightforward and you don't need to get the maths to be able to get what is going on in that step, although it often helps. What is confusing here will be that there are a number of steps and that they are arranged in two feedback loops. This is why it is valuable having the map given in Figure 1 in view throughout.

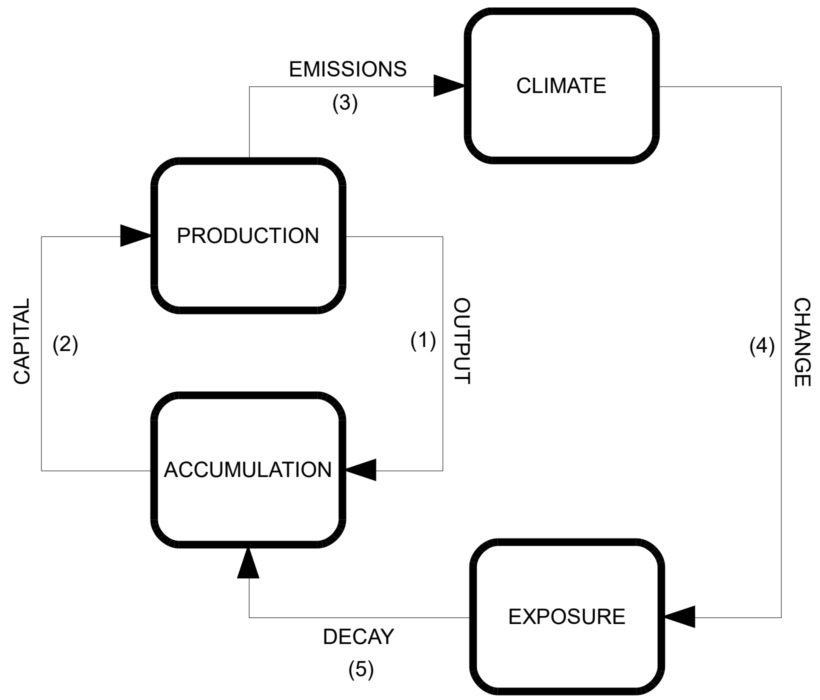

Figure 1. A schematic of the Simple Integrated Assessment Model (SIAM). Numbers denote which equations apply in the accompanying text below.

3.1. Production

Given SIAM is circular (because of the feedback relationships between climate and society – see Figure 1) we can start anywhere in the loop when describing the climate-economy system. I have elected to start where most economists would, with 'production', and specifically with what is traditionally referred to as the 'production function'. This describes how annual flows of output like GDP (or its global counterpart Gross World Product, GWP) are 'produced'[4]. The orthodox view of production is where the flow of GDP depends on 'factors of production', most commonly conceived as productivity, labour and capital. This view appears to be changing as

4 A group of economists called the post-Keynesian's object to this 'supply' view of the economy, preferring to see it as the economy 'demanding' something. The ecological economist is comfortable either way given the networks supply what the cells demand.

the World Bank are now favouring a different perspective centred on labour being viewed as human capital, but this does not change the fundamental role of the production function. Immediately you can see these are not politically neutral positions as it defines how we represent people in our analysis, and not surprisingly this has been a battleground for some of the great economic thinkers including Adam Smith and Karl Marx. I am going to go with the idea that people can be represented through human capital because, as we are about to see, it aligns with an ecological economics view of the world[5]

Having subsumed people into human capital, their contribution to generating output can be placed alongside that of the stuff they have made, which is generally referred to as produced capital. This allows us to throw both people and stuff into a huge pot called total capital and it is this we are going to say drives economic output. Before closing the book and walking away because you feel people are distinct from the things they make, I think it is worth hearing the ecological economists perspective, which would encourage you to view total capital as complex intertwined networks of people and stuff, arranged in very particular, peculiar and ingenious ways so as to produce directed flows of matter, energy and information. In this framing a more accurate label for total capital is 'productive structure' and I will use this term interchangeably with total capital hereon. I would argue it is more ridiculous to try and separate people from the things they make and use when looking at how economic flows happen simply because the network interactions between and within each class are so profound.

Having decided it is total capital that is doing the producing, it is useful to now reflect on what is being produced, which invariably is measured as GDP (or GWP at the global scale). There has been a considerable push-back against GDP of late and understandably so given it in no way attempts to measure only 'good' things, fails to account for a lot of valuable things that do happen, and accounts for things that likely don't happen. But GDP is the measure we have and use, and until a fully formed alternative is to hand, we shouldn't shy away from using it here. After all, the climate risks we are looking to characterise and address don't stem directly from the use of this measure, but rather from a desire to grow using fossil fuels, even though that growth is now measured using GDP.

Having tried to cast total capital as productive structure, I want to also now cast GDP as something physical too, and specifically as the flow of what a physicist or engineer might call useful work[6]. This work derives directly from the supply of primary energy to the economy from both fossil fuels, nuclear, renewables and food. This primary energy is captured and translated into its useful counterpart by the economy's productive structures, and the useful thing it does is to create yet more productive structure through the work of moving mass into highly ordered configurations. Round and round this goes as the economy ratchets itself into bigger ever more complex patterns of behaviour, until of course it can't.

We will go into more detail on what this useful work does in Section 3.3 when we look at how

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5 In previous iterations of this story I attempted to unpack both the difference between human capital and labour and why labour took hold of the orthodox view of production. I've since realised that is too much of a detour deserving a book on its own and hence have avoided that detour this time around. That said, we will revisit the significance of viewing people as human capital at various points. It's a sometimes more liberating perspective than the name might imply, although it always begs questions over who owns that capital.

6 The word 'useful' is also problematic because there of lots of flows that are valued by GDP that many could describe either as useless or, worse still, as harmful. The arms trade springs to mind. So I retain the use of useful in its strict physics/engineering definition, which implies achieving a stated outcome.

productive structures (capital) are made and maintained, but to try and calibrate you a little more, first let's look at this equivalence between the flow of money and the flow of useful work. I estimate that currently the productive structures of the global economy are about 10 % efficient at translating primary energy into useful work. The economy also consumes around 700 x 10^{18} Joules of primary energy a year. If global GDP is currently ~90 x 10^{12} $/yr, then a million Joules of useful work done by the economy is equivalent to (90 x 10^{12})/(0.1 x 700 x 10^{18}) = 1.3 dollars of value. At this exchange rate, a labourer would produce around four dollars a day[7]. That most people earn much more than this reflects the fact they have become adept at using machines to exploit energy sources other than food processed through their muscles. Although we have cast output as useful work, and that work as being the energy expended on productive structure creation, we also need sight of the materials being gathered together and baked into structures by that work. Perhaps most profoundly, we could also see this as the work to encode information in those productive structures.

With only total capital driving the production and GDP, we are led to the AK model of production[8]. Here K is total capital (produced plus human), while A represents the 'productivity' of this capital. By productivity we now mean a measure of the efficiency of productive structures at harvesting primary energy and materials from the environment and translating it into the useful work of creating more structures, although that certainly is not how an orthodox economist would see it. The AK view of production was rejected by economists because it proved unable to successfully accommodate labour. Seeing labour as human capital in the vast web of productive structure comprising the economy perhaps helps resolve this, and the latest available data for global GDP and total capital shown in Figure 3 offers strong support for our choice of the AK model.

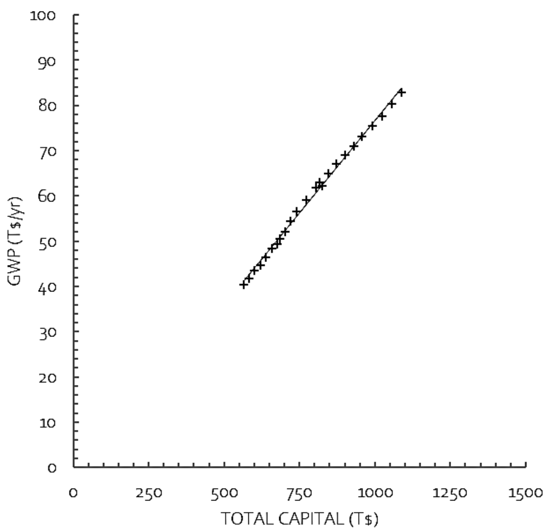

Figure 2. The relationship between World Bank estimates of total capital wealth (K; produced + human) and Gross World Product (y) 1995 – 2018, both in constant dollars. The near-linear

7 People can sustain about 100 Watts of useful power output over an 8 hour working day through their muscles. If a MJ of useful work is equivalent to 1.3 dollars of output, then a labourer could produce 100 x 3600 x 8 x 1.3 x 10^{-6} = 3.7 $/day.

8 This was originally proposed by Harrod and Dolmar over 70 years ago, although their view of production did include labour as a possible limiting factor but reduced to the AK view of production where capital was a limiting factor.

nature of this relationship lends support to equation (1) where $y = 0.075K$.

So if y is the annual flow global GDP (or GWP, or something akin to useful work), then we simply relate this to total capital K and productivity A,

$$y = AK \quad (1).$$

Figure 3 indicates global productivity wanders about a bit as things do in complex adaptive systems, but that is detail as far as we are concerned, and certainly something that is worth overlooking given the vagaries of the data. This is some radical simplification given the complexity of the system we are describing, but it will make our subsequent analysis of economic growth in Section 3.3 relatively easy and transparent.

3.2 Capital

So far, we have described how GWP is 'produced' by the productive structures we call capital. That description required us knowing how big the accumulated stock of total capital, K, is. We create these structures through investing output (in our case GWP) to do the necessary useful work of productive structure making - structures liberating useful work and useful work creating structures, round and round in a feedback (see Figure 1).

It takes work to create productive structures because you have to collect all the necessary materials together (the work of moving things) and then knit them together in the appropriate configuration (the work of connecting and fixing things). Although we are drawn to think of these structures as somewhat fixed, and some certainly are, many of them are much more fluid and ethereal. All of them involve human interactions with each other and the things they make.

Like everything in the universe, once made, structures will immediately start falling apart or decaying. Economist and accountants call that depreciation. Put simply, the increase (or decrease) in the total amount of capital, K, is the difference between the investment of useful work (GWP) making new productive structures, and the inevitable effects of wear and tear, death, destruction and the related end-of-life decommissioning things removing old productive structures. This applies equally to the human capital component of productive structures. People forget, or retire, or have a skill set that becomes obsolete, or lose contact with each other. The accumulation of the stock of the capital of the global economy can and is described by the balance between these creation and destruction processes.

We can state this balance in words as follows. The amount of capital we have this year is the amount we had last year, plus whatever additional new capital we made from investing last year's GWP to make more productive structure, minus any capital we lost last year through depreciation of last year's stock of capital. Let t be time in annual steps such that if t = 2020 then t - 1 = 2019. Now the balance we have just described is given by,

$$K(t) = K(t\text{-}1) + iy(t\text{-}1) - dK(t\text{-}1) \quad (2)$$

Study this and you will quickly see it simply reflects the capital balance articulated in words above if we remember y is GWP, i is the portion of GWP that is invested in the capital creation process each year and d is the representative decay rate of all productive structures.

We could stop here and, as if by magic, simply offer 'suitable' literature-sourced values for i and d to use in our framework as would be the norm in a lot of IAM construction. However, there are some things we need to appreciate about investment and depreciation that have profound implications for both our understanding of the global economy, people's relationship with it, and climate change. I want to start with depreciation and strongly encourage you to dwell here until you absorbed this as it bears heavily on everything that follows. We will discuss the value of i in Section 3.3 when looking at growth.

d has units of per year, so its inverse has units of years and hence $1/d$ is a timescale. Specifically, it can be seen as the average amount of time a piece of representative capital resides in the pool of total capital. The reason why it is important to know this value is because it describes the inertia of the economy and hence how quickly we can lose 'high-carbon' capital and replace it with its 'low-carbon' counterpart. This forms a critical component of the simulations we will look at later and, more importantly, how much of our current high carbon investments we would need to smash up or abandon if we want to meet the terms of the Paris Agreement.

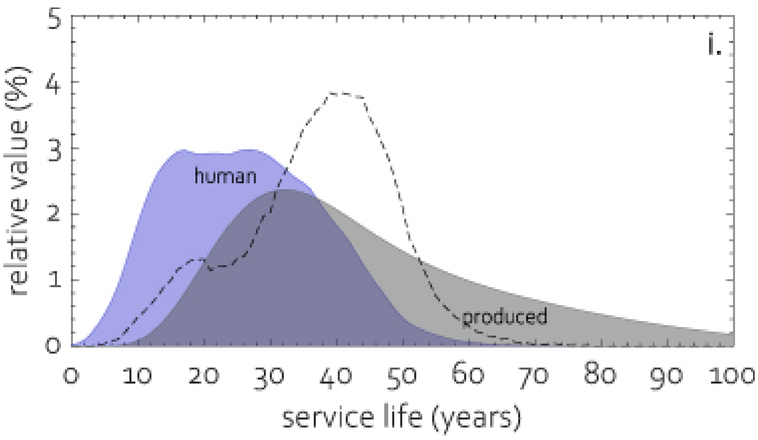

Figure 3. The relationship between capital value and turnover timescale for the global economy[9].

So what value should d take? People tend to think that modern society is characterised by ever more short-lived stuff. However, this view is biased by the fact that, in an exponentially growing system like the global economy, the amount of new stuff always dominates, even if most of it goes on to live a long time. We also forget about the long-lived stuff too quickly even though it is part of everyday life (think bridges, roads, tunnels, forever chemicals, languages ...). Perhaps more profoundly though is how we believe human capital behaves. Careers are built to last decades, with the expected working lifetime having hovered between 35-40 years across the developed world for perhaps a century or more. But the people underpinning this human capital 'consume' a lot of very short-lived things in order to build and sustain these long-lived careers. This line of thinking re-emerges when we consider what

9 https://iopscience.iop.org/article/10.1088/2752-5295/ad7313

value investment, i, should take, but for now the message is that although there are a vast array of turnover timescales attached to the productive structures of the economy, they arrange themselves around a 30 to 40 year average (Figure 3), giving a representative decay (depreciation) rate in the region of 3 %/yr. A review of the IAM models out there would indicate d sits typically somewhere in the range 2 to 5 %/yr, suggesting a representative survival time for capital in those models somewhere in the range of 20 to 50 years.

I argue it is no accident that the turnover timescales for human and produced capital overlap as shown in Figure 3 because this highlights that current investment practices of the people dominating the behaviour of the global economy appear to centre on working to create or support productive structures that provide returns on investment within their working lifetime, for themselves. This is not to say this is an entirely individualistic strategy; it can't be because it involves creating and exploiting productive structures that are large networks of people and things, so when you work on the network you unavoidably make the network work for others too. The actors also inherit productive structures from the preceding overlapping generation and likewise pass a legacy on to the following overlapping generation as part of the social contract. However, the 30-40 year timescale baked into this practice underscores the within generation thinking underpinning it and is simply not long enough to fully embrace the downsides of any emissions these efforts elicit. Furthermore, we have immunised ourselves against knowing that some people and places are disadvantaged by the investment decisions we make.

Capital turnover also tells us a lot about the risks of trying to change the economy too quickly. For example, if you had to transition to a zero-carbon economy in say 25 years in line with a 2050 net-zero objective and yet the economy can only evolve (by replacing productive structures with newer ones) on a 30 to 40 year timescale, something has to fall off the lorry so to speak to allow it to go round the imposed 25 year bend. Of course, that risk has to be offset against the risk of not acting to avoid dangerous climate change. We will also explore this in PART 2 as it relates to the stranded asset problem.

It is vital to gain an appreciation of the growth dynamics equation (2) is attempting to represent. If the fabric of the economy is being produced faster than it is decaying then $iy > dK$ and the capital stock and hence the economy is growing. Alternatively, if that fabric is decaying faster than it is being created then $iy < dK$ and the economy is shrinking. This is a critical aspect of the analysis that follows because we will assume that, prior to climate change becoming significant, iy is 3 % bigger than dK i.e. the structures and output of the economy is growing at 3 %/yr as it has approximately done for a good while (Figure 4). However, as the climate changes the economy will experience ever increasing climate damages, which we are going to assume are expressed through increases in the decay rate of infrastructure, d, so that ultimately $iy < dK$ and the economy shrinks if climate change is not addressed! We unpack this in more detail in Section 3.5 and PART 2.

Before moving on to look at growth in more detail it is important to realise that the combination of the production function (equations (1) or similar) and the capital balance (equation (2) or similar) form the beating heart of mainstream economic growth models, even if they would want to distance themselves from the AK framework. Therefore, if you want to understand where the orthodoxy and its growth agenda is coming from, I strongly recommend you familiarise yourself with these two concepts and their feedback interaction. Simply put, capital liberates flows of output (useful energy) and this output is invested to create capital (productive structure), and so on and so on… It turns out it is no different for your body mass, or the growth of a forest, or the development of a river network. This is how things grow, or stop growing, or shrink and die, which leads nicely onto a consideration of growth.

3.3 Growth

Like it or not, we increasingly see the pursuit of growth as the primary political and economic objective, building on decades if not centuries of growth historically. We don't even discuss GDP much, but rather the focus is on the relative growth rate of GDP. For example, you are very unlikely to know how big global or national GDP is without looking back at Figure 2, but you are much more likely to be able to say what their growth rates were/are. When I ask people from all walks of life to guess GDP growth rates I am always surprised they pretty much always place their guess in the right ball park, at around 3 %/yr globally.

3 %/yr growth sounds modest rather than explosive, after all it means output going up by just a few percent each year. This is only a matter of perspective though: the characteristic timescale for this growth is a little over 30 years, and the doubling time around 20 years (i.e. with 3% growth it takes only 20 years for the economy to double in size), so while on human timescales it is difficult to describe this as explosive, as far as the earth system is concerned it certainly is. Also, by definition growth represents a state on the unstable side of a tipping point, a runaway condition dominated by net positive feedback. Not only has this come to define the current era, it also poses the question of when, how and why we tipped into this state? It certainly was much less of a thing before the industrial era. My money is on relaxing views on charging each other interest, because under it all, economic growth is driven by the expectation of positive returns on loans and investments. That said, I imagine there is in all likelihood a thermodynamic cause behind that becoming a thing.

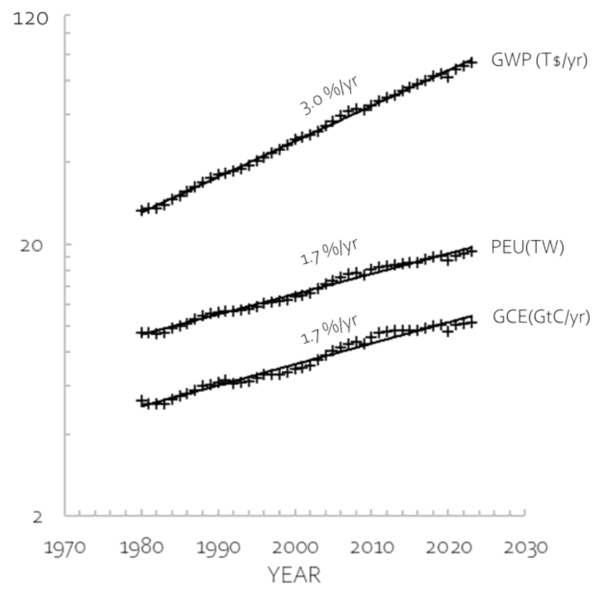

Figure 4. Gross world product (GWP), Primary Energy Use (PEU) and Global Carbon Emissions (GCE) 1980 – 2023. Data and sources listed in SIAM_2025.xls

However we view the reasons for growth, it is a reality that has such profound effects on shaping the current climate change problem (and many other global issues) that it must be a central component of our analysis, even if we might want to explore rowing away from it as an option. Not only does this allow us to explore the consequences of business-as-usual (BAU) behaviours, it also allows us to explore radical alternatives like degrowth, and everything in between, as we will in PART 2. Let's start by defining the relative growth rate, r, using equations (1) and (2). It turns out because equations (1) and (2) are so simple/linear, it doesn't matter whether we look at either GWP or capital, so let's look at GWP growth given this is what we currently choose to talk about so much. Combining (1) and (2) we get $r = iA - d$.

Like the depreciation rate d, the relative growth rate r is an inverse timescale and 3 %/yr again equates to a timescale of 33 years i.e. around that of the turnover timescale of capital itself. This suggests we design capital to live (and die) at the same rate as the economy grows on average, and I would argue this is no accident. Growth demands innovation because getting bigger and more complicated creates problems you have to solve. Innovation means replacing old, less productive structures with new, more productive ones. But you can't replace them too fast otherwise they don't fully yield the returns they were created for. Instead, you try to replace them as slow as possible to get as much return as you can, but just fast enough to counter the considerable downsides of growth. These downsides stem from the obvious fact that as all systems grow in size the cost of distributing resources within them necessarily increases as everything tends to get further apart and the last mile gets ever more tortuous to navigate. This effect is what ultimately halts growth in our bodies and hence limits our size. Economies invest heavily on innovation to overcome these effects through honing distribution networks. In a similar vein, as systems become more complicated, finding the next, more productive configuration of productive structure becomes progressively harder. As a result, we end up replacing productive structures with their fitter children at the rate the system grows. This ties the growth rate of the economy r to the turnover rate of its productive structures d, a topic we will return to in Section 3.6 when looking at climate damages, and again when calculating the cost of carbon in PART 2.

If $r \simeq 3$ %/yr, $d \simeq 3$ %/yr and, from Figure 2, $A \simeq 7.5$ %/yr, then from our growth rate equation $r = iA - d$, we get $i = 6/7.5 = 80\%$ i.e. only 20 % of output is left over once you have accounted for all the investment made in capital creation. Mainstream economics believes it's the other way around, with 80 % being left free for the consumers to have fun consuming. This difference stems from having represented people as human capital, which is approximately three times larger than the capital tied up in 'stuff' or produced capital. A lot of what is currently called 'consumption' appears to actually be productive investments people make in human capital, both in themselves and those they network with[10]. That meal you just ate is helping you now read this, and hopefully that is going to have some lasting impact on your life. This is an important observation because it means the amount of output available to help repair climate damages is rather limited and can't be whisked up by simply consuming less. In PART 2 we will argue that the 20 % of GWP that is left over is also spoken for, invested in order to try and protect productive structures from decay. This issue will be front and centre in the ADAPTATION scenario we tackle in PART 2. All this doesn't mean the planet is not being consumed - it absolutely is, but it is being consumed by being turned into the economy, sometimes referred to as the technosphere.

10 The idea that consumption could actually be productive and underpin peoples ability to do useful things in the future has been around for a long time, as has the realisation that the distinction between consumption and investment is far from clear when you take a closer look. Arthur Pigou wrote about this in the 1920's.

3.4 Emissions

We have spent some time describing the economy, and rightly so, but now it is time to focus on the how this economic activity gives rise to greenhouse gas emissions. Again, it would be good to refer back to the map in Figure 1 to orientate yourself. Here we are going to use carbon and CO_2 as a representative for all greenhouse gas emissions both because carbon dominates our story and because the flows of other non-carbon greenhouse gases are somewhat correlated to fossil fuel use. That said, it would be good for you to get familiar with the sources of these non-CO_2 greenhouse agents perhaps starting with methane.

As a result of the near exponential growth of the global economy and the fact that fossil fuels have powered that growth, global carbon emissions have also been growing near exponentially (Figure 4). We have come to conceptualise the drivers for emissions through something called the Kaya identity[11], which states the emissions rate as the product of four factors; population, GDP per person, the energy intensity of GDP and the carbon intensity of energy. It would be very easy to weave population into our account and you will be encouraged to in PART 2, but in sympathy with all the preceding model description and to keep things as simple as possible, for now I'm going to merge population and GDP per person to give GDP and/or GWP.

We can understand the Kaya identity for CO_2 emissions in the context of the growth analysis we did in Section 3.3, which states that if variables are multiplied together their growth rates are added. Since 1980, GWP has been growing at ~3 %/yr while primary energy use (PEU) has grown at ~1.7 %/yr (Figure 2). The difference between the two is because the energy intensity of GWP has been falling, or put another way, the efficiency of the economy at translating primary energy into useful work and GWP has been increasing at 3.0 – 1.7 = 1.3 %/yr. Note how these efficiency improvements are associated with continuing growth in PEU and GWP, not their reduction, alerting us to the risks of using efficiency improvements to drive down emissions if output growth is being pursued simultaneously. For reference, just short of half of all current pledges to reduce emissions globally are attached to efficiency improvements, which is worrying given growth is such a ubiquitous economic goal. We will be looking at this in the ENERGY EFFICIENCY scenario in PART 2.

If PEU has been growing at 1.7 %/yr, CO_2 emissions have also been growing at 1.7 %/yr (Figure 4) telling us the carbon intensity of primary energy hasn't changed much in the last 40 years, despite decarbonisation of the global economy being the primary focus of international climate negotiations and national climate policy over this time. This doesn't mean nothing has been going on in the low carbon economy, but rather that any expansion of the low carbon economy has been additive to the global economy rather than displacing its high carbon relative. This isn't too surprising when you realise the returns from investing in the low carbon economy feed back into growth of the high carbon economy and vice versa. In PART 2 we argue that it is only when we firewall off the low from the high carbon economy can we prevent this co-evolution such that the global economy decarbonises at rates compatible with the <2 ˚C Paris guardrail.

Without any changes to the historic pattern of decarbonisation, annual global carbon emissions, u, might follow a business-as-usual trajectory defined by,

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11 https://en.wikipedia.org/wiki/Kaya_identity

$u = ay^{(1.7/3)}$ (3)

where y is again GWP and a is a scaling factor between GWP and emissions which we estimate to be 0.9 GtC/yr for the GWP and emissions data in Figure 4.

In forming equation 3 we have related GWP to what is known as 'industrial emissions' of CO_2, the fossil fuel burn and cement production. There are however significant amounts of CO_2 released from land use change (largely deforestation) and the associated biomass burn. It turns out somewhat surprisingly that this is much less related to global economic activity and as a result we will be treating it as a constant background of 1.5 GtC/yr, the value it appears to have varied about over the last 40 years.

As we are about to see when looking at the climate system, we are going to add up the emissions over time to produce cumulative emissions because this is what the warming relates closest to. Because it is the cumulative emissions driving the warming of the planet, the annual emissions rate has to fall to zero if we want global temperature to stabilise. This means emissions growth rates going negative. If growth in GWP was held at 3%/yr, this would require emissions degrowing faster than 3 %/yr. Again, in the DECARBONISATION scenario in PART 2 we will look at this by growing a parallel (alternative) economy which uses only carbon-free energy.

3.5 Climate

There are two elements to the global climate system relevant to our IAM; the global carbon cycle and the global energy balance. The global carbon cycle translates CO_2 emissions into the CO_2 concentration in the atmosphere and hence the degree to which climate is 'forced' to warm. The global energy balance translates this forcing into global warming. Like the global economy, both are highly complex and complicated systems in their own right and modelling them 'accurately' remains a fundamental challenge in the climate sciences.

Fortunately for us, Damon Mathews found an incredibly simple way to represent both the carbon cycle and the global energy balance that is now heavily used in a broad range of climate studies[12]. What Mathews et al. did was to plot cumulative carbon emissions (i.e. the running total of emissions since the beginning of the Industrial Revolution) against the associated increases in Global Mean Surface Temperature (GMST). They found they both fell on a relatively straight line (Figure 5). This is good news for our radical simplification agenda because it means we can reliably represent the carbon cycle-climate system using that straight line. Specifically,

$\Delta T = s_T \Sigma u$ (4)

where Σu are the cumulative carbon emissions added up since the start of the industrial era (in GtC) and ΔT is the associated increase in GMST attributed to human activity also since the

12 https://doi.org/10.1038/nature08047

Industrial Revolution, otherwise known as Human-Induced Warming (HIW). s_T is referred to as the transient climate sensitivity to cumulative emissions, although we are going to simplify that to the climate sensitivity here on.

If you measure from a pre-1700 pre-industrial baseline, present-day HIW is estimated to be in the region of 1.5 ˚C, although the preference is to measure from 1850-1900 which overlooks about 0.2 ˚C of warming[13]. Looking at the accumulation of CO_2 in the atmosphere humans have released ~680 GtC since the start of the industrial era (Figure 5)[14]. This gives s_T = 1.5/680 = 2.2 ˚C/TtC. CO_2 is not responsible for all the warming but approximately 80 % of it, with methane, nitrous oxides, CFCs etc. covering the rest, but these additional warming factors appear to be somewhat correlated with CO_2 to date, which is another reason why we are using CO_2 as a catch all.[15]

Equation (3) is unbelievably useful, which is why I felt obliged to flag Damon's contribution specifically. In addition to helping us massively simplify our analysis, we can use it to estimate HIW and define remaining carbon budgets to keep within the Paris Agreement. For example, keeping below 2.0 ˚C means emitting 1000(2)/2.2 = 900 GtC, and because we have emitted approaching 700 GtC so far, the remaining carbon budget might be somewhere near 200 GtC. If we are currently emitting in the region of 10 GtC/yr, then we have 20 years of budget left if we emit at current rates. This is highly relevant to the scenarios we will explore in PART 2 because, as you will see, there are emissions locked into the current stock of capital which will live and hence emit for decades. In PART 2 we will explore whether there is enough carbon locked into the economy already to breach the Paris 2.0 ˚C guardrail.

The reasons for the linearity shown in Figure 5 are interesting but a little complicated and still not well understood. In essence it boils down to two things. First and foremost, the global carbon cycle is thought to be conservative with respect to CO_2 emissions on all geopolitical timescales. So if you put some CO_2 into the atmosphere, a little more than half of it is lost to the oceans and the vegetation within months, but the rest stays in the atmosphere in effect permanently, and if it stays there it has a persistent warming effect leading to persistent temperature change. The result of this is that the cumulative sum of CO_2 emissions is what is important for determining the relationship between emissions and temperature change, not the rate emissions are added to the system, which simply determines how quickly the temperature changes. The second effect of relevance is that the potency of the greenhouse effects of CO_2 decreases as atmospheric concentrations increase. However, this appears to be largely offset by the decreasing efficiency of the oceans to absorb CO_2 as their temperature rises. These two effects appear to cancel each other out to give the linearity we observe in Figure 5.

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13 https://www.nature.com/articles/s41561-024-01580-5#citeas

14 Total anthropogenic carbon emissions are made up from burning fossil fuels, making cement, burning biomass and changing land use.

15 If you account for the non-CO2 drivers of warming the climate sensitivity becomes 0.8(2.2) = 1.7 degC/TtC, which is what people cite as its value. We will stick with 2.2 degC/TtC simply because we are using CO2 as a catch all in our model.

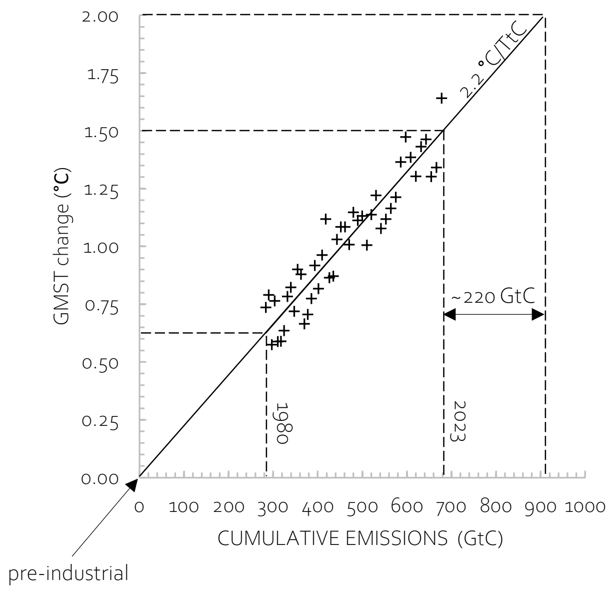

Figure 5. The relationship between cumulative carbon emissions[13] and the UK Hadley Centre Global Mean Surface Temperature (GMST) change[16].

It is useful to unpack what global average temperature changes mean because there is a lot of regional variability sat behind these averages and this in part drives variability in the impacts. When this variability maps on to the huge inequalities in income distribution and resilience sat behind global aggregate measures such as GWP we see the potential for very significant regional disparities in the impacts of climate change. We could attempt to capture this spatial variability explicitly in our model, but it will immediately lose its simple character. Instead, I encourage you to do the regional disaggregations in your head, qualitatively. To help guide this for climate change there are some useful rules of thumb to appreciate. Firstly, the Earth's surface is 70 % sea, which experiences significant evaporative cooling and has a high thermal inertia. As a result, land warming is approximately twice that of the global average. Secondly, the greenhouse effect is largest at high latitudes, and hence we might double the global mean again when looking at warming over land in high latitudes. Lastly, if we double the annual average we could do the same for the extremes, and it is often these extremes that house the significant impacts. And of course we are not just interested in temperature, but also rainfall, humidity, wind, sea level rise etc., which we again tally with changes in global temperature either qualitatively of quantitatively. This regional unpacking is what global climate models do, and the results they produce help us construct a picture of how regional changes in climate map to global measures like HIW. If you are feeling bold and have the time, perhaps you'd like to have a go at applying something called patter scaling[17] to the global scale SIAM estimates, although keep in mind these scaling patterns are quite uncertain and don't necessarily hold going forward.

16 https://www.metoffice.gov.uk/hadobs/hadcrut4/data/current/download.html

17 There is a way of generating regional patterns from our global metrics using something called pattern scaling. If you are interested, then you can find the patterns you need for this on https://github.com/USEPA/pattern-scaled-climate-variables although you need R to extract them.

3.7 Damages

In the specification of the coupled climate-society system we have thus far described how the economy drives climate change, but we haven't described how climate change now feeds-back and drives the economy. Again, orientate yourself using Figure 1. To complete our picture we need to specify what is known as 'the damage function' i.e. how climate change (here represented through changes in HIW) affects material losses to the economy. There are three possible ways of accounting for climate losses in our framework:

1. By increasing the proportion of GWP that is not invested (decreasing i in equation 1b). Here output is being diverted away from investment in order to pay for the unforeseen immediate costs of climate change. For example, needing to hire more firefighters.

2. By reducing productivity (decreasing A in equation 1) as the performance of productive structures and hence capital is diminished by a changed climate. For example, the people in the field had to stop working because it was now too hot or too wet.

3. By increasing the decay rate of productive structures and hence capital (increasing d in equation 2) as the increased temperature of the climate system increases its ability to do destructive work on the economy, smashing up the things we value. For example, the wind blew the roof off my house when before it would have survived.

It's a matter of debate which is the 'best' way to represent climate damages given all three modes described above are likely to occur. However, ultimately they amount to the same thing because output is being diverted away from planned activity to address unplanned losses both now and in the future. Because of this, we will attribute losses to increasing the decay rate of productive structures (mode 3) because there is something physically defensible about this mode of action where warmer, more energetic climates erode societal structures faster. We will also be covering mode 1 because we will divert output away from planned activity to repair and replace lost capital.

The controversy over the relationship between climate change and the economic damage this elicits is less about the mode of action. It is controversial because it is about how the economy performs in a different climate to the one it grew up in, and that represents an extreme economic forecast surrounded by huge uncertainties. Not only is it very difficult to predict the magnitude of economic losses, we also have to think about how the economy would naturally (endogenously) react/adapt to these experienced losses. As a result, for now any climate damage function is at best a guess, leading some to conclude that attempts quantify future losses using IAMs is a pointless exercise[18]. However, we wouldn't be having this discussion if we didn't believe the risks of climate change were significant, and it is this perception of risk, informed by a broad range of information, that underpins our entire understanding of climate change as an issue as well as driving our differing positions on it. This places us in a very uncomfortable position because the future could then be either far worse or, ironically, far better, than we have imagined, and everything in between.

[18]Pindyck R (2017) The Use and Misuse of Models for Climate Policy. Review of Environmental Economics and Policy 11(1):100-114

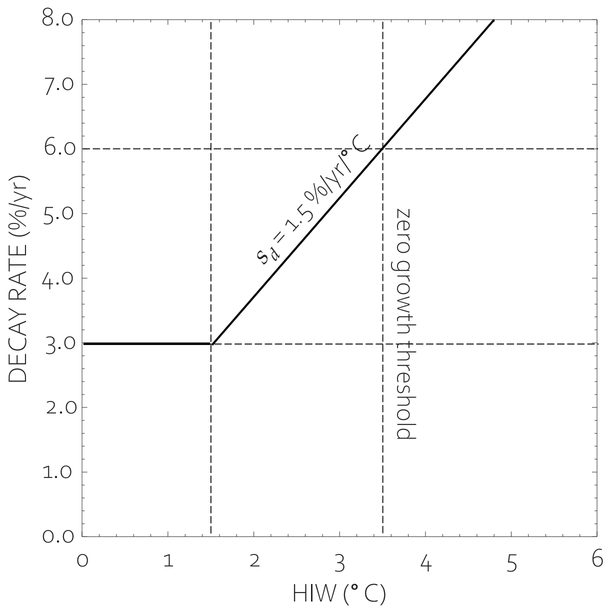

Figure 6. A speculated relationship between Human-Induced Warming (HIW) and the decay rate of total global capital.

Marshall Burke[19] present an interesting line of evidence where he correlated deviations in a country's output to deviations in the annual weather about a local climatic mean. They found that the effects of climate variability are best represented as growth effects. They also found that until now, the winnings approximately cancelled the losings globally, but from hereon the losings start to rapidly outweigh the winnings. This is largely consistent with the shared experience of climate change where, thus far, the warming we have experienced has not really had a drastic impact on the global economy, even if there have been significant local and regional impacts. It is also consistent with our emerging experience of climate change where, as we exceed say 1.5 ˚C of warming, it appears the net impacts are starting to become globally significant (think Australian, Canadian and Californian wildfires, the flood in Pakistan, …).

We can also say something about the extreme end of the climate change spectrum. It is hard to envisage a world where the global economy is still prospering enough to grow if the temperature change hits say 6 ˚C. After all, this could be 12 ˚C on land, which is simply huge as an average increase let alone how big the climate extremes would be with this. This thinking feels like it bounds our damage function, as does the observation that not much happened below 1.5 ˚C. So perhaps somewhere between 1.5 and 6 degrees of warming the global economy gives out, and by gives out perhaps we mean 'can no longer grow', given growth is what the global economy currently sets out to do. This now poses an interesting question. How much warming would it take to wipe out the growth i.e. for the growth to go from 3 %/yr to zero? Having asked this question to quite a lot of people now, both experts and non-experts, it appears folk are surprisingly happy to provide their guestimate, even though we all know it's an extremely muddy question. Unsurprisingly, people provide a broad range of answers, but surprisingly there appears to be a tendency for there being a preferred answer, with little or no difference between experts and non-experts. I would be very interested to hear your answer before I share some preliminary results with you so as to not bias your contribution to

19 https://www.nature.com/articles/nature15725

the survey. You can provide your answer here.

From the responses we have gathered to date, a reasonable synthesis of people's perception of the risks of climate change is that they believe 3 to 4 ˚C of warming is enough to kill off the growth. Having now seen this, hopefully you can see that perhaps it isn't too unrealistic? After all this could easily represent 6 to 8 ˚C on land, and much more in the extreme. Again, this implies changing the climate within which productive structures operate means they are now so maladapted their rate decay doubles (mode 3 damages), thereby abolishing growth.

Let's start by looking at how to represent increases in the decay rate of capital with increasing temperature. Below say 1.5 ˚C of warming d = 3 %/yr (refer back to Section 3.2 if you need to). Once warming increases above 1.5 ˚C we will keep it simple and assume decay rises in proportion to the temperature such that,

$$d = \max(3, 3 + s_d(\Delta T - 1.5)) \qquad (5).$$

There is a plot of this in Figure 6 which you can use to satisfy yourself equation 5 is actually very simple and broadly does what we have discussed. We are going to call s_d the economic sensitivity (of capital decay to warming), and we need a value for it that honours a collective belief that between 3 and 4 ˚C of warming is enough to kill off the growth in the economy. Let's go with 3.5 ˚C as the zero growth warming level, so I make that s_d = 3/(3.5-1.5) = 1.5 %/yr/˚C (see Figure 6).

I appreciate that was probably a lot to take on, but I wanted to kick start our thinking on how we describe the effects of climate damages. Although it is almost certainly wrong, I believe it is useful as it gets us thinking about some of the important issues surrounding climate risks. An important thing missing from this picture is an explicit account of how we subsequently respond to the experienced losses. I am going to save introducing that for when we unpack the ADAPTATION scenario in PART 2. For now I want to again challenge you to think about what kind of events our unfolding losses relate to and hence what structures are being lost. Although we have necessarily aggregated to the global scale, we know these losses are wildly unequally and unfairly spread across the planet and it would be good to imagine this too. We also are now finding that through repairing the effects of climate damages in an emergency, we are amplifying fossil fuel emissions (think flying helicopters to pour flame retardant on forest fires).

4. Reflections

And that is that in terms of model description. In PART 2 we turn equations 1-5 into a working model in Excel and use it to explore four scenarios - BUSINESS-AS-USUAL (or do nothing), DECARBONISATION (anticipatory reductions in emissions through investing in the zero carbon economy), ADAPTATION (making things more robust so they survive climate change longer) and EFFICIENCY (investing in energy efficiency to decouple the economy from energy use and hence emissions). This will not simply be a dry coding exercise but instead is designed to help us start to explore our values around these very different ways of seeing the future unfold. As a result, even if you don't think you are interested in the practical modelling, I believe the read should be rich, as I hope you have found PART 1 to be. The last section of PART 2 uses SIAM to estimate how much it costs us all if we add a tonne of carbon to the atmosphere, something referred to as the Social Cost of Carbon (SCC).

PART 2 – Model Building and Scenarios

In PART 1 we laid out the model description for SIAM. In PART 2 we will now have a go at assembling the model in Excel so that we can run our four scenarios. The first explores what happens under a business-as-usual regime where there is no attempt to manage the effects of climate change (the BUSINESS-AS-USUAL scenario). Once you have become familiar with this baseline scenario 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), or one with more robust economic structures to try and protect the economy from climate change (the ADAPTATION scenario). Finally, we will look at a more efficient economy (the EFFICIENCY scenario).

The word 'scenario' tries to get us away from thinking what we are about to do are forecasts of the future. Forecasting the future, particularly for highly evolutionary things like the economy, is a doomed enterprise, especially over the relatively long time horizons we will be looking at. Who knows what the world looks like in 2100? Scenarios on the other hand are about having sight of possible futures (plural) and learning from what these might teach us, much like watching a good film. Hopefully you can learn a lot about how climate and society might interact under these different regimes. However, you can also reflect on the range of scenarios we are about to build and have a go at blending these scenarios in some way when you think about the messy world we live in and how that might unfold over the coming decades.

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 some of the systemic characteristics of the economy experiencing 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 represent and their relationship to one another.

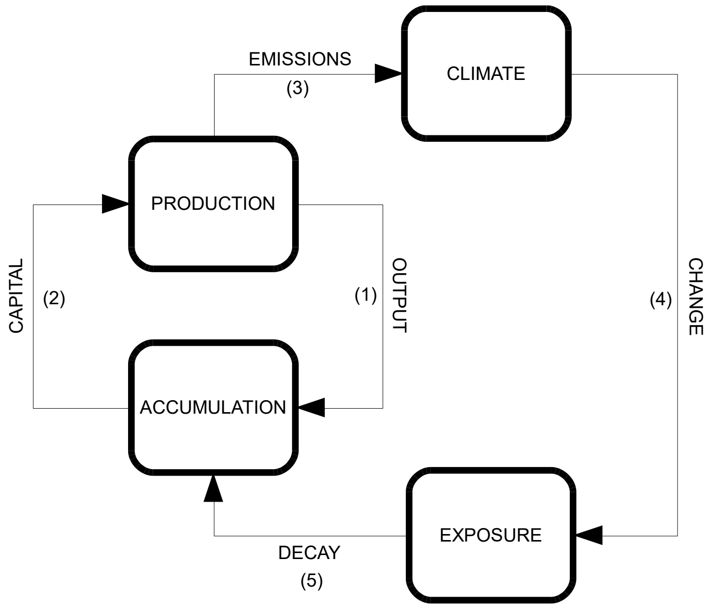

Figure 1. A schematic of the Simple Integrated Assessment Model (SIAM). Numbers denote which equations apply in the accompanying text below.

1. BUSINESS-AS-USUAL

In five equations developed in PART 1 (1-5; see Table 1 below) we have all the steps we need to specify a basic 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 handful of tech-heads amongst you, the task ahead likely feels like a challenge. However, if we break it down into its component parts and take it one **S**tep at a time it is much easier than you might imagine. I am hoping that in addition to acquiring some useful analysis 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 reasoned judgements of your own. These steps start small but slowly encourage you to increase your stride. This includes leaving some space for you to think then and join the dots up for yourself, something that I believe is key to the learning process. If you don't want to have the DIY IAM experience then you can download a complete model here[20], which houses all four scenarios. For those building their own model this finished version will provide a useful check so you may want to have it open in the background.

S.1.1 Open up Excel or some other spreadsheet of your choosing and save the fresh file somewhere with an appropriate name (e.g. mySIAM_v1). You do not want to lose your work so remember to keep saving periodically. Now rename the worksheet 'BUSINESS-AS-USUAL'. This is to distinguish it from the other three scenarios we will investigate later using separate worksheets.

S.1.2 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 find it hard 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.1.3 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. Label the first seven columns 'VARIABLES' and mark this section off by shading the 8th column. Then label the next four columns 'PARAMETERS'.

S.1.4. Label up the seven variables columns; 'YEAR', 'CAPITAL', 'GWP', 'EMISSIONS', 'CUMULATIVE EMISSIONS', 'HUMAN-INDUCED WARMING' and 'DECAY RATE'. Units are a big deal here so add them clearly under each column label, they are all defined in Table 2 below. Make sure you become familiar with these units as you work through, they are themselves an important currency in climate discussions.

S.1.5 Table 2 below also shows the eight parameter values you will need. Label the four columns in your PARAMETERS table 'SYMBOL', 'DEFINITION', 'VALUE','UNITS','EQUATION' and populate these columns with the eight parameters in Table 2. **Please note that, wherever possible, I present parameter values as percentages to help communication. Remember to divide these values by 100 when you come to use them!**

S.1.6 We will start our simulation in 1980 because the associated data is quite good across all our variables and 40 years ago feels long enough in the past to check how our framework has

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20 https://www.lancaster.ac.uk/staff/bsaajj/siam.html

performed. I have provided the data you need in the 'DATA' tab in the worked example so you can go back and look at how well your model does against these in your own time. We will end our simulations in 2100 because that is where most IPCC scenarios 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, something you will be doing more of shortly.

S.1.7 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 2. Add these to your parameter table and refer to them to populate these 1980 values in your VARIABLES columns. Now use equation (1) to produce the 1980 value for GWP; equation (3) to produce the 1980 value of EMISSIONS; equation (4) to produce the 1980 value of HIW and equation (5) 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.1.8 Now move to the 1981 value for CAPITAL (only!) and, using equation (2), specify the value, carefully referring to the 1980 values of CAPITAL, GWP and CAPITAL DECAY RATE.

S.1.9 Now move to the 1981 value for CUMULATIVE EMISSIONS and calculate it by adding the 1980 INDUSRTIAL EMISSIONS and the LAND USE CHANGE EMISSIONS to the 1980 CUMULATIVE EMISSIONS.

S.1.10 You can now fill in the remaining missing 1981 values of the VARIABLES by dragging down their 1980 values. When you do this you will see something is wrong. The problem is that the PARAMETERS in the associated equations also incremented rather than remaining fixed on the right values in your PARAMETERs table. We don't want this, we want them to remain fixed on the right values in the PARAMETERS table. 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 parameters used in equations throughout the model, so go back and add the $ symbol to your VARIABLES equations wherever you see a PARAMETER.

S.1.11 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. You may also want to 'freeze' the column headings so you can still see what each number represents as you scroll down the years.

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 just short of 1.5 °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 ~90 T$/yr)? There should be an extra ~700 GtC added to the atmosphere since the beginning of the industrial era, which is a clear anchor for our analysis because this is one of the measurements we know best given we can derive it relatively easily from the atmospheric CO_2 record. Hopefully you should be gaining some idea of what these numbers should be, which is valuable. If it all appears to be working, continue dragging down to 2100.

Table 1. Core SIAM equations

DESCRIPTION	EQUATION	LABEL
Production function	$y = AK$	1
Capital turnover	$K(t) = K(t\text{-}1) + iy(t\text{-}1) - dK(t\text{-}1)$	2
Emissions scaling with GWP	$u = ay^b$	3
Transient climate response	$\Delta T = s_T \Sigma u$	4
Damage function	$d = \max(d_0, d_0 + s_d(\Delta T\text{-}1.5))$	5
Observed GWP relative growth rate	$r(t) = (y(t) - y(t\text{-}1))/ y(t\text{-}1)$	

Table 2. Core SIAM parameters and variables

SYMBOL	DEFINITION	VALUE	UNITS	EQUATION
Variables				
y	Gross World Product	variable	T$/yr	1,2
K	Total capital	variable	T$	1,2
d	Capital depreciation (decay) rate	variable	%/yr	2,5
U	Annual carbon emissions	variable	GtC/yr	3
Σu	Cumulative carbon emissions	variable	GtC	4
ΔT	Human-Induced Warming	variable	°C	4,5
Parameters				
A	Productivity	7.5	%/yr	1
I	Fraction of output invested	80	%	2
A	GWP to emissions scaling	0.9	GtC/yr	3
B	GWP to emissions scaling	1.7/3.0		3
s_T	Climate sensitivity	2.2	°C/TtC	4
d_0	Historic capital depreciation rate	3	%/yr	5
r_0	Historic GWP growth rate	3	%/yr	
s_d	Economic sensitivity	1.5	%/yr/°C	5
L	Annual land use change emissions	1.5	GtC/yr	4
Initial conditions				
$K(1980)$	Total capital in 1980	400	T$	1
$\Sigma u(1980)$	Cumulative carbon emissions in 1980	284	GtC	4

S.1.12 It is going to pay to make some graphs to visualise what is going on. Insert a new worksheet and name it DASHBOARD. On this sheet insert an x-y graph and set the YEAR as the horizontal axis and whatever you are interested in on the y axis. Add as many of these as you want. The ones I initially chose to plot were GWP, EMISSIONS, and HIW. Once you have created these add the data provided in the DATA worksheet to all your DASHBOARD plots and judge for yourself if what you are looking at is credible, at least historically.

Looking at GWP, it peaks in around 2080 and then falls. Looking across at HIW we see this hit 3.5 ˚C in around 2080 too. The point GWP peaks is when the growth rate hits zero, so this happening at 3.5 ˚C is precisely what we set the model up to do, reflecting our survey results where people felt that is when the growth would give out. To further clarify this, let's calculate the GWP GROWTH RATE and see what happens to that.

S.1.13 Insert a new column to the right of GWP and populate it with GWP GROWTH RATE using the expression given in Table 1. You won't be able to calculate this for 1980, but all subsequent years should be fine. Now add a figure for this to your DASHBOARD and check it makes sense i.e. does it start off at 3 %/yr then hit zero %/yr when HIW hits 3.5 ˚C?

It is important to understand what is now happening in this BAU scenario. The BAU scenario produces results at the 'bad' end of the IAM-BAU scenarios because the damages are far higher high than traditional IAMs believe are credible. There are two reasons for this. Firstly, the future endogenous decarbonisation of the energy sector is much less optimistic than that assumed in other BAU scenarios. History hasn't been kind to decarbonisation, with much lower rates happening over the last 40 years than had been hoped. Secondly, the damage function is a lot more aggressive than others assume. However, this damage function is only an attempted synthesis of how people see the relationship between warming and growth, and as a result articulates beliefs over the risks of climate change. Because on average those who have been asked the question believe the economy gives out between 3 to 4 ˚C of warming, and that 3 to 4 ˚C is possible within the next 80 years if we do nothing, perhaps more BAU scenarios should reflect this level of risk? The other side of 4 ˚C leads to secular contraction of the economy and the world becoming progressively poorer in this scenario i.e. climate-induced economic collapse. Is that possible in a do-nothing world?

S.1.14 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 just 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 to start destroying itself, in the next section we try to 'save' the global economy by transitioning to a zero carbon world.

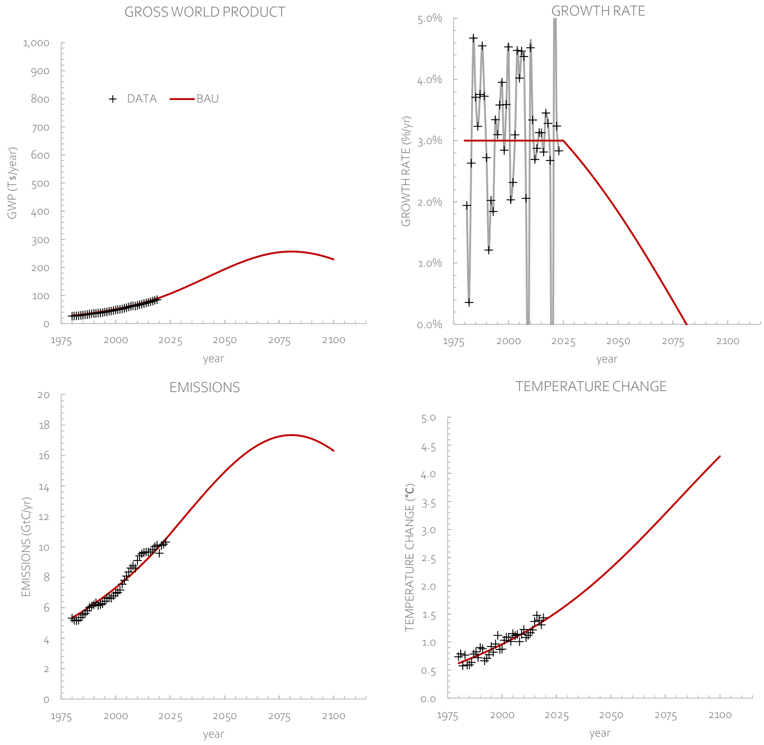

Figure 2. SIAM output for the BAU scenario

2. DECARBONISATION

In this section we are now going to try to avoid dangerous interference with the climate system in line with the decarbonisation ambitions of 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 if nothing is done and then use this information to take pre-emptive steps which avoid the unwanted effects of climate change.

2.1 The Low Carbon Economy (LCE)

As we touched on when introducing the Kaya identity in in Section 3.4 of PART 1, if we want to reduce annual emissions then, unless we want to have a discussion about reducing either population or GDP, we are left having to focus on either increasing energy efficiency, reducing the carbon intensity of the energy we use, or reaching for carbon offsets. We will discuss raising energy efficiency and offsets later, so for now we will explore decarbonising the energy we use.

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)[21], and whether output from the LCE is allowed to feed back into supporting the HCE. This new LCE uses energy in exactly the same way the current HCE does, other than its energy flows are carbon free. In addition to this energy being sourced from nuclear and renewables and facilitated through the associated electrification of infrastructure

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

and activities, the LCE could also be seen as changes in land use practices, dietary habits, or even the development of emissions removal technologies.

Currently both renewables and nuclear co-evolve with fossil fuel energy use, with the proceeds of the one 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 leading to slower than expected systemic decarbonisation. As a result, if we want the creation of the LCE to be truly effective at reducing emissions we need to put a firewall between the LCE and the HCE, where output from the HCE can be invested to grow the LCE but output from the LCE cannot be returned to grow the HCE. In reality, such a firewall would be very difficult to implement and doing so would mark a radical transition in the global economy. I believe this firewall could be supported by charging for carbon emissions at source because this could deter re-investment in the HCE at source though making it appropriately less attractive. This charge could act to either compensate for any difference in productivity associated with LCE capital, or to penalise slow adopters of low carbon options.

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 LCE as starting from a low base when growing alongside its HCE counterpart. Here we are going to assume that, although they are mixed together currently, the economy can be split in 2020 into 80 % HCE: 20 % LCE reflecting the 2020 composition of the primary energy portfolio.

In the DECARBONISATION scenario we are going to be ambitious and invest all available output into the LCE. This will result in the rapid expansion of LCE whilst the remaining HCE is left to waste away naturally at its planned rate d. This is equivalent to seeing how quickly we can decarbonise if the secular turnover of capital 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 in order to meet a climate goal, something referred to as 'stranded asset'[22]. We will discuss this later, along with the fact that despite needing the HCE to die off rapidly, we are continuing to invest in its growth.

We will be making our LCE investment decisions from 2020 onwards, even though this is now in the past and something the global community hasn’t done enough of to impact the growth in emissions. The reason for focusing on 2020 is that was is meant to be the implementation date for the Paris Agreement. Of course, we could start taking action later (otherwise referred to as delayed action), which can be advisable when we are unclear about the relationship between our actions and their consequences. Although this is true for climate decision making given the very significant uncertainties associated with some of the steps set out in Figure 1, 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. As we are about to see, even if we stopped building new fossil fuel dependent structures today, it would take more than 50 years for this infrastructure and its emissions to disappear from the economy. The precautionary principle would suggest that early action should take precedence over delayed action when avoiding dangerous climate change, although delaying action is very much what we have been doing.

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22 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.

You will see these issues raise their head in all the scenarios we are about to explore.

What follows is challenging but revealing, so I encourage you to wrestle with it. The very act of partitioning the global economy as we are about to 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 available output 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 wildly optimistic, but we will see this is now close to what needs to happen if we are to keep below 2 °C of warming without having to rely heavily on either carbon removal technologies or stranding assets. The critical thing to appreciate here is that we are going to prevent all investment in the development of new fossil fuel reserves and the downstream capital dependent on it, including high carbon human capital.

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

It will help you to briefly study the structure of the DECARBONISATION scenario I have produced to get an overview. Also please keep referring back to this model if you get stuck. You will see that in 2020 we have split the global economy in two to create separate HCE and LCE components, with the global economy being the sum of the two. Prior to 2020 we assume we have followed the BAU pathway developed in the previous section and so we begin our scenario in 2020 using the BAU 2020 values as our initial conditions.

S.2.1 Create a new worksheet and name it 'DECARBONISATION'. We are now going to have to share parameter values with other scenarios so I am going to suggest we create another worksheet and call it PARAMETERS. You can now cut and paste your parameter table from the BAU scenario into this new shared space.

S.2.2 Back in your DECARBONISATION worksheet label column A 'YEAR'. We now want to label columns C and D 'CAPITAL' and 'GWP' headed with HCE. Now label columns F and G 'CAPITAL' and 'GWP' headed with LCE. Finally, label columns I to N (I think) 'CAPITAL', 'GWP', 'EMISSIONS', 'CUMULATIVE EMISSIONS', 'HIW' and 'DECAY RATE', and head these with 'TOTAL ECONOMY'. I am leaving certain columns blank to hopefully clarify the HCE-LCE separation. Again, refer to SIAM_2025.xls if you need to as we want to get this structure right before pushing on.

S.2.3 Make the first year 2020 and populate the 2020 values of CAPITAL and CUMULATIVE EMISSIONS for the TOTAL ECONOMY by referring to the corresponding cells in your BAU scenario. Because you may need to keep looking back at the 2020 values in your BAU scenario it could help you to highlight that row in the BAU scenario.

S.2.4 Now label the next row 'SPLIT TOTAL ECONOMY INTO HCE & LCE' and label the YEAR cell for the following row '2020' again. We are now going to split the 2020 TOTAL ECONOMY into its HCE and LCE components. Make the 2020 HCE CAPITAL equal to 0.8 of the 2020 pre-split TOTAL CAPITAL and the 2020 LCE CAPITAL equal to 0.2 of the 2020 pre-split TOTAL CAPITAL. Again the 80:20 split derives from 2020 fossil fuel/renewables+nuclear makeup of global primary energy use.

Hopefully what follows will feel very similar to what you did for the BAU scenario, but with applied to two parallel economies.

S.2.5 Specify the 2020 GWP for both HCE and LCE using equation 1 and add these together to calculate the 2020 GWP of the TOTAL ECONOMY.

S.2.6 We now want to calculate the EMISSIONS for the TOTAL ECONOMY. Clearly these are only going to come from the HCE because the LCE is comprised of zero carbon activities. In the BAU scenario we used equation 3 for this, but this only held true when the LCE and HCE components evolved together. Not only have we separated them out, we are no longer going to add any new HCE capital, so the HCE is going to be comprised of frozen technology and hence a constant carbon intensity here on. First, we must calculate the 2020 carbon intensity of the HCE, which is the 2020 EMISSIONS divided by the 2020 HCE GWP. I suggest you add this to your PARAMETER table. Once you have calculated it use it to produce your 2020 EMISSIONS. You can check you have done this correctly because it must be the same as the 2020 EMISSIONS in your BAU scenario.

S.2.7 Populate the remaining 2020 values for the TOTAL ECONOMY

S.2.8 Move to the 2021 value for HCE CAPITAL. Calculate this using equation 2 just like in the BAU scenario, but don't invest any GWP into it i.e. equation 2 reduces to

$$K_{HCE}(t) = K_{HCE}(t\text{-}1) - dK_{HCE}(t\text{-}1). \qquad (6a)$$

Hopefully you can see from this that the HCE is going to slowly dwindle away at the decay rate *d* because of the lack of investment. Repeat this for the LCE but here we are going to invest all output set aside for capital creation into the LCE i.e. equation 2 becomes

$$K_{LCE}(t) = K_{LCE}(t\text{-}1) + iy(t\text{-}1) - dK_{LCE}(t\text{-}1). \qquad (6b)$$

Once you have completed the 2021 calculations for the HCE and the LCE CAPITAL you should be able to calculate their corresponding 2021 GWP values and populate the rest of the 2021 cells for the TOTAL ECONOMY. You may need to remind yourself how to do this by referring to your BAU scenario and/or the SIAM_2025.xls master.

S.2.9 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. Now add in the GWP GROWTH RATES for all three GWP variables (HCE, LCE and TOTAL). These are interesting. Firstly, in 2021 the HCE is now degrowing at 3 %/yr (or growing at −3 %/yr). In contrast, the LCE is growing at +27 %/yr in 2021 because of the huge endowment it is receiving from the HCE without leaking anything back. As a result, overall growth remains at 3 %/yr but the LCE replaces the HCE as the mainstay of the global economy. I make it that they become the same size in 2028. So we have degrown the thing laying waste to climate and the economy and grown its climate neutral counterpart.

This is an interesting opportunity for a discussion. Unlike the BAU scenario where growth is halted by the warming, rapid decarbonisation limits the warming to the extent that growth can be maintained, albeit at 2.5 %/yr rather than 3 %/yr because it is some 2 ˚C warmer. So we could view decarbonisation as a way to keep growth alive. If there are non-climate downsides to growth (e.g. biodiversity loss, inequality, unmanageable complexity etc.) then although we appear to have solved one problem, we could have easily exacerbated others.

Add the DECARBONISATION TOTAL GWP, EMISSIONS, HIW and GROWTH RATE to your

DASHBOARD plots. Hopefully this looks something like my Figure 3 below. 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 HIW tend to a constant, which for the latter is about 2 ˚C. Given the Paris Agreement called for "well below 2 ˚C" we haven't met that objective. We have learnt however that there appears to be enough CO_2 locked up in existing capital to add about 0.5 ˚C of warming post 2020 even if we don't add any more high carbon capital to the mix. If we did want to keep well below 2 ˚C in our DECARBONISATION scenario we would have to retire some of the HCE capital early. If you want, you could explore how much more HCE capital you need to actively remove to keep well below 2 ˚C by adding an additional loss term to the HCE CAPITAL equation. That additional loss would be the stranded asset.

It is also interesting to explore the effects of delaying radical action on emissions reduction beyond 2020. How about starting the radical decarbonisation investments in 2025? Not surprisingly you will find that you exceed 2 ˚C. This is because you have both 5 years more HCE growth to account for, so the HCE is 16 % bigger, and you have used up 5 more years worth of your carbon budget. You could also try and find when you would have needed to split the economy in the past if you wanted to keep below 1.5 ˚C.

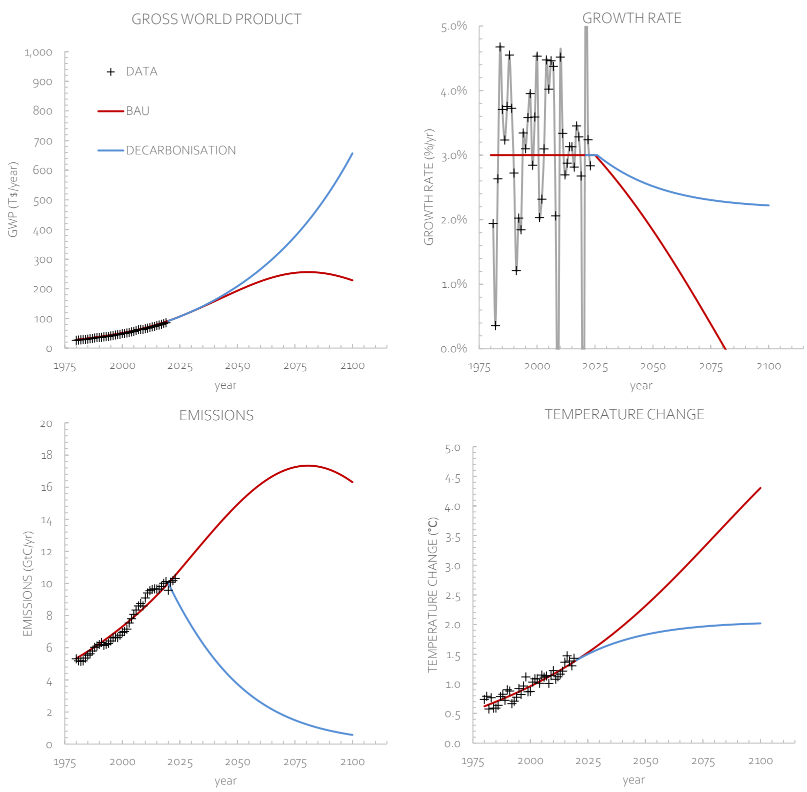

Figure 3. SIAM output for the BAU and DECARBONISATION scenarios

3. ADAPTATION

Perhaps the defining attribute of our economy is its adaptability. By this I mean that when presented with a problem you can bet that the economy will try very hard to solve or evolve around it so that it can continue on its way. If by 'continue on its way' we mean grow, then even decarbonisation can be interpreted in this light as it removed the climate change obstacle to that growth. Given a response to anything getting in the economy's way can be classed as adaptation, we are going to spend some time trying to untangle what we mean by this deeply complex process. Please don't see this as an unnecessary detour because, despite it getting a little deep in places, adaptation is so important for climate change I think we need to dwell here a while before climbing any higher.

A common way we categorise adaptation is by saying whether it is anticipatory or reactive. As the name suggests, anticipatory adaptation are actions in the now precipitated by foresight, likely involving models of some sort used to predict different outcomes or scenarios. This is what you are doing when working through PART 2, and the DECARBONISATION scenario fits this description because what drove the transition to the LCE in model world was a desire to avoid future emissions and the changes in climate and climate-induced economic losses foreseen in the BAU scenario. However, it turns out that foresightedness is not one of the economy's strong suites, it instead preferring to react to the environment it finds itself in rather than trying to anticipate things well in advance. This certainly describes our response to climate change to date where, despite fair warning, we are only just starting to think about meaningful emissions reduction perhaps because the experienced losses appear to have only just started to bite.

If there was one area where the economy appeared to behave with foresight it is in the investment process itself, where productive structures are created in order to produce valuable flows often decades into the future. This of course requires anticipating the environment these structures (investments) will find themselves in often decades in the future, although invariably we assume that future resembles the present and that our investments will behave much like they have done historically. The economy also appears willing to take on the risk the forecasted returns don't materialise, as if it only ever partially believes in its predictive capabilities. This of course makes complete sense because the future is so uncertain, but it is also deeply problematic when it comes to slowly unfolding problems like climate change that demand a good deal of foresight and believe in that foresight in order to steer the super-tanker away from the rocks.

There is also a vast array of things that can be adapted and things that can't, and it is not surprising that the IPCC dedicate the most space to this critically important yet slippery topic in their Assessment Report process. It certainly is the most complex of the climate change processes, mirroring many facets of biological evolution. However, we are going to focus on one obvious and important dimension of adaptation that relates directly to the way we have portrayed capital as productive structures. When structures are created through investment, part of the investment is simply focused on making structures live long enough to be worthwhile, with the remainder going on creating the productivity of that structure. When you buy a car some of the money spent on its creation went into making it good at going from A to B, but some of it went into it going from A to B for longer. If the former is productivity, the latter is protectivity.

Productivity v protectivity investment smells like a trade-off . Put another way, if we didn't have to invest anything to protect structures from decay, they would be far cheaper to produce for an equivalent amount of output. Why is this important for climate change? Hopefully you can now appreciate that changing the environment of a structure means that more might need to be invested to secure how long you want it to live, and this would divert investment away from developing its productivity and with that the system's growth.

The productive structures we see around us have already been shaped by centuries of adaptive processes in an attempt to make them fit for their current environment. Houses for example have particular roof angles and wall compositions to withstand temperature, wind, rain and snow extremes. If they didn't, in all likelihood they would have failed and would have been replaced by their better adapted relatives. Similarly, the crops in our fields are planted where they are because their genetic make-up leads to traits that fit their environment so they can be productive. If they didn't, the farmer would see them fail and plant something else next year if he himself didn't fail. Likewise, the clothes in my wardrobe have been selected following many years of exposure to the weather here in the Atlantic North West, and if I moved to Italy my wardrobe would evolve again in response. In each case, part of the investment made to create these various structures was made to make them last long enough to live out their planned lifetimes, fulfil their roles and yield their planned returns. Again, let's call that an investment into 'protectivity' and contrast it to an investment in productivity which is exclusively interested in the annual output from these structures, not their productive lifetime.

Believing investment can be made in the protectivity of capital as opposed to its productivity can be further illustrated by examining the production function and capital accumulation set out in equations 1 and 2 in PART 1. In the production function, GWP output y is produced by capital K with a productivity A. However, this says nothing about how long that capital produces for and hence what the lifetime Return On Investment (ROI) in K was. That is decided by the decay rate d, or more specifically in its inverse τ, which is the expected lifetime of that capital. The lifetime return on a unit of investment in productive capital is simply $A\tau$ i.e. a unit of capital has an annual output of A and a lifetime output of $A\tau$. If A = 7.5 %/yr and τ = 1/(3 %/yr) = 33 years, then the ROI of an investment in a unit of capital in the current the global economy is 2.5:1, so for every dollar invested the global economy should expect 2.5 dollars back spread over the next 33 years.

Securing an investment from the effects of decay for, on average, 33 years itself likely requires a significant investment. Previously we estimated that i = 80% of output was invested in productive structure creation annually. I am going to assume that the leftover of GWP, or 1 - i = 20 %, is used for protectivity, making productive structures last long enough to yield the returns they were designed for. As the climate warms and our productive structures are exposed to increased decay, if you want to secure your returns as investors invariably do, you will need to invest more GWP into this protectivity, but this diverts investment away from productivity. Presumably the 80:20 split of investment in productivity v protectivity reflects the 'right' trade off historically. The following ADAPTATION scenario explores changing this trade off as if it was reacting to the effects of climate change increasing the decay rate (shortening the lifetime) of capital.

The question for us now is how to decide the division of investment between productivity and protectivity going forward under climate change? For this we are going to treat the associated adaptation as being reactive, so the next question is what is the adaptation reacting to? Well, in our framework climate change is increasing the decay rate of the economy, d, and hence reducing its expected lifetime, τ. Because that lifetime determines the ROI of the economy let's assume the protectivity investment will be increased in order to try and preserve ROI because that is what an investor is ultimately interested in.

S.3.1 Create a copy of your BAU worksheet and rename it ADAPTATION.

S.3.2 Insert a new column to the right of the TOTAL CAPITAL and label it 'PROTECTIVE CAPITAL', K_P. Now rename the TOTAL CAPITAL 'PRODUCTIVE CAPITAL', K_A, because that is what is being measured when we measure produced and human capital - we are only measuring the productive fraction of our investments. If TOTAL CAPITAL is the productive fraction, then the unseen PROTECTIVE CAPITAL is (1-0.8)/0.8 = 0.25 of this initially. You can now populate the 1980 values for PRODUCTIVE and PROTECTIVE CAPITAL.

S.3.3 So far we have assumed the productivity investment i is constant at 80 % of output. We are now going to treat it as a variable, adjusting it in order to increase the stock of protective capital in response to increasing climate losses, so label the next free columns (I make that J) 'PRODUCTIVITY INVESTMENT' and make the 1980 value 0.8 as before.

S.3.4 Now move to the 1981 value for PROTECTIVE CAPITAL and invest (1- i) of output in it in contrast to the i invested in its productive counterpart.

S.3.5 We now want to use the value for PROTECTIVE CAPITAL to say how long our productive structures are designed to last and hence how quickly they decay. The more protective capital we have relative to its productive counterpart the longer things should last and the lower the decay rate, so we are going to use the ratio of protective to productive capital to specify the the design lifetime of capital, τ, and hence the expected decay rate. In 1980 that ratio was one quarter, and that gave a capital lifetime of 1/0.03 = 33.3 years. If so, then let's assume for simplicity that the relationship between the K_P/K_A and design lifetimes τ is given by,

$$\tau = (4/0.03)(K_P/K_A) \qquad (7)$$

because K_P/K_A in 1980 is again one quarter. Insert a new column to the right of your PROTECTIVE CAPITAL and call it DESIGN LIFETIME and use our new lifetime equation (7) to calculate this for 1980 and 1981.

S.3.6 We now need to update how we calculate the CAPITAL DECAY RATE recognising that not only is climate change making it bigger, adaptation is making it smaller through our enhanced investment in protective capital. This is actually rather straightforward. Refer back to equation 4 in Table 1 and our use of it to specify d (in column J now I think). Simply replace d_0 with $1/\tau$. Now when you calculate d you will be including the effects of *both* adaptation through increasing investments in protectivity and the effects of climate change through temperature induced increases in decay. Please refer to SIAM_2025.xls if any of that was confusing, hopefully that should set you straight.

S.3.7 We have one final task to complete for our ADAPTATION scenario, and that is to build in the adaptation response which will adjust the balance of investment between protection and production in response to climate-induced increases in the decay rate of capital. For this we need to represent some goal-seeking behaviour where specifically we want to adjust the PRODUCTIVITY INVESTMENT depending on how far we are from a certain goal. Again, I am going to make the goal 'achieving historic levels of return on investment (ROI)'. In words what we want is the following goal-seeking behaviour[23]:

This years PRODUCTIVITY INVESTMENT, $i(t)$, equals what it was last year, $i(t - 1)$, minus some

23 Although apparently simple, this algorithm is powerful because it can push you toward your goals simply based on knowing how far you are from those goals. Although control engineers will claim they invented it, nature discovered it millions if not billions of years before them.

fraction of the difference between our desired ROI and last years observed ROI[24].

$$i(t) = i(t - 1) - s_i(A/d_0 - A/d(t - 1)) \qquad (8)$$

Perhaps it is worthwhile reminding ourselves why the goal is for capital to yield its planned returns. This is because this makes the investor is happy. Without this adaptation, climate change reduces the lifetime of capital curtailing future returns leading to vey unhappy investors. Again, please feel free to disagree with this framing, but be a little careful when you do so because it appears you too are a habitual investor.

Have a go at implementing this in your 1981 PRODUCTIVITY INVESTMENT cell. I have used a value of s_i = 5 %/yr [25] which I have added to my parameter table. That should now complete your model such that you can highlight the 1981 row and drag it down to 2100. If you have no bugs what you should see is that as we cross the 1.5 °C threshold the decay rate starts to rise, and in response more investment is switched over to protectivity in order to try and preserve ROI. This has two effects on the growth rate of GWP, $iA - d$. Firstly, the decay rate is less than it would be without adaptation, supporting growth. However, less is now being invested in the productive side of the economy reducing growth.

Add your ADAPTATION scenario to your DASHBOARD. As you can now see growth is reduced by ADAPTATION showing how the effects of reducing i are more potent than the reductions in d we get. This is because reducing i affects growth straight away, whereas it takes time for the investments in protectivity to build up and take effect. What can be seen as the positive impact of this form of adaptation is that things live for more of their design lifetime than they would without it, and this means that ROI holds up and investors are able to collect more of their planned returns. Why not add an ROI column to both the ADAPTATION and the BAU scenarios and compare them. Remember, ROI = $A\tau = A/d$. The problem is that there is increasingly less to invest in the ADAPTATION scenario because the productive side of the economy is being starved of investment.

One thing we can be sure of is that the current economy would not tolerate these radical drops in growth we observe for both the BAU and ADAPTATION scenarios, or even the less radical declines experienced under DECARBONISATION, with these experienced losses precipitating innovations in order to try and restore growth. Because $iA - d$, we could easily conceive of a secondary adaptive goal-seeking action which acted in response to any drop in the observed growth rate below 3 %/yr by raising productivity A. This is precisely what enhanced energy efficiency is, changing the way capital behaves to extract more useful work from any given flow of primary energy in response to a drop in say growth. 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

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24 If you look back you will see ROI is simply the annual output of one dollar of capital, A, times how many years the capital lives, $\tau = 1/d$. So ROI = A/d.

25 I'm sorry to have to do this yet again, but this number is a rate too, and so its inverse is a timescale just as it was for d. However, the timescale in question is the adaptation rate i.e. the timescale over which we are trying to drive the observed ROI to its desired value of 2.5.

obstacle, and underperformance for at least the last 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.

If you are feeling bold, why not have a go at adapting the productivity A too, in response to the growth rate say!

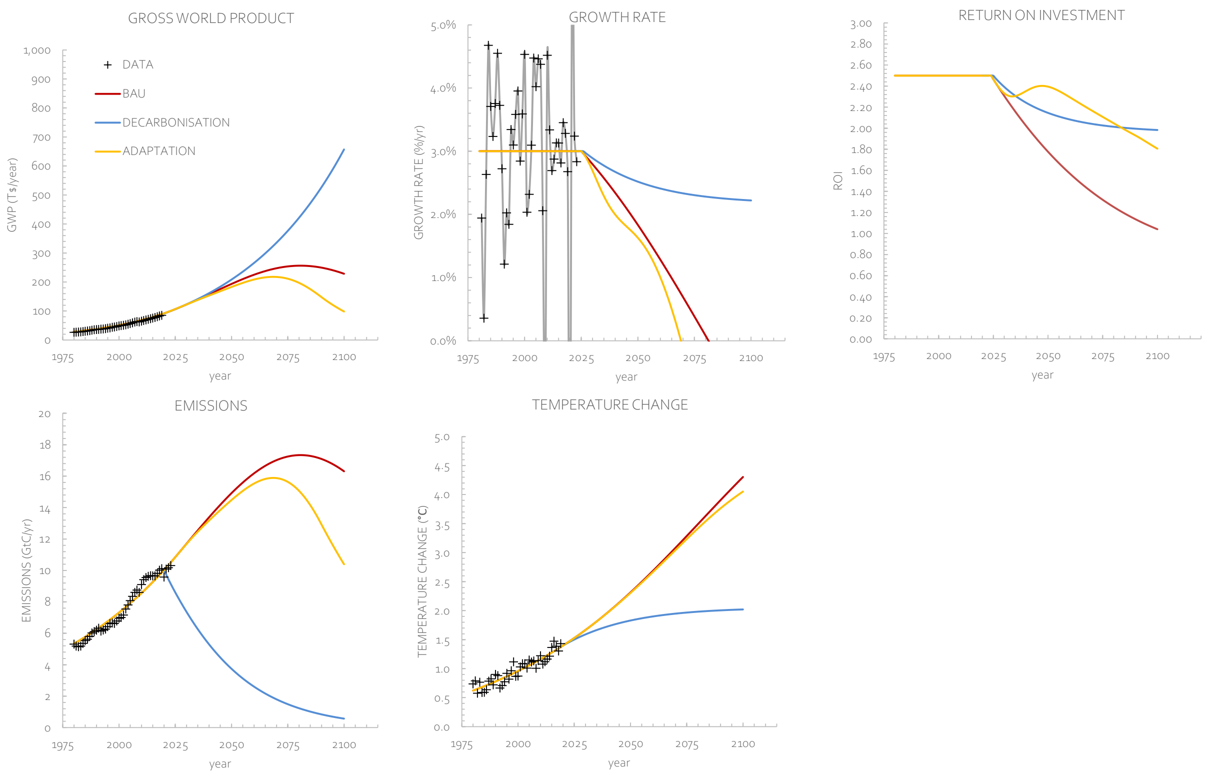

Figure 4. SIAM output for the BAU, DECARBONISATION and ADPTATION scenarios

4. ENERGY EFFICIENCY

About 40 % of the promises made to meet our collective commitment to reduce emissions in line with the Paris Agreement are currently on increasing energy efficiency. The argument appears obvious - make things more efficient and they will use less energy and as a result we will burn less fossil fuel and release less CO_2. The UN process supporting global emissions reduction has gone further and declared a target to double energy efficiency by 2030, the scenario we will explore here. Unfortunately, our model of the global economy doesn't have an energy input or any explicit role for energy efficiency, which is instead implicitly wrapped up inside our productivity value A. So we are going to have to modify our model so that it has an energy efficiency lever to pull so we can see what happens when we double the level of investment in energy efficiency. Having made it this far you clearly are or have become a competent climber, so providing we ensure you have the necessary anchors to clip on to, I think we can expect some actual rock climbing, because what we are about to do is to further develop our view of the economy by becoming truly metabolic thinkers.

In PART 1 we started talking about the economy as if it was an organism with a metabolism, and that it did useful work through this metabolism making the productive structures that in turn enabled it to do more useful work and so on. We even drew a parallel between the useful work of structure creation and measures of economic output like GDP and GWP. The AK framework that fell out of this was conveniently simple and has served us well. Hopefully what follows can still be called simple because we are going to stay with the metabolic view of the economy, but we are going to have to enrich that view in order to unearth the energy efficiency leaver.

In the ADAPTATION scenario we introduced the idea of there being productive and protective investment. We are now going to introduce the idea that productive investment can be further broken down into investments in energy efficiency as well as investments in acquiring resources – specifically primary energy[26]. Our way in here is again to start by thinking metabolically, assuming economic output is just final useful work, and that work is the creation of productive (and protective!) structure. For all its significant flaws, let's again assume GDP measures the annual rate of this useful activity, so if w is the annual rate the useful work of structure creation is happening, then it directly translates to GDP (or GWP)

$$y = \lambda w. \qquad (9)$$

Here λ is a number that simply converts between final useful work and GDP, which we will assume is 1.2 dollars for every megajoule of final useful work done.

The reason why it is good to spell out the relationship between money flows and flows of final useful work is because we can now write down how final useful work relates to the primary energy use p the final useful work w depends on. In words, the ability of the economy's productive structures in translating primary energy inputs into final useful work outputs is, by definition, the energy efficiency of the economy, η.

$$w = \eta p. \qquad (10)$$

Each time I see this equation I have in mind the Sankey diagram[27] of the global economy, with all the primary energy sources lined up on the left, the final useful work lined up on the right, and the spaghetti of networks linking the two determining the energy efficiency in the middle. This also makes plain the amount of energy wasted by the global economy because of its inefficiency 1- η.

What equation (10) does is to partition final useful work and hence economic output into two 'factors', energy efficiency and primary energy, just as the AK framework partitioned economic output into factors of capital K and productivity A. However, in the AK framework you could only invest in capital, whereas we are about to propose being able to invest output in building

26 Although we will be focusing in on energy, materials and matter will never be far away because the work being done is the harvesting of these materials and their arrangement into productive structures.

27 https://en.wikipedia.org/wiki/Sankey_diagram

capital to support either energy efficiency or primary energy inputs. To reassure you that everything you've learnt so far using the AK framework isn't being ripped up, we will see that increasing investment in energy efficiency is equivalent to raising the productivity A in the AK framework, it is just that this new ηp framework will allow us to track what happens to primary energy use and emissions when we invest in energy efficiency.

Now we need to think about the productive structures supporting η and p and how they are created through investing final useful work. This is no different to thinking about investing in productivity verses protectivity as we did for the ADAPTATION scenario. Perhaps it is useful to start with an example, so let's look at a house. This house is a certain size and hence contains a certain amount of useful activity inside it demanding energy. The bigger the house the more useful activities in it and the bigger the demand for primary energy inputs. However, the amount of primary energy needed to service this demand, the gas, electricity, and wood flowing into the house, also depends on how efficient the house is at translating this primary energy flow into the flow of final useful energy being demanded. How well insulated are the walls and roof when maintaining the required temperature gradient between inside and out? How efficient is the boiler, heat pump, cooker and kettle at converting primary energy into useful heat? Or the CPUs in all the devices at converting primary energy into the useful work of information creation and curation? From this hopefully you can see that both the size of the house and the efficiency of the house are separate if related traits and that we can make decisions about in order to affect the pattern of energy use of the house through investing in each of these traits. We are going to assume the global economy is no different.

Again, just like we did for productivity and protectivity, let's assume there is an accumulation rule for investments in energy efficiency and/or primary energy acquisition i.e. there are pools of capital (productive structure) attached to each trait, K_η and K_p. Hopefully you would straight away want to write out the accumulation rule for these two stocks given what we have done previously. I make them

$$K_\eta(t) = K_\eta(t\text{-}1) + ify(t\text{-}1) - dK_\eta(t\text{-}1) \qquad (11)$$

and

$$K_p(t) = K_p(t\text{-}1) + i(1 - f)y(t\text{-}1) - dK_p(t\text{-}1) \qquad (12)$$

because i = 80% of output is being invested overall in these productive activities, with the remaining 20 % still going into the protectivity to try and make sure that these structures live τ years and hence produce the desired lifetime returns. Now f of the productive investment is feeding into creating the efficiency of productive structures and $1 - f$ is feeding into creating their energy harvesting/demanding capacity.

All that is left to do before we have a go at implementing this to explore doubling investment in energy efficiency is to set out how both energy efficiency η and primary energy use p relate to their associated stocks K_η and K_p. Earlier in PART 1 we saw that GWP is growing at 3 %/yr but primary energy use is only growing at 1.7 %/yr. Equation (10) then tells us that energy efficiency must be growing at 3.0 – 1.7 = 1.3 %/yr. From this we learn that because GWP scales linearly with total capital ($y = AK$), both η and p must scale nonlinearly with their capital stocks and specifically that,

$$\eta = a_\eta K_\eta^{(1.3/3)} \qquad (13)$$

and

$$p = a_p K_p^{(1.7/3)} \qquad (14)$$

Some would say we are now straying dangerously close to mainstream macroeconomics and its now infamous Cobb-Douglas production function, although this is unfounded because our factors of production simply honour the laws of thermodynamics through equation (10), something the C-D framework is a mile away from doing. Our model is certainly now more complicated than the AK framework we started with, but we have climbed to this place gradually. Perhaps what we need to do before we move on is say something about those two scaling relationships, and I will try my best to not fall down the very deep rabbit hole they lead us to.

What equation (13) is saying is that as the pool of investment in energy efficiency increases it becomes less able to increase energy efficiency. Why would that be so? Well, increasing energy efficiency is invariably achieved by finding cleverer pathways through the Sankey diagram, and it gets progressively harder to find these cleverer, more efficient pathways not only because the number of more efficient configurations shrinks as complexity increases, but also because you can only ever build from where you are which again greatly restricts what is possible[28].

Equation (14) is also saying that as the pool of investment in acquiring primary energy increases it becomes progressively less able to increase primary energy flows. This can be viewed through either demanding or supplying more energy as our house example attempted to articulate. From the supply side, increasing supply means extending supply networks out into nature and hence space and likely pursuing ever more depleted resources as we pick the lower hanging fruit first. As I warned, we are now glimpsing down the rabbit hole of metabolic theory and perhaps the interested reader can look more into this in their own time[29] allowing us to move on and set out our ENERGY EFFICIENCY scenario. That said, it is a fascinating area to look into so please don't think I am trying to put you off.

S.4.1 Create a new worksheet and label it ENERGY EFFICIENCY.

S.4.2 Just like we did with the high and low carbon economy or the productive and protective economy, we are going to split the global economy into its efficient and inefficient (energy gathering/demanding) components. Let's start from scratch, labelling the first column YEAR and populating it 1980 to 2100. Now mark off the next three columns and head them ENERGY EFFICIENT ECONOMY with subheadings of CAPITAL, EFFICIENCY and GROWTH RATE. Repeat

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28 Stuart Kaufmann refers to this as the adjacent possible

29 https://en.wikipedia.org/wiki/Metabolic_theory_of_ecology

this for the ENERGY INEFFICIENT ECONOMY[30], labelling the three columns CAPITAL, PRIMARY ENERGY USE and GROWTH RATE. Finally, head the next seven columns TOTAL ECONOMY with GWP, GROWTH RATE, EMISSIONS, CUMULATIVE EMISSIONS, HIW and DECAY RATE as sub-headings.

S.4.3 We start by specifying the 1980 initial conditions for the efficient and inefficient capital. These are given by 1980 total capital split according to the historic levels of efficient ($f = 0.19$) and inefficient ($1 - f = 0.81$) investment. Now calculate the corresponding 1980 values for EFFICIENCY and PRIMAR ENERGY USE using equations (13) and (14). Refer to my master copy if you need to.

S.4.4 Populate the remaining 1980 values for everything other than the GROWTH RATES.

S.4.5 Turning to 1981, populate the EFFICIENT and INEFFICIENT capital values using equations (11) and (12) and follow this by populating the remaining 1981 values across the EFFICIENT, INEFFICIENT and TOTAL ECONOMY. Again, refer to my master copy if you need to.

S.4.6 Providing there are no bugs, you should be able to drag your 1981 values all the way to 2100. Add GWP, GROWTH RATE, EMISSIONS, and HIW to your DASHBOARD to make sure it is working properly.

S.4.7 Our scenario is to double the level of investment in the EFFICIENT ECONOMY in line with current global climate policy[31]. We will do this in 2020, again simulating the adoption of Paris Agreement-like practices. To implement this simply double f in 2020 through to 2100. However, for the EMISSIONS we can no longer use equation 3 and GWP because we have now broken that scaling relationship[32]. Fortunately, we now have PEU as a variable, and we know that PEU and CO_2 emissions have grown at roughly the same rate (1.7 %/yr) since 1980 suggesting the carbon intensity of global PEU hasn't changed much. After all, we are not exploring decarbonisation in this scenario[33]. Linearly scale EMISSIONS off of PEU using the carbon intensity of PEU from 2019 and amend your 2020 to 2100 EMISSIONS calculation accordingly.

S.4.8 To interpret the result it would be helpful to add a primary energy use plot to your dashboard. In addition to adding the PEU data provided in the DATA worksheet, add your doubled efficiency investment scenario and then generate its BAU counterpart by not changing the level of efficiency investment in 2020 and add that too to your DASHBOARD.

Hopefully what you see is that if we double the level of efficiency investment we do indeed see a slowing in the growth rate of PEU and hence emissions, but only a mild slowing, not any emissions degrowth. This is because the enhanced energy efficiency investment boosted output growth, which you can see rises rapidly post-2020 to more than 4 %/yr, and this counteracts the increased growth in energy efficiency. More importantly, this enhanced output growth leads to a bigger economy which washes away any long run energy and emissions savings, with both variables ending up significantly higher than their BAU counterparts. This

30 This isn't a good name for this trait, but I thought it might help by keeping the construction process clean. This is the energy acquisition/demanding side of the economy after all.

31 https://www.cop28.com/en/global-renewables-and-energy-efficiency-pledge

32 This is because the relative contributions of energy efficiency and PEU to GWP growth will change

33 If we were looking at a combined efficiency/decarbonisation scenario both the HCE and LCE would have differing levels of efficiency and PEU forcing us into tracking a four way split of the global economy.

is know as backfire because our attempt to use efficiency to drive emissions down has backfired on us[34].

Beyond the subtlety of the simulation you have just done, there are very good reasons to suspect that energy efficiency backfire presents a significant risk to global climate policy. Enhanced energy efficiency is a very attractive policy option because it can and is presented as a win-win, save the planet AND save yourself money. And therein lies the problem, because monetary savings are not simply put under the mattress but are instead actively invested with an expectation of future returns.

It is interesting that the global political community settled on doubling energy efficiency by 2030 because that is just about the right amount to boost GWP growth to the max. This tells me that perhaps that was really the game, or at least what was/is more important to current global politics. But the story around energy efficiency is a little more rich than this. Instead of doubling investment in energy efficiency, try increasing it five-fold. Now PEU and EMISSIONS really do start to go down. Why? Because not only is there a dramatic growth in energy efficiency greater than any promotion of GWP growth, we also end up starving the economy of energy through under investment. Like the ADAPTATION scenario, here we are actively impacting on output growth, boosting it in the short run but causing degrowth in the long run. There is a much wider discussion that spills out of this as you might imagine. The one thing I would want to add in to that discussion is to think about what accelerated efficiency feels like. When we were introducing the scaling relationship for energy efficiency (equation 13) we speculated that the reason investments became less potent as the stock of investment increased was because the economy was becoming more complex/complicated. If that is true, then you could imagine that living in a world that was more than twice as efficient as it is today could easily feel bewildering and perplexing leading to a mental health crisis. I can also see good reason to suspect efficiency and inequality are bed fellows given the two have come to characterise our current state.

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34 We have known that energy efficiency improvements can lead to energy use going up ever since William Stanley Jevons published The Coal Question in 1865.

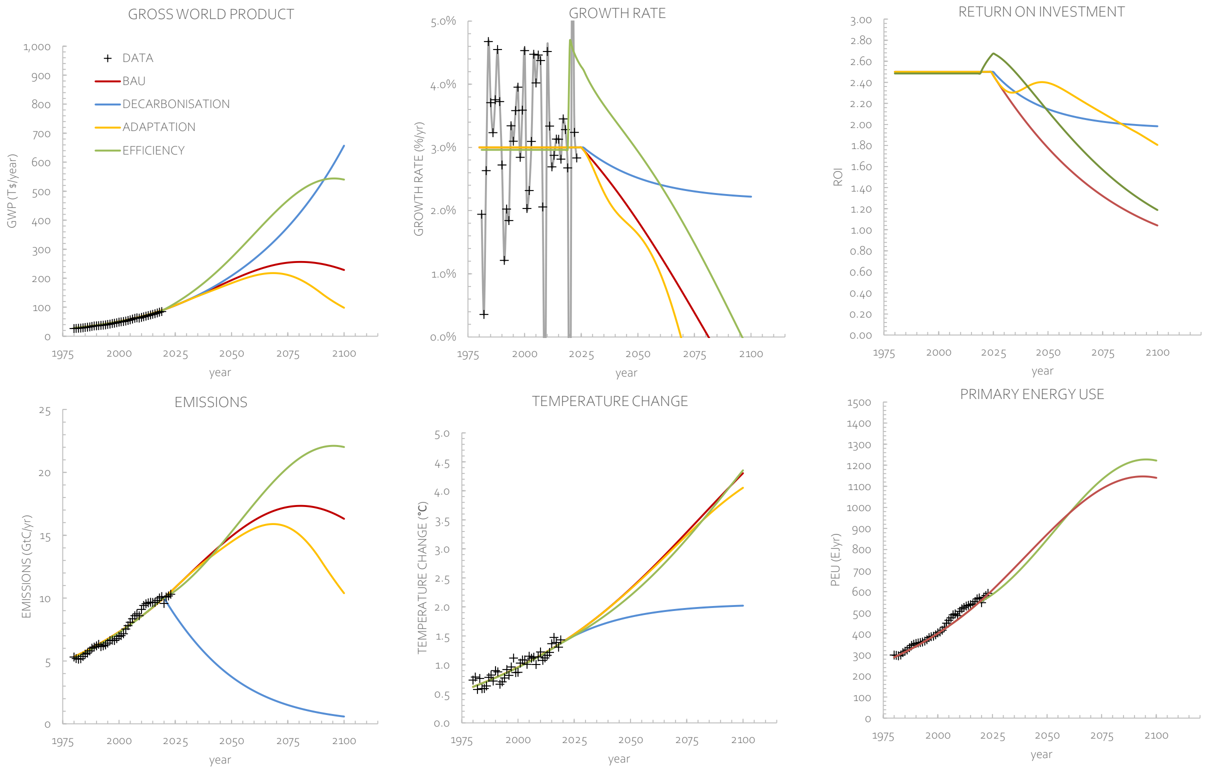

Figure 4. SIAM output for the BAU, DECARBONISATION, ADAPATION and EFFICIENCY scenarios.

5. The HYBRID scenario

We have developed our four scenarios independently, whereas it is obvious that any real world transition to avoid dangerous climate change will be some hybrid of these four ingredients with other features thrown in. However, rather than me detail a hybrid scenario blending together the four scenarios, I am laying that challenge at your door as the ultimate SIAM consolidation activity. I will happily look at and comment on your efforts, and will award an annual prize for the most insightful hybrid.

Perhaps the biggest challenge you face when hybridising is reconciling the representation of DECARBONISATION with that of ENERGY EFFICIENCY given the need to clearly demark what is 'high' and 'low' (net-zero) carbon activity. Saying that, by now you should have become adept at partitioning the economy into high/low carbon, efficient/inefficient and even productive/protective, and in essence any hybridisation will involve being able to do that accurately.

One additional feature you may want to bring in that is much discussed is carbon removal, or its offsetting poor relation. This is of course easy to implement in SIAM even if it is difficult to do at scale in the real world. SIAM is already adding in non-fossil fuel carbon in the form of land use change, you just need to throw that into reverse in some credible way. We have also touched on more unorthodox approaches around degrowth and I would strongly encourage you to look at these less explored options because the IAM community has taken too much status quo economics on board, especially if we accept that we are describing a transition i.e. a move to something different.

As you start to think about your hybrid scenario I think it is also important to keep asking yourself ‘are we straying towards forecasting?’.

6. The Cost of Carbon

The price of something 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 either not visible or are not 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 a process. Climate change is perhaps the biggest externality.

The externality of climate change arises from the fact that the making or use of the thing you are selling or using is associated with some greenhouse gas emissions, which are released into a well-mixed global atmosphere, which in turn results in climate change and impacts (mainly costs) on wider society, both now and in the future. The spatial distribution of external costs across society makes the release of greenhouse gasses a tragedy-of-the-commons issue, with the commons being say the carrying capacity of the atmosphere. These external costs are also spread over time because of the persistence of CO_2 in the atmosphere, making this a tragedy-of-the-horizons externality too, where one generation is robbing future generations of their climate headspace.

If climate change is an externality, then one solution is to attempt to internalise its effects i.e. to make sure climate costs are included into the price of everything. For that we need to know how much CO_2 a thing is responsible for and how much a tonne of carbon emission costs the global economy over some appropriate time frame. We then need to make sure that cost is woven into the price of everything in proportion to the emission it caused. Perhaps this is the next big battle in the fight against climate change, even though it has been a part of climate analysis for the last 30 years or more.

There are several ways of pricing carbon. The first is cap and trade, as exemplified by emissions trading schemes. Here there is no explicit attempt to calculate a price. Instead, a regulator sets a cap on emissions in a sector (to date this has been the power sector and heavy industry), and then issues 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 buy someone else’s spare quota. This approach has generally led to very low carbon prices, principally because regulators have been too generous on the number of permits issued in any given year.

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. Here, all options for reducing emissions from a given process are ranked by price per tonne saved 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 counterfactual, where some other possibly cheaper technologies could have been used that didn't reduce emissions. The UK and EU prefer the MAC approach because it is driven by technology prices, which are somewhat known, and carbon budgets, which can be fixed by policy decisions.

This brings us on to the most contentious and potentially yet most 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 a tonne causes, something we have discussed at length in PART 1 - Section 3.6, and how much damage that elicits, something we covered in PART 1 - Section 3.7, so it appears we are well placed for this.

Because we are trying to evaluate future costs, we will use standard economic practice of translating these into their Net Present Value (NPV). Traditionally this is done through the highly contentious act of discounting future costs prior to adding them up, which is one of the most problematic aspects of SCC estimation. Discounting is where you say that expenditure or income in the future is worth less when viewed from the present than today. If I gave you a choice of having £10 now or £10 this time next year, I bet you you'd take the £10 now unless you want to use me as a zero interest bank for a year. What if I offered you £10 now or £15 this time next year? Hopefully 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. However, if you apply this thinking to very long-term intergenerational problems like climate change it has the effect of penalising those future generations by assuming they matter less when viewed from the present.

We are not going to be discounting future generations. However, because CO_2 has such long lifetimes in the atmosphere this implies the climate cost of our additional tonne will keep rising indefinitely the longer we keep looking into that future. This ignores the fact that the economy will try and respond to that tonne through adaptation and so, building on our ADAPTATION scenario, we will be eroding future climate damages through adaptation. This will still mean we will need to think about the time frame over which adaptation occurs and hence we are adding up climate losses to get the NPV.

Hopefully what follows will echo and build on your experiences in SIAM to date. It is certainly a lot simpler than what you did in all the scenarios you have done so far and so should 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.

S.6.1. Insert a blank worksheet in your SIAM model and label it COSTING CARBON. Add the following column headings: YEAR, EMISSIONS, CUMULATIVE EMISSIONS, HIW, ADDITIONAL DECAY, CAPITAL, CAPITAL LOSSES, ADAPTATION FACTOR, ADAPTED CAPITAL LOSSES, NET PRESENT VALUE.

S.6.2. Fill down the YEAR from 2020 to 2100.

S.6.3. Emit one tonne of carbon to the atmosphere in 2020.

S.6.4. 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.

S.6.5. Now translate these cumulative emissions into global temperature changes 2020 to 2100 just like you have been doing in SIAM i.e. using the transient climate response to cumulative emissions approach where you simply multiply these cumulative emissions by the climate sensitivity. Remember we are in tC, not GtC! What you should get is a tiny amount of global warming, it is associated with just one tonne of carbon after all. It may help to express the number in scientific format as it is a very small number.

S.2.6. As you might predict from everything we have done previously in SIAM, this temperature change is going to increase the decay rate of total capital. Given we are at or above the 1.5 °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,

$\Delta d = s_d \Delta T$ (15).

S.2.7. If equation (15) 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

$\Delta K = \Delta d K$ (16).

where K is total capital in any given year.

It is valuable to pause here and think about what the loss of capital, ΔK, represents. Imagine you emit a tonne of carbon on an intercontinental flight. This mixes into the atmosphere, warms the entire planet a tiny bit (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 can be defined as the time discounted value of all future returns from an investment, and hence this loss of capital should be the cost of the decision to fly if we have valued capital accurately, which of course we don't, but we are where we are.

As we discussed in Section 3.7, this perspective of climate costs contrasts with the alternative income-based view traditionally implemented in IAMs. There, 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 (mode 1 costs from Section 3.7 in PART1). 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.

Again as we discussed in Section 3.7, there is another mode of climate cost we are 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. As with all our scenarios, we do not include income and productivity related climate costs here, but instead lump all costs onto capital and that should be kept in mind here on.

Move to the CAPITAL column and populate the 2020 value with its current World Bank total capital estimate of 1200 T$. We are now left with an important choice to make. What pathway should the stock of global total capital take that our tonne of carbon is going to chip away at? We could adopt one of our previous scenarios where it changes over time, but I am going to suggest we keep it constant because I think we should be comparing today's economy with its equivalently rich future counterpart to try and bring some intergenerational equity to the framework. I certainly don't want to take growth as a given here. So populate CAPITAL through to 2100 with its 2020 value (in $ not T$). Again, the scientific number format is helpful here as the global economy is worth a lot of dollars.

S.6.8. Now predict the CAPITAL LOSSES attached to our additional one tonne of carbon by multiplying the change in decay by the total capital following equations (15) and (16). Almost miraculously you should see that a tiny change in temperature leads to a tiny change in the decay rate of the global economy, but when multiplied by a huge total capital value gives a few dollars of loss per year! Populate these annual losses from 2020 to 2100.

S.6.9. We could now add up these annual losses through to 2100 and from that get an SCC estimate. However, that assumes the effects of our additional tonne on the decay rate of capital persists[35] through to 2100 and thereby ignores the fact that the economy would try and adapt in response to these losses. I say try, because the whole point of our 'when does the warming kill the growth?' question was to point to a level of warming when we can no longer adapt, but for now it appears to be able to do some adaptation. So the question is how quickly can it adapt away the effects of our additional tonne of carbon? We addressed this in PART1 – Section 3.3, where we argued the economy adapts at the rate it turns over, and it turns over at the rate it grows. If currently $r = d = 3$ %/yr we will take that as the adaptation rate.

To capture this adaptation we are going to multiply our annual capital loss by an ADAPTATION FACTOR which will start at 1 in 2020 (i.e. no adaptation and all the loss is experienced) and will diminish by 3 %/yr going forwards to 2100 to account for the economy coming to terms with the effects of the tiny amount of additional warming. Now multiply this ADAPTATION FACTOR by the CAPITAL LOSSES to give the ADAPTED CAPITAL LOSSES. Although we have invoked adaptation as the mechanism for eroding the size of the future losses, the maths for doing this is identical to how people apply discounting. The difference is that we have appealed to the hopefully less contentious process of adaptation rather than the highly contentious process of discounting for this.

S.6.10. We are now ready to add up the ADAPTED CAPITAL LOSSES to get our total costs to the global economy of adding that one tonne of carbon to the atmosphere in 2020. You are now faced with a choice over how long into the future you want to add up for. Mainstream economics might suggest you do that for the next 30 years as if it is only the current generation that matters. The UK Treasury Green Book has recently mandated adding up at least to 2100[36]. Let's do both and compare the results. I get ~800 $/tC adding up for the next 30 years and ~1200 $/tC if I add up for the next 80 years. These costs are, by definition, the Social Cost of Carbon! It is common to report the SCC in $/tCO_2$, so why not express it in both units[37].

Our SCC estimates are about six times bigger than what you get from DICE. 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, and the economy is also far more sensitive to warming than DICE (and most other IAMs) think. Let's reflect back on these SCC estimates. If a return intercontinental flight was one tonne of carbon dioxide per person, then our SCC result suggests adding at least $200 to the ticket price to compensate the global economy for the economic losses this imposed. 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 they are very hard to identify. This suggests the need to put the money into a huge climate compensation

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[35] 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.

36 https://www.gov.uk/government/publications/green-book-supplementary-guidance-discounting

37 1 tC = 44/12 tCO2

scheme[38].

7. Reflections

We have reached the 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 in PART 1, 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 in climate-induced secular decline 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. Then we explored some adaptation on the protectivity of capital in order to attempt to maintain asset lifetimes and returns on investment in the face of increasing climate damages. The last scenario we explored was to double investment in energy efficiency, which we saw had some counter-intuitive rebound effects where energy use increased in the long term. Finally, we have lain out how the tools we have to hand in SIAM can be used to construct a relatively transparent estimate of the Social Cost of Carbon.

Hopefully your understanding of what an IAM is and how they are used has deepened. I am also hoping your understanding of the core climate and economic processes at play in climate science has both widened and deepened. I would be surprised if your rock climbing skills haven't also improved. If you have any constructive feedback that I can plough back into this exercise please do not hesitate to email me.

8. Acknowledgements

SIAM has evolved over the past 10 years as a teaching aid for a 3rd year undergraduates. Like me, the students have little or no economics training, and this current draft owes a lot to our slowly resolving ignorance. This 2025 revision has also benefited significantly from an ESRC funded project - Timescales and Investment Dynamics in the Economy (TIDE), along with ever skilful editing from Dan Chester.

The journey has also had a profound effect on my research and thinking. As Richard Feynman is alleged to have said, you understand nothing until you can teach it to anyone (or something like that). It is through the process of trying to render this material down to its essence to create something edible to more than IAM builders I stumbled across new insights, many of which have made it through the peer review process in good journals. The CO_2 – temperature linearity set out in Section 3.6 in PART 1 was published in Nature Geoscience[39], building on earlier work of Damon Mathews and co-workers. The DECARBONISATION scenario informed and was informed by our work on stranded assets published in Environmental Research[40].

38 Article 9 in the Paris Agreement: https://unfccc.int/files/meetings/paris_nov_2015/application/pdf/paris_agreement_english_.pdf

39 Jarvis & Forster 2024. https://www.nature.com/articles/s41561-024-01580-5#citeas

40 Chester et al 2024 https://iopscience.iop.org/article/10.1088/2752-5295/ad7313

The ENERGY EFFICIENCY scenario informed and was informed by our work on rebound effects published in Energy Efficiency[41]. The climate damage function presented in Section 3.7 of PART 1 has launched a research project with the University of Lisbon with publications forthcoming on both the calculation of SCC and the ADAPTATION scenario[42]. The interchange between rates and timescales which simplifies so much of the analysis of the economy derives from work published in Ecological Economics on the turnover of the US economy[43]. Finally, the conception of the global economy as an organism doing useful work derives from ongoing interactions with Carey King at the University of Texas – Austin, building on earlier work covering energy return on investment published in Ecological Economics[44].

41 Jarvis & King 2024 https://doi.org/10.1007/s12053-024-10236-7

42 https://docs.google.com/forms/d/17S1PFL87qq1EKBG-hTcptw4i1lRiaSSTgyLONH0guqE/edit?pli=1

43 Chester et al 2023 https://www.sciencedirect.com/science/article/pii/S0921800923003385

44 Jarvis 2018 https://doi.org/10.1016/j.ecolecon.2017.11.005