Timescales and Investment Dynamics in the Economy (TIDE)

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Abstract

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Global warming at a level greater than 1.5 °C above pre-industrial levels is widely understood to risk irreversible damage and is unlikely to be averted without a radical departure from current policy and patterns of investment within the coming decades. Moreover, such a transition is also likely to require large quantities of the economy's existing productive structures – both physical infrastructure and the workers who operate it – to be retired or repurposed before their expected end of life. If poorly managed, this threatens significant losses to investors (including pension funds) and widespread impacts on livelihoods.

This thesis seeks to understand how as a society we make investments in our future, and how the timescales over which these investments are made constrain the ability for the economy to move in novel directions. Investment lifetimes, despite their relevance to rates of both economic growth and transition, are poorly understood and have therefore been under-represented in models of economic transition. Using a systems dynamics approach which treats capital assets as flows and stocks rather than fixed artifacts – and is therefore able to replicate the description of other flowing systems in the natural sciences – new methods are introduced for estimating turnover timescales from available capital stocks data. This allows the timescale distribution of the whole economy to be derived, providing new insights into macroeconomic investment behaviour and the inertial dynamics of the economy.

The global risk of stranded assets is then estimated by a new model which simulates the turnover dynamics of capital. This uniquely includes human as well as produced capital, bringing to the forefront the risks to workers rather than just to financial investors. Several pathways to zero carbon emissions in 2050 are explored, finding that delaying a ban on new carbon-dependent investment from 2020 to 2030 increases the global capital value at risk from 117 T$ to 557 T$, over a third of the present-day economy, highlighting the perils of delaying emissions reduction policy.

Finally, the same ecology-inspired turnover model is applied to human working lifetimes, exploiting the widespread adoption of human capital (defined by expected lifetime earnings) to further understanding of working patterns and the importance of consumption to developing human productive potential. This leads to a final conclusion: that the common distinction in economics between consumption and investment is not so clear cut, and in fact almost all expenditure is some form of investment, with varying degrees of productivity and over varying timescales. This reinforces the value of the timescale-focused, systems dynamics view of the economy that this thesis introduces.

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iii. Acknowledgements

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iv. Declaration

This thesis is my original work and has not been submitted in substantially the same form for the award of a higher degree at this or any other university. All sections of the thesis which have been published or submitted for a higher degree elsewhere have been clearly identified. All quotations have been distinguished by indentation or quotation marks and the sources of information specifically acknowledged. This thesis is submitted for the degree of Doctor of Philosophy undertaken at Lancaster University (Lancaster, UK).

v. Statement of authorship

This thesis has been prepared in the alternative format, as a set of three papers presented in Chapters 2-4, as submitted to or intended for submission to peer-reviewed journals. Please find below details of these publications with information regarding my contributions using the CRediT taxonomy.

Chapter 2

Chester, D., Lynch, C., Szerszynski, B., Mercure, J.-F., Jarvis, A., 2024. Heterogeneous capital stocks and economic inertia in the US economy. *Ecological Economics*, 217, 108075. https://doi.org/10.1016/j.ecolecon.2023.108075

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Chapter 3

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Daniel Chester: Conceptualization, Methodology, Visualization, Formal analysis, Data curation, Writing – original draft, Writing – review and editing

An adapted version of this chapter was submitted for the award of Doctor of Philosophy at Exeter University by Cormac Lynch and is published in their thesis:

Lynch, C., 2025. Transformational impacts of the low-carbon transition - a mixed methods approach. PhD thesis, University of Exeter. https://ore.exeter.ac.uk/repository/handle/10871/139737

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1. Introduction

Capital works to dominate the long term through the short term. Our own model seeks to harmonise the rhythms of production with those of nature […] we are going to nationalise time.

Jean-Luc Mélenchon, 2022

The study of physics, geology, biology or any other natural science is largely the study of time. Rhythms are abundant throughout nature. From the atom to the solar system, natural processes take place across a near-incomprehensibly wide range of timescales. Human activity likewise takes place over a range of timescales: buildings and major infrastructure project are built with long lifetimes in mind, economies grow and evolve at particular rates, and political decisions aim at long term planning but are influenced by short election cycles. The "tragedy of the horizon," in the words of former Bank of England Governor Mark Carney, is that human decision-making timescales are significantly misaligned with those of the climate system they are perturbing.

Time is running out to prevent severe impacts from climate change on a global scale, with recent evidence (Jarvis and Forster, 2024) suggesting that the guardrail of 1.5 °C of warming since pre-industrial times may have already been breached. Urgent structural change is therefore needed to decarbonise the economy, and with the growing realisation that the rate of necessary change likely exceeds the natural lifetime of many of the productive structures making up the economy, fears are emerging that the necessary transition may pose significant risks to the global economy. This inspires hesitation on the part of policymakers to pursue far-reaching policy changes and demonstrates how the investments we make today shape the economy of tomorrow. Investment banker Carney and socialist firebrand Mélenchon may agree on very little else, but the significance of the timescale divergence between economy and climate has become equally clear to both. As this thesis will demonstrate, Mélenchon is wise to note the particular influence of capital.

If it is to better understand and respond to this challenge, economics could stand to embrace its role as the study of time. While individual investors have an intuitive awareness of the timescales over which they expect to receive returns on their investments, the lifetimes of the economy's productive structures and the investment returns they provide are poorly understood on a macroeconomic scale (Baldwin et al., 2007; Görzig, 2007; OECD, 2009; Rincon-Aznar et al., 2017). This not only in spite of the importance of these timescales in determining the ability of the economy to adapt (and potentially explaining long run economic growth rates), but also in spite of the fact that unlike the natural world – which the natural sciences more keenly view through the lens of time – every movement within the economy is helpfully measured and reported by accountants and statisticians. As a result of this blind spot, the models that have underpinned global climate change policy for decades typically under-represent the inertial influence of long-lived productive structures, and this has led them to encourage a wait-and-see approach which will likely have disastrous consequences.

This introduction provides an overview of climate change, the sources of socio-economic inertia to major economic change of the kind required to mitigate climate change, and how this inertia is poorly represented in conventional climate-economy models (the term inertia is used here as a catch-all description for phenomena which act to slow or prevent change, including lock-in, path dependence and hysteresis). Having identified the critical role of capital lifetimes and human working lifetimes in this process, it then describes the conventional methodology for measuring capital stocks (including human capital) and explores the state of the literature on capital lifetimes, which the thesis will later aim to improve. It concludes with an overview of the aims and structure of this thesis.

1.1. Climate change and inertia

Climate change is the tragedy of the horizon.

Mark Carney (2015)

1.1.1. Climate change

The effects of human-induced climate change are increasingly being felt worldwide. The evidence that human influence has warmed the atmosphere, ocean and land is "unequivocal" and this is affecting weather and climate extremes "in every region across the globe", posing risks to people and nature (IPCC, 2023, p. 5). As additional carbon dioxide has accumulated in the atmosphere (Figure 1.1b) the global temperature has risen (Figure 1.1a) in a relationship that has so far been consistently linear (Figure 1.1c) despite the many nonlinearities in the climate system (Allen et al., 2009; Canadell et al., 2021; Jarvis and Forster, 2024).

As temperatures rise, the impacts on people and nature will become greater at a disproportional rate. Some research, for example, suggests that global exposure to combined risks (including for example water availability, flooding, access to energy, heat exposure, crop yields and habitat degradation) is likely to double between 1.5 °C and 2 °C of warming above pre-industrial levels, and double again with 3 °C (Byers et al., 2018). This difference between 1.5 °C and 2 °C has been said to mark "the difference between events at the upper limit of present-day natural variability and a new climate regime" (Schleussner et al., 2016, p. 327), and moreover, the impacts of the additional 0.5 °C are expected to be disproportionately distributed in lower income countries which are at the same time more vulnerable and less culpable (King and Harrington, 2018; Shiogama et al., 2019). By 3 °C almost all of the world will likely be exposed to multiple forms of risk; for example the population exposed to heatwave risk in the EU has been estimated to increase from 12% to around 80% between 1.5 °C and 3.0 °C (Werning et al., 2024).

The global community near-unanimously agreed in the 2015 Paris Agreement to keep the increase in global temperature "well below 2 °C above pre-industrial levels" and to "pursue efforts to limit the temperature increase to 1.5 °C" (United Nations, 2015). The latter is likely to require global CO_2 emissions to be reduced to net zero by 2050, and this has become the declared target of most of the G20 member states including the European Union and the United Kingdom (Cointe and Guillemot, 2023; UNEP, 2024).

Despite targets set and agreements made, the 1.5 °C guardrail nonetheless looks set to be surpassed: it is now almost certain that this barrier will be breached even if the most extreme cuts in emissions were made (IPCC, 2023), and some evidence points to the global temperature being at or near this point already (Figure 1.1d; Cointe and Guillemot, 2023, Hansen et al., 2025). The policies currently in place by governments around the world do not meet the ambition of the targets that they themselves have set, with current policy estimated to put us on course for around 3 °C of warming (Burnett et al., 2024; UNEP, 2024). With each year that passes more carbon is emitted, reducing the 'budget' of emissions that can still be safely emitted, and the time in which cuts need to be made gets shorter. The window is therefore rapidly closing.

The size of the challenge is particularly stark if economic growth is to be maintained whilst cutting emissions: Jackson (2016) estimated that to keep incomes growing at 2 per cent per year and achieve a 95% reduction in emissions, the emissions intensity of the economy would need be cut from 497 gCO_2/$ to 10 gCO_2/$, a nearly 50-fold reduction that would need to be enacted by 2050. This becomes over 200-fold if incomes are allowed to increase more in poorer countries to catch up with richer countries.

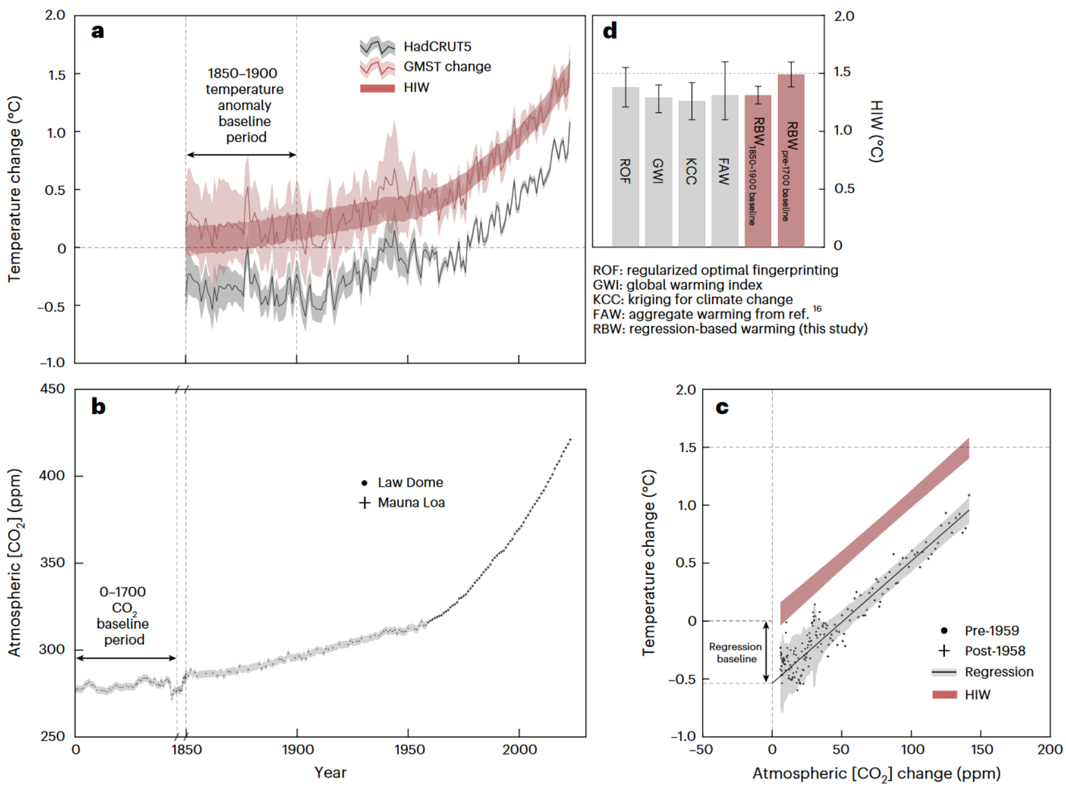

Figure 1.1: **(a)** Global mean surface temperature (GMST) change relative to its 1961–1990 mean (grey), GMST change relative to its 0-1700 mean (red), and human induced warming (HIW) estimated by removing the effects of natural variability (red window). **(b)** Atmospheric carbon dioxide concentrations, measured from the Law Dome ice core before 1959 and directly observed at Mauna Loa, Hawaii from 1959 onwards. **(c)** The relationship between (a) and (b). **(d)** A range of median estimates of HIW, using different methods, relative to a 1850–1900 baseline, demonstrating close proximity to the Paris 1.5 °C target. Reproduced from Jarvis and Forster (2024).

1.1.2. Economic inertia

To achieve the Paris Agreement outcomes – even keeping below 2 °C – the transition to a net zero global society will need to be achieved in a matter of years to decades (section 1.2.3 explores the targeting of *net* zero). The historical evidence suggests that making profound changes to economic systems in short periods of time can be exceptionally challenging, often prompting or coinciding with crises that threaten livelihoods and even lives. The fall of the Soviet Union and the subsequent shock therapy transition to capitalism sent poverty rates spiralling in the former USSR (Jaitner et al., 2018; Klugman and Braithwaite, 1998; Mattei, 2025). The closure of coal mines in England and Wales decimated communities that were reliant on the industry and had insufficient time or resources to adapt (Atteridge et al., 2020; Measham et al., 2024). While climate change presents ever-growing risks to the planet and the people that live on it – what we may call physical risks – in the other direction, the large-scale structural change required to avoid these risks presents transition risks which threaten livelihoods and the stability of the financial system (Bolton et al., 2020; Daumas, 2023; Semieniuk et al., 2021). This idea originated in the seminal assessment by Meinshausen *et al.* (2009) that full use of the planet's remaining fossil fuel reserves was incompatible with the 2 °C guardrail, prompting fears that fossil fuel companies may be over-valued (Daumas, 2023). Carney (2015) was among the first to highlight the trade-off that exists between physical and transition risks (though he was keen to point out that these risks are not inherently comparable in magnitude but are instead separated in time).

The presence (or fear, warranted or otherwise) of transition risks is naturally a hinderance to transition, and as such, they are an expression of the inertia of the socioeconomic system (Grubb, 1997; Ha-Duong et al., 1997), or what Grubb *et al.* (2020) refer to as "the dynamic characteristics of emitting systems". This inertia is particularly potent where climate change is concerned: "carbon lock-in is particularly prone to entrenchment given the large capital costs, long infrastructure lifetimes, and interrelationships between the socioeconomic and technical systems involved" (Seto et al., 2016, p. 425). Inertia in the economy is deeply multifaceted, stretching across the political, social, cultural, financial and technological realms, and understanding its many forms will be critical to overcoming it and securing the necessary transition in the urgent timeframe required to achieve the goals of the Paris Agreement. This section will set out some of the predominant forms of inertia that lock us in to our current carbon-fuelled economic system, bringing together literature in the overlapping fields of transition risks, carbon lock-in, path dependence and hysteresis.

1.1.2.1. Infrastructural inertia: stranded assets and the 'carbon bubble'

One of the most substantial sources of inertia, dominating transition risks discourse, is the lifetimes of physical capital infrastructure (Mercure, 2022). Buildings and machinery, for example, typically have lifetimes of the order of decades, and especially given how asset financing is structured – costs to investors typically accrue at the start of an asset's lifecycle, and payoffs at the end – their lifetimes can be costly to change (Figure 1.2). In some instances retrofitting can make infrastructure compatible with climate objectives, but this can often be impossible or prohibitively expensive (Streicher et al., 2021), or fail to address wider practices that are locked in by the infrastructure, such as supply chains, land use patterns and street layouts (Seto et al., 2016). Infrastructure investments therefore act to restrict transition to a rate which corresponds to their lifetime.

This is particularly acute in the context of climate change: IPCC (2007) observed that timescales of capital turnover "appear to be very long for most greenhouse-gas emitting sectors". The industrial infrastructure these sectors rely on is designed to last decades, while roads and other transport systems which lock in emissions can last centuries. The extent to which these timescales contribute inertia to the economy can be measured through committed emissions, the total cumulative CO_2 emissions that will result from the remaining lifetimes of already-existing infrastructure; 496 Gt of cumulative future CO_2 emissions are already thought to be 'locked in' (Davis et al., 2010). According to IPCC (2023, p. 20) "projected CO_2 emissions from existing fossil fuel infrastructure without additional abatement would exceed the remaining carbon budget for 1.5°C", and depending on the assumptions made in calculating committed emissions, 2°C may be locked in too (Guivarch and Hallegatte, 2011): "projected cumulative future CO_2 emissions over the lifetime of existing and planned fossil fuel infrastructure, if historical operating patterns are maintained and without additional abatement, are approximately equal to the remaining carbon budget for limiting warming to 2 °C with a likelihood of 83%" (IPCC, 2023, p. 20).

At least some long-lived infrastructure will therefore need to be retired before its expected end of life if internationally agreed targets are going to be met. This prospect has led to such assets being declared stranded (Caldecott, 2018), potentially losing value and therefore resulting in losses to investors (Figure 1.2). With the production and therefore employment tied to these assets put at risk, significant job losses also appear on the horizon, pushing wider losses on to the working public (not to mention that if the investors are governments or pension funds, for example, the loss in value could be indirectly felt by the population at large). Concern has even been increasing in financial circles in recent years about the potential impact that this 'carbon bubble' bursting may have on global financial stability (Agarwala et al., 2021; Carney, 2015; Semieniuk et al., 2021). It is likely, in fact, that some stranded assets will occur as a result of ongoing technological shifts regardless of climate policy intervention (see section 1.1.2.3) (Mercure et al., 2018). Various attempts have been made to estimate the global wealth loss as a result of stranded assets, with significantly varying outcomes. Some have put it at around 1 trillion US$ (Mercure et al., 2018; Semieniuk et al., 2022) and others as high as 20 T$ (IRENA, 2017), with higher estimates resulting from scenarios where climate action is delayed because – as is currently happening – investment in new fossil fuel ventures continues and the bubble grows bigger, making the costs of climate action ever more prohibitive (Malm and Carton, 2024). As the next section will highlight, this only considers the value of physical assets at risk; these estimates could be much higher if the value of the global workforce at risk of being stranded is included.

All of the above demonstrates that the lifetimes of capital assets are a critical determinant of the entrenchment of climate change and the risks of mitigating it. Capital vintage studies of US industries have found that "regardless of location, resource availability and production structure, an increase in the rate of capital turnover is the most important factor in permanently changing carbon emission profiles and energy efficiency" (Davidsdottir and Ruth, 2004; Ruth et al., 2004). Davis and Socolow (2014) study this phenomenon in energy generation, estimating that power plants currently existing globally would emit 307 Gt CO_2 if assumed to have a 40-year lifetime, 578 Gt CO_2 if 60 years, and only 98 Gt CO_2 if they last 20 years. Cui *et al.* (2019) find that coal power plants would need to have their lifetimes reduced to around 35 years to achieve 2 °C and 20 years to achieve 1.5 °C (these are reduced by a further 5 years if all plants currently under construction come online, and 10 years if all proposed plants are built). Additionally, while the literature focuses on those sectors most responsible for carbon emissions, it is worth noting that capital in sectors right across the economy can tie us into carbon emissions. Insufficient data exists on the lifetimes of capital assets across all sectors and therefore their contribution to inertia, as section 1.3 will discuss. This knowledge gap and the contribution of capital lifetimes to inertia through stranded assets will form a primary focus of this thesis, along with the introduction of stranded human capital, which the next section explores.

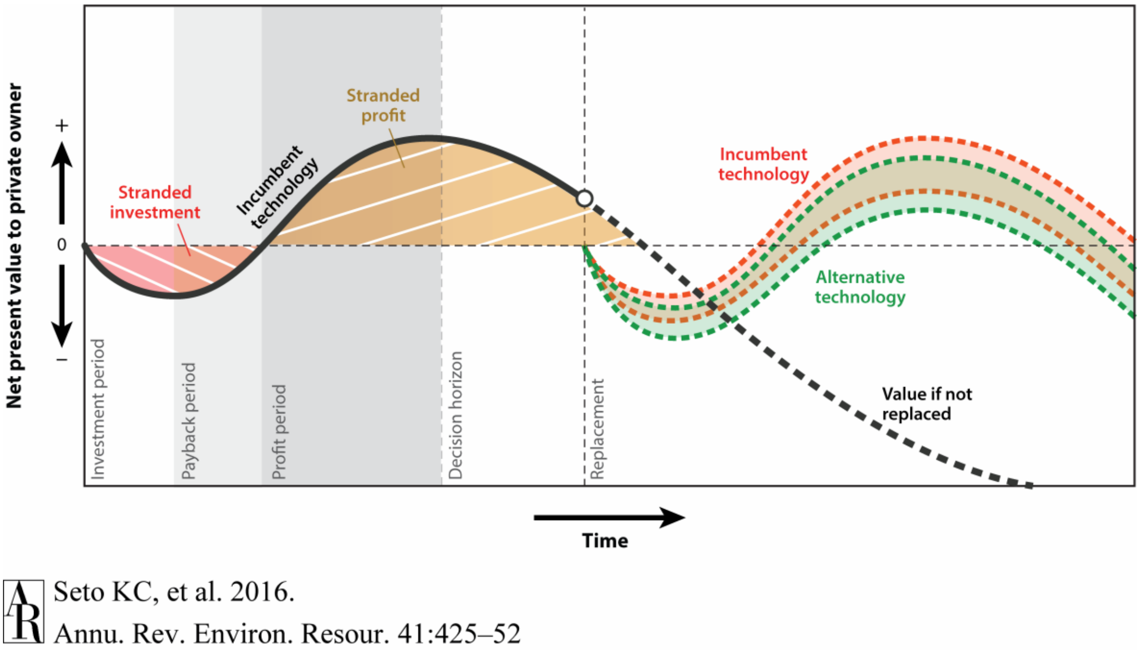

Figure 1.2: Schematic demonstration of the typical evolution of a privately-owned energy asset's net present value. Capital costs initially exceed returns, but as these costs diminish relative to returns they begin to be paid back, leading to a period of profit for the investor once the investment is paid off. Increasing running costs eventually displace this profit. At this point a decision must be made about the future of the asset, evaluating options including retrofitting or replacement with alternative technologies (all taking place within a social and policy context). If this takes place before the profit period has elapsed, some value will be stranded. Reproduced from Seto *et al.* (2016).

1.1.2.2. Livelihoods and a just transition

Capital is not, however, the only productive force with a remaining lifetime that is potentially incompatible with climate targets. The same is true of the workforce. Human working lifetimes are typically around 40 years, and this has remained remarkably stable over the past century (Ausubel and Grübler, 1995; Eurostat, 2024). An economic transition on a timeframe shorter than that, in which production across multiple sectors must be phased out, will inevitably put workers in those sectors at risk of losing their jobs before they naturally expect to retire, in the same way that fixed capital is at risk of premature retirement.

Of course, people are more readily able to repurpose themselves to new activities than physical structures which are often built for a specific purpose. Some evidence even suggests that a climate transition will be – or at least can be – a net creator of employment opportunities (low-carbon technologies tending to be more labour-intensive), and even that the new 'green' jobs created are likely to offer better pay, conditions and job security than those that will be lost (Climate Change Committee, 2023; Fankhauser et al., 2008; Malik et al., 2021). Models of climate policy often make optimistic assumptions about the ease with which this can be achieved, assuming that the workforce can be redirected into alternative sectors and modes of employment without significant economic disruption, but this relies on those workers being in the right place and possessing the necessary skills to take up this employment. Green jobs require different, often higher levels of education and training, and reskilling may be difficult, especially for those later in life or where the facilities for it are unavailable (Consoli et al., 2016; Martinez-Fernandez et al., 2010). The new jobs that are created are also likely to be concentrated in different regions to those based previously around fossil resources, resulting in a "redrawing [of] the global employment map" (Scott, 2014, p. 10) and therefore significant migration within and between countries (precipitating wider sociopolitical upheaval). Those unable to move or adapt as they are locked in to particular practices and places may find themselves left behind without employment (Seto et al., 2016). Those most likely to be left behind are those who are already poorest, reinforcing existing patterns of spatial inequality and labour market disadvantage (Markkanen and Anger-Kraavi, 2019; Sovacool et al., 2019; While and Eadson, 2022).

These risks have led to calls for a 'just transition' that would ensure workers are able to retain high quality employment through a comprehensive programme of retraining and job creation, and that decisions around the transition are made with social and environmental justice in mind (Lynch et al., 2024; McCauley and Heffron, 2018; Rosemberg, 2010). A just transition is likely to require a significant role for the state, as the only institution capable of mobilising resources on the scale that is required and able to allocate them at a national level based on the needs of at-risk communities (Newell and Mulvaney, 2013). With the costs of retraining – and therefore of delivering a just transition at scale – potentially high (Zhang et al., 2024), and state intervention politically challenging, many policymakers have been hesitant to embrace a fully-fledged just transition. In a sense, there will be costs in a climate transition either way, either in the form of state-led upskilling and job creation, or in the form of job losses and therefore state support for unemployed; in either case the perceived risks involved create sociopolitical inertia against a transition (Ciplet and Harrison, 2020; Evensen et al., 2018; Vona, 2019).

This inertia is often overlooked in the discourse around stranded assets and inertia, despite the increasing centrality of 'human capital' in mainstream economics as a direct representation, alongside produced capital, of the productive value of workers (von Dulong et al., 2023). Human capital, as will be discussed in more detail in section 1.3.5, is most often measured as the time-discounted future expected wages of any individual (or group). Human capital value is therefore defined by the expectation of future returns in much the same way as produced capital, and the loss of this value due to premature retirement in a climate transition could be therefore modelled in a similar fashion to produced capital. Ecological economists have perhaps hitherto been hesitant to subsume humans under the definition of capital on moral grounds, but used in this way human capital is simply a representation of people's financial expectations. Estimating the potential risk of stranded human capital would allow us to better understand the risk to (and therefore inertia created by) people's livelihoods, not just the risk to assets owned by investors. Chapter 3 will take up this task.

1.1.2.3. Technological and institutional inertia

Some other aspects of inertia are worth considering, before moving on to discuss the modelling of climate policy outcomes in more detail. Transition relies not only on the rate at which old capital can be removed, but also on the ability to replace it with new technology. Technological inertia therefore results from the rates at which new technologies proliferate through markets, as well as the economic and regulatory structures governing them which produce institutional inertia (Foxon, 2002; Grubb et al., 2021a). New energy technology and the networks to support it have often taken up to 50 years to reach their maximum saturation, and some infrastructure, such as transport networks, can take even longer to develop (Grübler et al., 1999) (Figure 1.3).

For new technologies to break through, they must change the existing sociotechnical configuration, a task which can find resistance from regulations and institutions which can be slow to adapt and prone to path dependency (Geels, 2002; Klitkou et al., 2015). In many cases "minor changes and marginal developments […] evolve into massive structural configurations that then restrict the variety of directions open to future changes" (Voß and Kemp, 2006, p. 13). This is compounded by the barriers presented by powerful economic, social and political actors who "seek either to reinforce a status quo trajectory that favors their interests against impending change or to create and then stabilize a new, more favorable, status quo" (Seto et al., 2016, p. 433), often through elite capture of firms and state agencies, creating a "battle over institutions" (Goldstein et al., 2023; Jacobsson and Lauber, 2006). The short time horizons on which politicians in liberal democracies typically operate, their natural tendency for risk aversion, and the under-representation of young people and future generations in the political process, can all make it difficult to overturn deeply-embedded policies and institutions (Boston and Lempp, 2011; Davies, 2017; Pierson, 2000). In particular "the costs of mitigation policies tend to be concentrated and fall mainly on easily identifiable and powerful vested interests, whereas the potential beneficiaries of mitigation are highly dispersed, both in spatial and temporal terms" (Boston and Lempp, 2011, p. 1006) creating poor political incentives to break the cycle. This can lead to critical aspects of the decision-making apparatus, like the choice of discount rates (see section 0), becoming embedded and difficult to change (Sunstein, 2014).

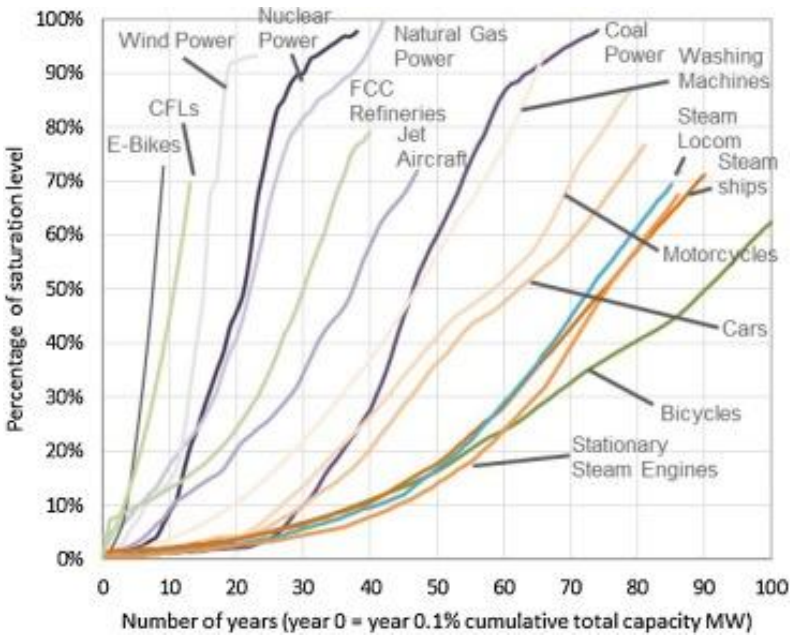

Figure 1.3: Diffusion of energy technologies within their market, from the point at which they reached 0.1% of their eventual maximum installed capacity. Reproduced from Bento and Wilson (2016).

1.1.2.4. Behaviour and other sources of inertia

"Carbon lock-in has primarily been considered a technological characteristic of sociotechnical systems, addressed without its social counterpart" (Seto et al., 2016, p. 438) but social norms, cultural values and behavioural traits can change even more slowly than policy and technology, and these also bind society to patterns of energy consumption and carbon emissions (Goldstein et al., 2023; O'Rourke and Lollo, 2015). "The rise in the popularity of the refrigerator," for example, "is correlated with increased household access to energy, but it also parallels changes in cultural norms around hygiene, modernity, efficiency, convenience, and material culture" (Nickles, 2002; Seto et al., 2016, p. 438). Changing technology and infrastructure may not be possible without simultaneously changing these cultural norms, demonstrating the layers of inertia that exist beyond the infrastructural and technological. Moreover, the demand for existing products over their alternatives is reinforced through sunk costs, learning effects and economies of scale which make them cheaper (or appear cheaper), but only because they are currently dominant (Groen et al., 2023; Klitkou et al., 2015). A significant literature has demonstrated the potentially wide effects of sunk-cost hysteresis: sunk costs result in the effects of past costs lingering, and therefore the previous state of the economy lingering (in terms of investment, production, employment, for example) (Adamonis and Göcke, 2018; Göcke, 2002). Knowledge, too, has an inertial/hysteretic aspect through dominant discourses, received wisdom, consensus formation, hegemonic common sense and popular narratives (Goldstein et al., 2023), with decision-making invariably guided by institutional memory and historical knowledge (Wilson, 2014) and structural inequalities determining access to education (Haider et al., 2021).

Behavioural inertia to climate action is an emerging field of study that has largely grown out of the health sciences – where understanding psychological obstacles to behavioural changes, and constructing choice architecture that encourages 'nudges' towards better decision-making, are similarly critical to achieving better long term outcomes (Seto et al., 2016; Thaler and Sunstein, 2008), while sociology has much to say on the formation of lifestyles, routines, social norms and cultural values and practices (Burton and Farstad, 2020; Goldstein et al., 2023).

1.2. Modelling climate and economy

All models are wrong, but some are useful.

George Box (1976)

If urgent economic transformation is required to mitigate the dangerous consequences of climate change, but transforming too much too quickly may equally threaten financial hardship, what path should policymakers take? How much fossil fuel should we use, and when? How much risk can be afforded, and to whom? Economists seek answers to these questions by switching on what Malm and Carton (2024, p. 55) semi-jokingly refer to as "the favoured crystal ball of late capitalism: the computer". The task is taken up by integrated assessment models (IAMs), which simulate the interaction between the climate and economic systems to enable the effect of various public policies on climate change outcomes to be studied (Wang et al., 2017). IAMs can be traced back to the 1970s when the World3 model, for example, informed the groundbreaking report *The Limits to Growth* (Meadows et al., 1972), but the idea grew rapidly after 1990 at which point the number of active IAM projects grew from 3 to over 40 (Hamilton et al., 2015; Parson and Fisher-Vanden, 1997; Weyant et al., 1995).

Though varying wildly in complexity – some represent the whole earth system with just a few equations while others contain intricate representations of the atmosphere, oceans and land use, and likewise for the economy – all IAMs operate, at a minimum, through the application of a feedback loop between economic and climatic processes (Wang et al., 2017; Weyant, 2017). A simple example is shown in Figure 1.4. The impact of economic production on energy consumption and therefore greenhouse gas emissions and global warming (or other environmental changes) is quantified, and this is fed back to the economic sphere through the introduction of 'damages' which reduce future production and economic growth. Weyant (2017) distinguished between process-based IAMs, which seek to provide projections of climate change impacts at detailed regional and sectoral levels under particular policy/emissions regimes, and benefit-cost IAMs, which aggregate the costs of climate change impacts and of climate change mitigation to produce a single metric for the total cost of climate change, typically to then identify policies which optimise this metric (most notably through the specification of a social cost of carbon, discussed in section 1.2.2) (Grubb et al., 2024; Nikas et al., 2019). The latter type now form a cornerstone for decision making on climate change in economics, particularly the DICE model for which William Nordhaus was awarded the Sveriges Riksbank Prize in Economic Sciences in Memory of Alfred Nobel (Grubb et al., 2021b).

This section will highlight some important considerations in IAM construction, before chapter 2 explores in more detail the treatment of capital in IAMs, and chapter 3 creates one to estimate the global risk of stranded assets.

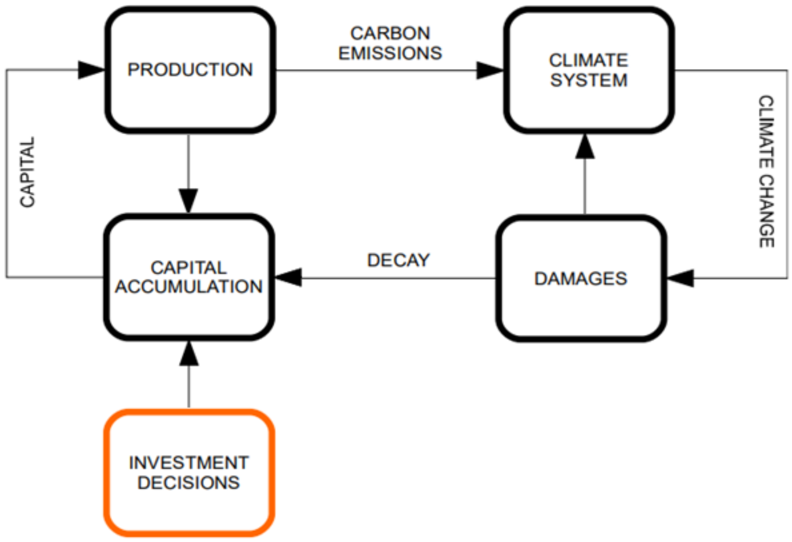

Figure 1.4: A schematic representation of the structure of integrated assessment models. Adapted from a similar figure in Jarvis (2021).

1.2.1. Inertia in IAMs

Given the purpose of integrated assessment modelling is to project climate outcomes and analyse the feasibility of policy pathways, and the barriers to these pathways are shaped by the inertial aspects of the economy described above, one might expect that these aspects would be a key feature of IAMs. The evidence suggests otherwise.

Thirty years ago Grubb et al. (1995) demonstrated that substantially different optimal outcomes can result from models in which the cost of abating emissions is dynamic and reflects inertial constraints, which they used to highlight the need to factor inertia into IAMs (Ha-Duong et al., 1997). Unfortunately inertia remains largely neglected in standard IAMs (Grubb et al., 2024, 2021b). The central issue identified by Grubb et al. (1995) was that, as Grubb et al. (2021b, p. 2) later put it, "across the now huge and diverse literature on DICE and related stylized models, the vast majority share one common structural assumption: that the cost of cutting emissions in a given period is unrelated to the previous pathway, and does not affect the subsequent prospects." Models typically applied a cost of reducing emissions that depended only on the amount of emissions being reduced and a cost function that simply declines exogenously over time. On this basis the answer invariably ends up coming out the same: it is economically preferable to defer abatement efforts until later to take advantage of falling costs. This is unrealistic, however, and neglects the dynamic effects of inertia, induced innovation and path dependence:

> It takes time, effort, and cost to change complex systems and to write-off, retrofit or replace existing capital stock. The cost of cutbacks depends on the inherited infrastructure, technologies and industries that have been built up over previous decades; it depends upon the prior efforts and inherited level of emissions. Indeed, the assumed "baseline" trajectory inevitably reflects the history of accumulated assets, infrastructure, industries, institutions, and indeed social norms. (Grubb et al., 2021b, p. 4)

The irony, that both Stern (2018) and Grubb *et al.* (2020) observe and that takes us back to the opening of this chapter, is that climate policy and IAMs are deeply concerned with time – when climate damages will be felt, when action should be taken – and yet this focus on the long run has led to a neglect of the processes of change involved.

Amending abatement costs to include dynamic inertial effects (such as the rate at which the economy is changing, the timescale of the transition, and the pliability of the system) leads to optimal outcomes where emissions are cut earlier and temperature increases are more heavily restrained, even under very moderate assumptions about the impact of climate damages (Grubb et al., 2024, 2021b; Vogt-Schilb et al., 2018). Unlike the likes of Nordhaus, Grubb *et al.* (2024) point to optimal temperature increases that are below 2 degrees. Even where costs are high these models find that "it is optimal to start a long-term emission-reduction strategy with significant short-term abatement investment" (Vogt-Schilb et al., 2018, p. 210) because a key factor is embedding long-lived capital that contributes to reducing emissions, such as power plants and public transport, in the system as early as possible (Jaccard and Rivers, 2007). Instead continuing to build brand new long-lived fossil capital rapidly accelerates the costs, because for capital "in its forties or fifties, retirement will be far less disastrous than if it has just sprung up" (Malm and Carton, 2024, p. 164), as discussed in section 1.1.2.1. "The more the system expands, the more it hardens into what it has always been" (Adorno, 2006, p. 171).

This points to an inertial aspect that is worthy of particular attention: the lifetimes of productive structures. As discussed earlier these are a critical determinant of the risk of stranded assets, but capital stocks are only represented at all in more complex IAMs (Jarvis (2021), shown in Figure 1.4, is an exception) and even where they are they represented they are typically simulated with a single stylised lifetime (Grubb et al., 2021b; Pauliuk et al., 2015). This neglects the significant heterogeneity of capital structures, some of which are short-lived and some (housing in particular) have average lifetimes over 75 years (Jaccard and Rivers, 2007; Shalizi and Lecocq, 2009). As a result of this omission these IAMs typically do not have a mechanism to simulate early retirement of capital, and therefore estimate of the cost of stranded assets and the impact this has optimal climate policy (Grubb et al., 2021b). To facilitate this a deeper treatment of capital turnover is required, and for this the integrated assessment modelling community needs to learn from capital accounting (Pauliuk et al., 2015).

Section 1.3 will describe how capital stocks are constructed in the world of accounting, and chapter 2 will explore why and how this should be applied in IAMs to improve consideration of inertia.

1.2.2. Utility maximisation and intertemporal discounting

Before proceeding, however, it is worth reflecting on what it means to 'optimise' climate policy and what choices get made along the way. Attempts to use IAMs for policy optimisation fit into a long tradition in neoclassical economics which structures decision-making around the assumed goal of maximising time-discounted utility (Simon, 2001). In other words, the goal is to maximise the economic prosperity of the current generation and, to a certain extent, future overlapping generations too. This is an extension of the longstanding utility maximisation debate in economics, which centres on the optimal balance of consumption (satisfying current desires) versus investment (allowing the greater satisfaction of future desires), a debate that will form the focus of chapter 4 given its implications for the creation of human capital. This has developed into the now-pervasive idea of the rational maximiser, the idea that as economic actors, we all make choices which deploy our scarce resources to maximise our long-run consumption, introduced in Frank Ramsey's seminal contribution to this debate *A Mathematical Theory of Saving* (Elsner et al., 2015; Ramsey, 1928). Needless to say, this assumption rarely characterises human motivations accurately (Manero et al., 2022).

A key aspect to the question of utility maximisation is the fact that humans tend to value present income over future income, a concept that John Rae termed 'intertemporal choice' in 1834 (Rae, 1905), and was later developed by Irving Fisher, who explained it through the idea of time preference, the extent to which an individual is inclined to value immediate gratification over delayed reward (Fisher, 1906). To Fisher, an individual's rate of time preference – motivated by perceived risks relating to future income growth, along with various hotly-contested psychological and philosophical factors (Frederick et al., 2002; Groom et al., 2022) – factors in their choice between consumption and saving (i.e. investing). Samuelson (1937) proposed the discounted-utility (DU) model, which condensed the multitude of variables influencing intertemporal choice into a single parameter: the discount rate, the rate at which the weight given to future utility decreases. Despite his own "manifest reservations about the normative and descriptive validity of the formulation he had proposed" (Frederick et al., 2002, p. 351) the model was widely and rapidly accepted as the preferred framework for analysing decisions that involve a trade-off between short-term and long-term benefits, and continues to be widely featured in IAMs and government investment guidelines, with most assuming an "arbitrary but positive" social discount rate (SDR) (Hanley and Spash, 1996, p. 133; Groom *et al.*, 2022).

The embrace of discount rates speaks to their immense practicality: for economic modelling they are utility maximisation made easy (Hepburn, 2007). The ability to compare the value of future benefits and costs on a present value basis facilitates very simple cost-benefit analysis and project evaluation, with straightforward outputs for decision-makers and policymakers. It provides a rational framework for allocating limited resources, where investment decisions often involve trade-offs between benefits accrued over very different timescales, and where the long-term involves risk and uncertainty (discounting is often used to derive risk-adjusted returns on investments). It is no surprise therefore that discount rates find particular relevance in IAMs seeking to balance the benefits and costs of climate action, especially given that the costs of emissions appear only after a significant time lag and are then long-lasting due to the long half-life of CO_2 in the atmosphere, meaning that the present generation pay the costs of climate action and future generations will be the primary beneficiaries (Dietz, 2008). Without future generations being able to speak for themselves, "people making decisions today on behalf of those not yet alive need to make collective ethical choices about what kind of opportunities (usually characterized as a particular state of the climate system measured by global mean temperature, GHG concentration, or maximum climate damages allowable by some future date) they want to leave future inhabitants of planet Earth" (Arrow et al., 2013; Weyant, 2017, p. 126). Discount rates are therefore a mechanism to address the tragedy of the horizon: they are a tool (albeit a crude one) that allows longer timescales to be considered in present-day decision making, but to a definable and manageable extent. They in part determine the inertia of the economy, with higher discount rates biasing decisions towards shorter-lived investments with more immediate returns, and vice versa.

The application of discount rates has such huge consequences for economic decision-making (Groom et al., 2022) that the choice of an appropriate discount rate has been described "one of the most critical problems in all of economics" (Weitzman, 2001, p. 260). Perhaps the most prominent example of its impact is the 2006 Stern Review (Stern, 2007), a landmark report for the UK government by economist Nicholas Stern which is often cited as one of the most influential economic reports on climate change, precipitating the landmark 2008 *Climate Change Act*. It used the PAGE IAM to generate estimates of the impact of climate change on the economy and laid the groundwork for stringent emissions targets to be achieved through carbon pricing which would reflect the "social cost of carbon". The review was the subject of significant criticism from other economists because its estimates of the present value of climate damages in a business-as-usual scenario (and therefore its estimates of the social cost of carbon) were outliers among the literature at the time, largely due to the approximately 1.4% social discount rate it used (Goulder and Williams, 2012). Nordhaus (2007) led the charge against the review arguing that because the discount rates were out of line with current market time preference behaviour, "the central questions about global-warming policy—how much, how fast, and how costly—remain open." By applying a significantly higher discount rate (around 4.3%) to DICE he made the case for much less aggressive climate action. Tol (2008) later demonstrated the extreme influence discounting can have on policy outcomes showing that the mean estimate of the social cost of carbon increases from $24/tC to $317/tC as the rate of pure time preference falls from 3% to 0%. Rather than providing empirical clarity on these central questions, models like IAMs can easily end up providing less clarity than existed before.

Amidst the wholehearted embrace of discounting by economists, to the extent that discounting at predetermined rates is an intrinsic and yet little known part of all capital investment decisions made by the UK government (HM Treasury, 2022), and with little public knowledge or debate in the contemporary literature aside from on the precise choice of discount rates, it is easy to lose sight of what they represent and the normative values in play (Hanley and Spash, 1996). The economist wields incredible, perhaps unwarranted, power when they cast away the welfare of whole generations with the choice of a single number; a power that earlier economists were hesitant to use, and one that has deeply troubled philosophers:

> One might think that moral philosophers could be of some help in at least guiding this discussion. Unfortunately, the specific proposal that most philosophers and environmental ethicists have been inclined to make, with respect to the social discount rate, is so far outside the ballpark of what economists and policy-makers have been considering, that it has resulted in them being largely sidelined in the discussion. This is because most philosophers, being of the view that it is morally impermissible to treat future harms as less serious than present ones, move immediately to the conclusion that the only acceptable social rate of time preference is zero.

> Indeed, this strikes many philosophers as being so obvious as to require little or no argument. The problem with this view is that it has extremely radical implications – indeed, unless some other factor is introduced that raises the overall discount rate above zero, it generates conclusions that are straightforwardly absurd. (This is why most economists, despite being puzzled by what the appropriate discount rate should be, nevertheless consider it essential that it be greater than zero.) (Heath, 2017, p. 3)

In introducing the DU model, Samuelson (1937, p. 161) was clear that it was merely a theoretical tool, and that "any connection between utility as discussed here and any welfare concept is disavowed. The idea that the results of such a statistical investigation could have any influence upon ethical judgments of policy is one which deserves the impatience of modern economists." (Samuelson, 1937, p. 161). Ramsey, indeed, decried discounting as "a practice which is ethically indefensible and arises merely from the weakness of the imagination" (Ramsey, 1928, p. 553). As such "while it is not clear that they possess any special expertise on the ethics of intergenerational welfare, governmental discounting guidance has almost exclusively been influenced by economists" (Nesje et al., 2023, p. 515). Stern (2018), indeed, expressed deep concern over its effect on integrated assessment modelling:

> Attempts to build integrated assessment models (IAMs) for the analysis of climate change have been largely misplaced and omit key effects and questions of [this] kind. Intertemporal issues and values are at the core of policy towards climate change and [this] paper shows that much of the intertemporal economic analysis of the issues around climate change has been misguided and has ridden roughshod over the analytical underpinnings and the underlying ethics of discounting. (Stern, 2018, p. 4)

Perhaps unsurprisingly, the contested moral dimension of the discounting decision and varying social attitudes and economic fundamentals between countries result in dramatic differences between discount rates used globally (Groom et al., 2022). As the above examples show, these differences have serious implications for policy. Countries that discount the future more – some at a rate nearly 10 times greater than others – will make investment decisions that focus on yielding returns in the short term, and will construct a policy regime that prioritises these returns over the wellbeing of future generations, contributing institutional inertia (Sunstein, 2014). The outcome of IAMs, like all models, is subject to the assumptions made in their construction (Pindyck, 2017).

1.2.3. IAMs *as* inertia: the political economy of modelling

This opens up a wider question, one always worth having in mind, about the role that economists and economic models play in the system they are studying. They are not outside it, in fact the decisions they make when creating models are not only informed by norms in policy and practice (as demonstrated by discounting, for example) but they also in turn inform those norms (Haikola et al., 2019b). More than just failing to accurately model inertia opposing climate action, IAMs can directly contribute their own inertia through the possibilities they include and exclude. This section will briefly outline these risks, particularly exemplified by the mainstreaming of carbon removals and net zero emissions targets; these will be relevant in chapter 3 which sees the construction of an IAM.

As Malm and Carton (2024, pp. 82–83) witheringly put it:

> When modelling how glaciers react to heat, the results and their dissemination do not in and of themselves change that reaction. But when the modelling concerns human responses to warming, this can, due to a *differentia specifica* of the social sciences – the object of inquiry also being a subject – happen: in the early Paris era, the IAMs themselves came to condition 'policymaking'. Some two dozen models in the global North defined the spectrum of possibilities. They mass-produced scenarios then packaged and bundled by the IPCC and passed on for consumption by governments. They were like leviathan computers, with inner workings inscrutable to outsiders. They had to be taken at their words, which allowed them to operate as '"Trojan horses" for undeclared interests', most effectively through the work of exclusion: the IAMs would not touch degrowth, the Green New Deal, rewilding, nationalisation of fossil fuel companies, a state-led shift to 100 per cent renewable energy (of which

> more below), half-earth socialism, ecological war communism or other proposals that veered from the middle of the road. They worked to 'shut down alternative imaginations'. In the early years of the third decade, these machines determined the bounds of acceptable climate politics, above all through the one theme that increasingly dominated it: carbon dioxide removal.

The potential for models – through the construction of scenarios and the choice of parameters – to create inertia themselves is evident in the choices made around abatement costs and discount rates discussed in the last two sections, but it can even emerge under the guise of representing inertia itself. The creators of the influential IAM IMAGE modelled emissions reductions assuming a "maximum reduction rate […] reflecting the technical (and political) inertia that limits emissions reductions", fearful that "fast reduction rates would require the early retirement of existing fossil-fuel-based capital stock, and this may involve high costs" (van Vuuren et al., 2007, p. 131). This was a peculiar choice: rather than helping us understand inertia any better, the decision to evoke the concept of inertia to presuppose the range of permissible outcomes in fact only served to restrict the climate policy pathways available in the literature, furthering the very assumptions that were made in their construction.

This is not an isolated example, indeed, IMAGE also finds itself at the centre of the story of net zero and what Malm and Carton (2024) label the 'overshoot conjecture' which have profoundly shaped the global debate on climate policy. The model was created in response to growing political interest in the idea of a 2 °C target as a step up in global ambition, particularly pushed by the EU, but one which needed scientific justification (McLaren and Markusson, 2020; van Beek et al., 2020). Penned in on the one hand by their commitment (noted above) to ensuring that "reduction rates were only allowed to change slowly over time" and therefore that emissions reductions "were spread out over time as far as possible" (van Vuuren et al., 2007, p. 131), and on the other by the need to work backwards from the fixed outcome of 2 °C above pre-industrial levels in 2100, the IMAGE team had a problem on their hands:

one requirement was simply not compatible with the other. Unlike other IAMs, however, they found something new to put in their crystal ball: overshoot. What if temperatures could by allowed to exceed 2 °C for a while, as long as they could be brought back down to that level by the end of the century? All it would take is a widespread deployment of bio-energy with carbon capture and storage (BECCS) to remove carbon from the atmosphere further down the line. With this, the IMAGE team were able to return a satisfied answer to the EU and other interested governments: "even very low limits are eminently feasible. You just have to give yourself the freedom to first go beyond them" (Fuss et al., 2014; Malm and Carton, 2024, p. 63; McLaren and Markusson, 2020). The EU secured the 2 °C target at the Copenhagen summit in 2009, and 'overshoot ideology' rapidly took over IAMs: out of 400 scenarios that gave a 50% or better chance of keeping within 2 °C, 344 assumed massive rollout of technologies for carbon dioxide removal (Anderson, 2015). The plan suddenly became, in the words of the IPCC, "overshoot, adapt and recover" (Parry et al., 2009).

Herein lies the origin of net zero which, as discussed in section 1.1.1, now forms the basis of targets set by over 150 countries. The special report on 1.5 °C produced by the IPCC in the aftermath of the Paris Agreement identified that being on the right side of 1.5 °C at the end of the century would require reaching carbon neutrality by 2050 (Cointe and Guillemot, 2023; Masson-Delmotte et al., 2018). At this point any remaining emissions (referred to as 'residual', 'hard to abate' or even 'unavoidable') would be 'balanced' by removals – by BECCS, or 'nature-based solutions' such as afforestation or soil carbon sequestration (Buck, 2021; Buck et al., 2023; Buylova et al., 2021). The alternative route that avoided overshoot and the need for carbon removals could "only be achieved if global CO2 emissions start to decline well before 2030" (Masson-Delmotte et al., 2018, p. 18), a radical timeline that would require enormous economic upheaval with "rapid forced closure of fossil-fuelled power plants" (van Vuuren et al., 2018, p. 396). Faced therefore with the choice of “overshoot or revolution”, countries were quick to side with the former and began to declare net zero ambitions (Malm and Carton, 2024, p. 68).

Unfortunately for this strategy, the possibility of deploying carbon removal technologies on this scale is speculative at best. IAMs have typically made optimistic assumptions about the technical abilities of BECCs (Butnar et al., 2020; Rickels et al., 2019), its costs (Field and Mach, 2017; Fuss et al., 2018), and the ability to deploy it at scale (Fridahl and Lehtveer, 2018; Smith et al., 2016; Stavrakas et al., 2018).

> The idea was born out of the rejection of systemic change, on the argument that it was a pipe dream only starry-eyed environmentalists could possibly entertain. Yet what its architects substituted for it was, if anything, even more a figment of the imagination: when climate policy and science swerved towards it, BECCS did not exist. At the time of Paris, there was exactly one pilot plant in the whole world, in Illinois. If BECCS had any existence to speak of, it was in the minds of modellers, in the fantasy futures of the IAMs; in real life, the technology had zero proven efficiency. (Malm and Carton, 2024, p. 79)

Additionally, overshoot beyond 1.5 °C has been estimated to increase the impacts of risks from climate change compared to a scenario without overshoot (Schleussner et al., 2024), and to particularly increase the chance of climate tipping elements (Möller et al., 2024).

This did eventually set some alarm bells ringing among the IAM community, with increasing urges for socio-political ‘reality checks’ on carbon removal to be introduced (Gambhir et al., 2019; Low and Schäfer, 2020; van Vuuren et al., 2017; Waller et al., 2020), but in terms of the impact it has had on climate policy, the damage has already been done:

> CDR [carbon dioxide removal]'s current visibility is due to BECCS’ profile in IAM projections, and IAMs prioritized BECCS precisely because—as an immature technology—its components (biomass availability, storage capacity) were understood sufficiently to be calculable, but malleable enough to allow models to envision deployment at politically daunting

> scales. In turn, technical projections have had political effects in making the Paris targets appear achievable with (temporary) overshoot of carbon emissions trajectories, and thereby normalizing the need for CDR in climate policy (Geden, 2016; Haikola et al., 2019a). […] It is important to remember that climate strategy is emerging—with a powerful message of allowing the carbon economy to overshoot—based on an immature carbon sink used as a modeling backstop (Beck and Mahony, 2018). (Low and Honegger, 2022, pp. 1968–1969)

A question always worth asking: in whose interest is this strategy? Who benefits from "less mitigation today in exchange for greater reductions later" (Carton, 2019; IPCC, 2014, p. 433)? It is hard not to see it as an attempt to let the present generation off the hook for difficult decisions to and pass the burden on to our direct descendants, as if discounting did not already make this intergenerational buck-passing sufficiently explicit. Malm and Carton (2024) in particular note that the effect of this process has been to protect the interests of (present-day) capital, channelling Gramsci to distinguish between *active* capital protection – the direct intervention of, say, oil producers or investment banks in climate policy processes – and *passive* protection on their behalf, however inadvertent, by integrated assessment modellers for example (such as the IMAGE team) who rule out scenarios that threaten the interests of capital a priori, or make exceptional assumptions about abatement costs or carbon removals that lead to the same.

None of this is to dismiss the role of modelling in understanding processes of economic transition and in crafting climate policy. As Box (1976) reminds us, some models are useful, despite their assumptions and contradictions. This thesis hopes to contribute one such model (chapter 3, which will avoid use of carbon dioxide removal and overshoot pathways entirely). It is a reminder, however, that modelling is not a neutral science and it is not conducted in a vacuum; it is laced with ideology and, in the absence of careful oversight, this ideology tends towards the status quo. The 'optimal' climate policy may not be a compromise as is so often assumed, such as between transition risks and physical risks. The projected financial losses from stranded assets fall vastly disproportionately on the top 1% of earners (even once the impact of pension fund investments are considered) (Semieniuk et al., 2023, 2022) – it is possible that a more egalitarian society, for example, may be able to swallow this risk more easily than one reliant on perpetual growth and capital accumulation. To assume the continuation of the status quo is to subsume oneself into to the very inertia that is at the heart of the problem (Beck and Oomen, 2021; Rubiano Rivadeneira and Carton, 2022). The stakes are high: nothing should be ruled out.

1.3. Capital dynamics

> *The measurement of capital is one of the nastiest jobs that economists have set to statisticians.*
>
> ***John Richard Hicks (1984)***

1.3.1. Capital stocks and flows

The definition of capital has long been contested. It is, it can broadly be agreed, "that part of man's stock which he expects to afford him [future] revenue" (Smith, 1776, p. 279), the goose "that lays golden eggs" (Marx, 1867, p. 255), seemingly creating more value than that which went into creating it. This quality makes it central to the generation of wealth and economic growth. Beyond this, the disagreement begins:

> The theory of capital is one of the most difficult and contentious areas of economic theory. From Karl Marx to the Cambridge controversies, there has been an ongoing disagreement among economists as to what capital is and how it should be measured.' Economists have variously defined capital as congealed labor, as deferred consumption, as the "degree of round-a-boutness," as a stock of durable commodities, or as a flow of factor services. There is also disagreement about whether capital can be aggregated into a single measure, and, even within the relatively hospitable confines of neoclassical theory, exact aggregation is known to be problematic.
>
> This presents the practical economist with something of a dilemma since many interesting economic problems require a measure of capital. How, for example, are we to understand the process of economic growth if we cannot agree on how to measure one of the potentially most important factors influencing that process? What can we say about such important issues as the productivity slowdown of the 1970s and why growth rates differ across countries? These issues are too important to ignore, and estimates of capital, income, and wealth, however imperfect, must somehow be developed in order to get on with the larger tasks at hand. (Hulten, 1991, p. 119)

In the spirit of Hulten's final remark, the following pages will embrace the neoclassical definition of capital and explore the conventional methods used for measuring capital stocks in national accounts. This is not to exclude the possibility of other theories of capital, many of which are valid and instructive, but rather to better understand how the inertial dynamics of capital are represented in the economic orthodoxy. Disagreement over the methods used to measure and interpret capital can make it seem an abstract concept, but it is constructed from real productive structures (networks of physical infrastructure and people), the lifetimes of which result in inertia that potentially impedes economic transition. The capital stocks that are currently available provide a tool for understanding this inertia. Moreover, while this inertia may have its basis in the economy, it is enforced in the realm of politics, on which neoclassical economics forms the predominant influence. In this sense, to understand inertia is to understand capital through the lens of the orthodoxy.

In the neoclassical theory of capital, the term capital refers to the total stock of productive structures that are used as inputs for further production of goods and services (Bannock and Baxter, 2011). Capital goods (or, henceforth, assets) are created through investment and destroyed through retirement and depreciation, and the relative size of these forces therefore determines the size of the capital stock, the total capital in a given country at a given time. Physical structures – machinery, tools, vehicles, buildings – have historically dominated this notion of capital, but in some cases intangible assets such as software and intellectual property have also been included in capital stocks (Van Criekingen et al., 2022), while the definition has extended further to include non-produced forms of capital (which are nonetheless productive structures) including human and natural capital, which are increasingly being measured and aggregated into stocks in a similar manner to produced capital (World Bank, 2021). This section will predominantly focus on produced capital as the more conventional stock and the main subject of the stranded assets and inertia discourse, but human capital will be explored in section 1.3.5.

Fundamental to Adam Smith's description of the economy, and persistent throughout the various shifts in economic thinking since, is the idea that capital accumulates through investment of residual income – that which is remaining after consumption is accounted for – and that this capital in turn facilitates income through further production, which may itself be re-invested (Garrett et al., 2020). This aggregates to the macroeconomic level, forming the basis for economic growth. According to much of modern economics, production (and therefore total output in the form of say GDP) can be generically summarised by the production function $Y = f\{A, K\}$ where Y is the total output of the economy, A is the total factor productivity (the productive efficiency of capital), and K is total capital (including human capital), assuming constant returns to capital (Romer, 1986).

As accounts typically operate on an annual period, the capital that is measured is typically 'fixed capital', defined as assets which are productive for more than one accounting cycle, typically a year (they are therefore said to be 'durable'). Capital lasting less than one year, such as raw materials and intermediate goods, is instead labelled 'circulating capital' and is effectively treated the same as consumption, disregarded for the purposes of measuring capital and its effects (Blaug, 2017). Indeed some have argued that it was only in the emergence of annual accounting that the concept of capital – and in turn capitalism – originated ("one can say that capital, as a category, did not exist before double-entry bookkeeping" (Lane and Riemersma, 1953, p. 38; Sombart, 1902)), with many definitions of capital defining it as wealth which enters into accounts and persists from year to year (Bryer, 2000; Chiapello, 2007; Weber, 1981).

The capital stock can therefore be defined as the current sum total of productive economic structures with a lifetime of more than one year residing in a particular economy (Hill, 2001). The rate at which capital accumulates in this stock is the difference between the inflow of investments and the outflow of depreciations. This leads to the natural conclusion that capital is a stock and investment and depreciation are flows, like water accumulating in a lake while simultaneously flowing both in and out, a conclusion first made in these terms by Fisher (1896) and which is now so prominent that it forms the primary example of a stock and flow system on Wikipedia (2024). The following sections will explore how stocks of capital are estimated and the implications (in both current and potential methods) of this ecologically-inspired perspective on capital stocks.

1.3.2. Valuation of capital

To the extent that it is possible to claim authority over the fraught subject of capital valuation, the OECD Manual *Measuring Capital* (OECD, 2009) has become the authoritative guide to this topic, providing common methodology for statistical offices worldwide to estimate their national capital stocks. It does this in conjunction with the System of National Accounts, which describes internationally agreed processes for measuring and reporting wider aspects of national accounts such data on growth, output, incomes and balance sheets (the origins of which lie in post-war efforts to spread and homogenise Western capitalism (Vanoli, 2005)).

The challenge of attributing a value to capital is, as the Manual is quick to note, the "fundamental dual nature of capital" in which it is "both storage of wealth and a source of capital services in production" (OECD, 2009, p. 11). In other words, "the cost of producing an asset is equal to the value of owning the asset, which, in turn, is equal to the present value of the expected rents (user costs) generated over the life of the asset" (Hulten, 1991, p. 127); capital can be valued both according to the price tag associated with producing it, and by the value of its expected future returns. These will henceforth be referred to as backward-looking and forward-looking valuations respectively. National accounting relies on the assumption that these two perspectives converge on the same value when the net present value of assets is estimated – that depreciation-adjusted past investments in capital equal their time-discounted future benefits (here once again the idea of time discounting appears) –

an assumption that the Manual notes dates all the way back to Walras (1874) and Böhm-Bawerk (1891) (OECD, 2009).

This convergence is contingent, however, on a perfect market environment under stable economic conditions, with accurate accounting of depreciation, complete data and full foresight of expected returns (Diewert, 2005; Hulten, 1991). This underlines the difficulty of the task, requiring constant vigilance on the part of statisticians to changing patterns of depreciation or asset returns – sometimes requiring backward-looking stocks to be revalued based on updated market data or changing economic circumstances – and as we shall see, current assumptions about depreciation in particular are made with far from perfect information. Indeed, concern about the inherent volatility of capital utilisation – and therefore forward-looking valuations – forms a key pillar of post-Keynesianism (Hart & Kriesler, 2015).

Capital stocks are typically constructed in a backwards-looking framework using the perpetual inventory method (PIM), introduced by Goldsmith (1951) (Berlemann and Wesselhöft, 2014; OECD, 2009). The premise of this method is that statisticians are not able to constantly measure the total stock of capital in a country, but they know how much is invested in the creation of new capital each year, and thus (perhaps without realising it) they borrow from the natural sciences and study the system through the lens of mass/energy conservation (Young and Musgrave, 1980). In the PIM past investments are accumulated into the stock, and removed from it according to their expected lifespan (estimated in the form of a service life, the expected economically useful life of an asset) and the rate at which their value is expected to depreciate through wear and tear or obsolesce, producing an annual estimate of the capital stock. As such three parameters are crucial in simulating the dynamics of capital: asset service lives, survival functions for cohorts of assets, and depreciation rates (Dey-Chowdhury, 2008; Usher, 1980).

While the PIM simulates the survival of capital, in the context of inertia there is another important consideration: the financing of capital. While the service life describes the length of time over which an asset is actively contributing to production, the time over which these assets are simply repaying the initial owner's initial investment on the asset can be referred to as the payback time. Beyond this point all returns on the investment are expected to be pure profit, as shown in green in Figure 1.5. It was in the expectation of this profit that the investment was made, and the longer this period can last the more the investor has maximised their returns (hence the ubiquitous drive to extend the lives of infrastructure assets beyond their expected lifetime wherever possible). As discussed in section 1.1.2.1, if the asset is retired or requires unexpected maintenance or retrofitting prior to its payback time, real financial losses are likely to accrue to the owner, and if this occurs prior to the service life, a loss of profit will still be incurred (Figure 1.5). This creates a disincentive towards investment or policy decisions which would have this effect, thus creating inertia associated with these timescales (Seto et al., 2016).

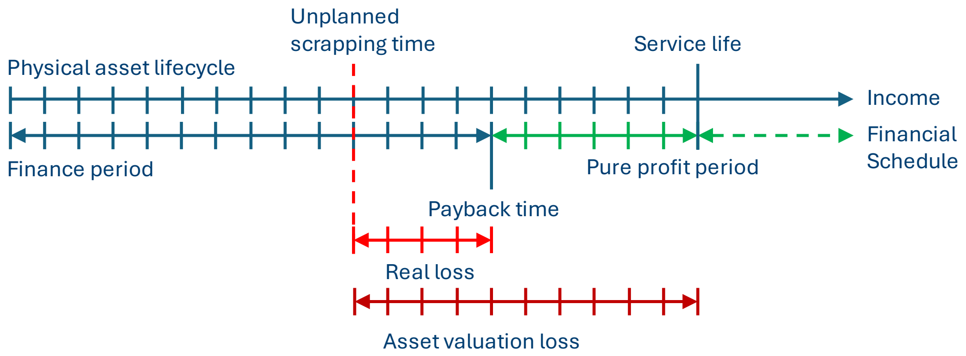

Figure 1.5. The physical and financial lifetimes of a capital asset. The period between its payback time and its service life (green) is the period over which its investor expects to receive pure profit, having paid off the cost of the initial investment. Premature retirement of an asset after its payback time will result in the investor forgoing planned profits, while retirement before its payback time will result in a real loss on the initial investment.

1.3.3. Conservation of capital

As it is impossible to monitor the behaviour of individual assets en masse, assets are grouped into cohorts of similar type. These may be, for example, laptops, tractors, or office buildings – the crucial aspect being that the assets share a similar expected lifespan. Assets will enter and leave this cohort each year such that the annual change in the total value of the cohort's stock $\dot{K} = I - D$ where I is annual investment in the asset type and D is value lost through depreciation (the reduction in asset value over time, for example due to wear and tear) or retirement (the removal of assets from the productive stock after reaching the end of their service life) (Usher, 1980).

To reflect the fact that assets within a cohort rarely exhibit perfectly homogenous behaviour and in reality some will last longer relative to their expected service life than others, retirements within a cohort are typically conducted using a mortality function, which dictates the rate at which assets are removed from the stock at each age (or, seen another way, the probabilistic chance that a given asset is removed in each year of their life). As Figure 1.6 shows, various types of mortality function are possible, each with a different logic. Each can also be expressed as a survival function, showing the total amount of the stock remaining each year. OECD (1993) document the retirement functions chosen by statistics agencies and their justifications, with some form of bell-shaped function being most common (types of which are variously described as log-normal, gamma, logistic, Weibull and Winfrey).

Depreciation of an asset's value over time, meanwhile, is determined by age-efficiency and age-price profiles. These respectively represent the change in an asset's productive capacity (and therefore the value it delivers to its owner) over time, and the change in an asset's price over time, which are often different but not independent of each other (OECD, 2009). Fortunately, the details of these profiles and their relation to retirements need not trouble us too much, because of a crucial aspect described in the Manual:

> An important result from the literature, dealt with at some length in the Manual is that, for a cohort of assets, the combined age-efficiency and retirement profile or the combined age-price and retirement profile often resemble a geometric pattern, i.e. a decline at a constant relative rate. While this may appear to be a technical point, it has major practical advantages for capital measurement. The Manual therefore recommends the use of geometric patterns for depreciation because they tend to be empirically supported, conceptually correct and easy to implement. (OECD, 2009, p. 12)

When assets are aggregated into a cohort, the combined effect of retirements and value depreciation is a geometric pattern of depreciation, even when the combined depreciation profile for a single asset is say linear. "Reasoning in terms of a single asset is thus not a good guide to the depreciation profile of a whole cohort" (OECD, 2009, p. 41). A proof of this can be found in Oulton and Srinivasan (2003), and evidence for it was demonstrated for the US by Hulten and Wykoff (1981) and for Canada by Koumanakos and Hwang (1993).

This means that capital of a cohort can be assumed to depreciate at a constant relative rate over time according to a single representative depreciation rate for the cohort (Oulton and Srinivasan, 2003), combining the effects of value depreciation and retirement. The inertial dynamics of capital can therefore be broadly summarised by

$$\dot{K}_i = I_i - D_i = I_i - d_i K_i \qquad (1)$$

where K is the stock of a given cohort of capital i, I_i is annual investment in that cohort, D_i is its annual depreciation, and d_i is therefore a depreciation rate representative of the cohort. This equation, henceforth referred to as the capital conservation equation, forms the basis of the perpetual inventory (potentially with the addition of annual price adjustments) (Usher, 1980).

How, then, is d determined? This is the great challenge in capital measurement, with all other variables in equation 1 being known. In some instances age-efficiency profiles are known and d can be derived from these, and in others econometric analysis of used asset prices can reveal d directly, but the necessary data for these methods is not always available or accurate (Fraumeni, 1997). In national accounts this relation is instead most often estimated using service lives, which relate to d through the declining balance method, summarised by Hulten and Wykoff (1996) as $d_i = \frac{R}{T_i}$ where R is a declining balance rate which determines the curvature of the geometric decline and T_i is the service life of cohort i. A common value of 2 for R (described as a double declining balance) has historically been used by statistics agencies, largely because it provides reassurance by producing a similar outcome to straight line depreciation which is common in accounting (Baldwin et al., 2007; Rincon-Aznar et al., 2017), but the Manual notes that "there are no broad-based empirical results that would generally support that value" (OECD, 2009, p. 52) and argues that "generally it is preferable to turn to empirical results for the shape of the geometric depreciation pattern" (p. 97). The US BEA now uses a small variety of estimates for R depending on the asset type, as outlined by Fraumeni (1997): most notably R = 1.65 for equipment and R = 0.91 for private non-residential structures, based on Wykoff and Hulten (1979) and Hulten and Wykoff (1981). These have been criticised, however, for lacking transparency and using seemingly arbitrary methods (Rincon-Aznar et al., 2017). Baldwin et al. (2007) found R values between 2 and 3.

One might expect that service lives (T_i), at least, are better known. Surprisingly, despite meticulous accounting processes and the abundance of economic records going back centuries, and the importance of accurate depreciation measures to the success of the PIM, estimates of service lives are patchy and inconsistent too (Rincon-Aznar et al., 2017). Not only does this hinder capital measurement but it also therefore affects international comparisons of growth and productivity (Görzig, 2007), making it surprising that this topic does not have greater prominence in the literature. Rincon-Aznar et al. (2017) – in their comprehensive review of the service lives used in major economies – and the Manual (OECD, 2009) cite the following as typical sources of information used in combination in the estimation of service lives:

- Administrative records.
- Expert advice.
- Asset lives prescribed by tax authorities.
- Company accounts.
- Surveys of capital investment, industrial production or specific surveys on asset lives.
- Direct observation of the stock of capital.
- Other countries' estimates.

Despite the breadth of these sources, service lives are unavailable for many asset types, industries and countries, and therefore very broad asset cohorts end up being used, service lives are assumed from other countries, and insufficient updates are made to reflect changes over time. The scale of this is evident in Table C in BEA (2003), which displays the service lives and declining-balance rates used in the construction of capital stocks in the US national accounts for each cohort based on studies by Hulten and Wykoff, categorised into those that are directly estimated by Hulten and Wykoff using real data, those for which they were required to use empirical research by others "as well as their own judgement", and those for which no data was available at all, so the average service life of a broad category of similar assets is assumed. The latter category appears more times in the table than the others.

> Ideally, what is required for accurate implementation of the PIM is a set of service lives for narrowly-defined asset groups that are used in different sectors and kinds of activity. Moreover, this set of service lives should be updated regularly to reflect cyclical or longer-term changes in the lengths of time that assets remain in the stock. From the review of the sources above it is clear that the information actually available falls far short of this

> ideal. Service life estimates are generally available only for broad asset groups, there is limited information available on differences in lives of asset groups between sectors and kinds of activity and service lives are updated at rare intervals in most countries. (OECD, 2009, pp. 112–113)

Although a lack of international consensus on the necessary degree of asset breakdown makes comparison between countries difficult, the evidence points to a high degree of inconsistency, more than would reasonably be expected from international variations in capital dynamics (Baldwin et al., 2007; Görzig, 2007; OECD, 2009; Rincon-Aznar et al., 2017). A sensitivity analysis by Statistics Canada estimated that varying the service lives used for their PIM estimates of manufacturing capital by 10% varied the stock levels by +/–8% (OECD, 2009). The international comparison literature cited here would suggest that the margin of error may in fact be even larger than this.

To the ecologically-minded, the supposed complexity of the relationship between depreciation rate and asset lifetime may seem a little odd, because T strongly resembles a residence time or turnover timescale: the average amount of time matter – in this case a capital asset – spends in a system, again like water molecules in a lake or any other substance mixed in a physical system, which can be easily calculated with knowledge of the inflows or outflows. It is widely proven in studies of system dynamics that in such a system the residence time $T_i = {d_i}^{-1}$ (Cucco and Umgiesser, 2006; Han, 1997; Hansen et al., 1985; Jarvis, 2018; Kreft and Zuber, 1978; Rueda et al., 2006), because when close to equilibrium, dynamic or static, "total residence time equals the ratio of total standing stock to total system outflow or total system inflow" (Han, 1997, p. 301). Given the assumed exponential nature of the decay T_i is also the time constant or e-folding time of the system, the time it takes to lower the concentration to 1/e of its initial value following a perturbation (Cucco and Umgiesser, 2006). This is also essentially an application of Little's law in mathematical queuing theory which relates waiting times to the number of people waiting, and which has proven usage in a very wide range of applications, even ones far from equilibrium (Elgart et al., 2010; Hendijani, 2021; Ho et al., 2021; Kim and Whitt, 2013; Potter et al., 2020).

Given that the inflows to any given cohort (investment) are known and data on historical outflows (depreciation) are widely available, estimation of turnover timescales for all types of asset is possible, and by applying Little's law as described above, estimates of d could then be derived. The only challenge to this application is its reliance on the system being close to dynamic equilibrium, when in reality most economic systems are growing and constantly undergoing other transformations. Nonetheless, as the application of Littles Law has indicated, the margin of error this produces is unlikely to be vastly greater than the already significant margin of error identified with service life estimates, even where they are available, and such a method could be revolutionary in filling the problematic gaps and inconsistencies in the current mix of service lives. Chapter 2 takes up this challenge.

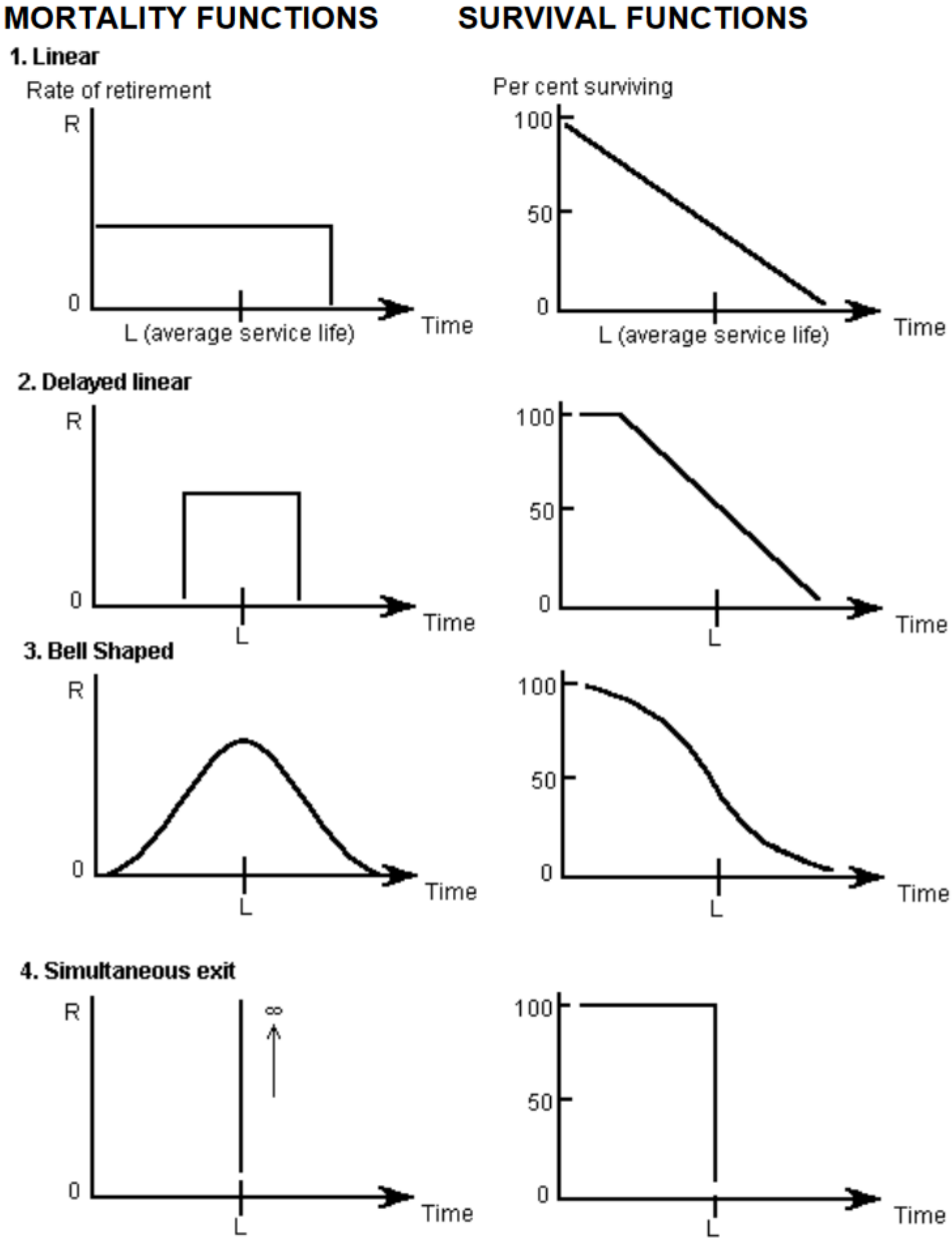

Figure 1.6. Examples of mortality functions commonly used to retire capital assets within a cohort, and their corresponding survival functions. Reproduced from OECD (1993).

1.3.4. Representative depreciation rates: a dominant mode analysis

In this chapter much has been made of *average* service lives and *representative* depreciation rates of cohorts of similar assets. However, as the literature on the service lives has demonstrated, these cohorts can be quite broad. The lifespans of their constituent assets will rarely be perfectly homogenous, for example the asset class 'passenger cars' will feature a variety of makes and models of car which can be expected to reside in the economy for different lengths of time; the service life given to the cohort is simply an approximate representation of this wider distribution. Likewise identically-designed assets will last varying amounts of time in practice compared to their expected service life, depending on the conditions in which they are manufactured and used; this is the purpose of mortality functions (see previous section). It would be reasonable, therefore, to question whether a single depreciation rate can truly reflect the inertial dynamics of a full cohort of assets. This section will present a brief analysis of a selection of stylised asset timescale distributions to explore the effectiveness of d as a representative inverse timescale.

To illustrate this important point, Figure 1.7 shows five artificial distributions of capital asset cohorts, each with a range of service lives (Figure 1.7i). Three of these (a-c) are symmetrical around a mean service life of 75 years, one (d) is a positively skewed gamma distribution also with a mean of 75 years, and one (e) is a bimodal distribution with a mean of 35.8 years. The latter has been retrospectively introduced from chapter 2 of this thesis and reflects the timescale distribution of the capital stock of the United States. A simple perpetual inventory simulation was then performed on each distribution in which investment (I) is assumed to be zero and the capital cohorts instead simply depreciate over time. Capital at each point on the service life distribution (T) is assumed to depreciate at a rate $d = \frac{1}{T}$ such that for each year t,

$$K_{T(t)} = (1 - \frac{1}{T})K_{T(t-1)}. \quad (2)$$

The time evolution of total capital in each cohort reveals the inertial behaviour of the cohort. Exponential decay, suggesting behaviour in line with the capital conservation equation (equation 1) and the geometric assumption underpinning this, is implied by a straight line in the logarithm space (Figure 1.7ii). This is strongly evident for all but the multimodal distribution (c, the broader normal distribution, gives a slightly less straight line than a, b and d, most likely as a side effect of the truncation of this distribution below 0 and above 150 years). The gradient of this log decay (Table 1.1) reflects the decay rate of the cohort and therefore provides an estimate of d, which per the arguments over geometric decay in the previous section we stipulate equals T^{-1}. The simulated T values for cohorts a b and d, 74.5, 76.2 and 76.8 respectively, are strong approximations of the mean service life, while c is a weaker approximation, and e bears little resemblance.

These findings suggest that it is possible for a single representative depreciation rate to suitably approximate the inertial dynamics of a single-mode cohort with diverse service lives, including in scenarios where the service life distribution is not symmetrical. The accuracy of this depreciation rate can, however, be dependent on the size of the service live range being represented. This emphasises the importance of cohorts being specialised to particular categories of assets, as highlighted in the previous section, particularly by the OECD (2009).

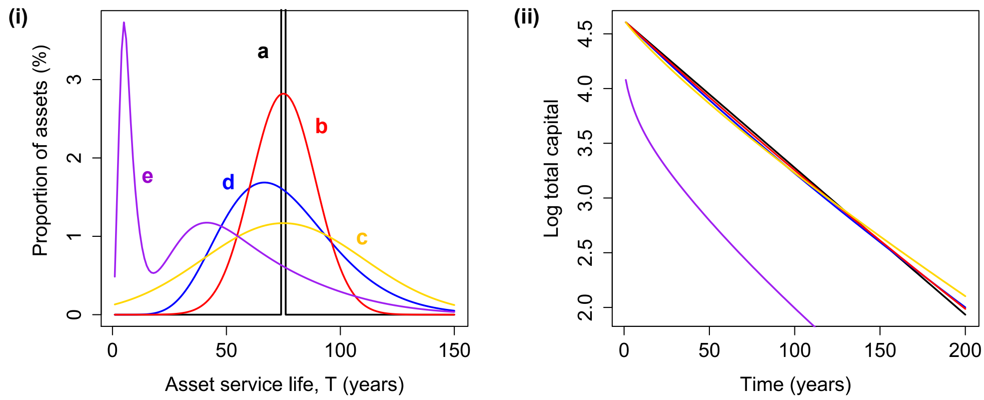

Figure 1.7. **(i)** Five hypothetical distributions of capital asset cohorts according to their service life, all (with the exception of one) with a mean service life of 75 years. **(ii)** The simulated decay of each capital cohort, presented as the natural logarithm of the annual total sum of each cohort. A straight line indicates exponential decay in line with equation (1).

Table 1.1. Characteristics of the capital cohort distributions presented in Fig. 6 above. The gradient of log decay (Fig. 6ii) approximates d_i, the representative depreciation rate for the cohort; coherence between this value and the mean timescale T suggests that the cohort exhibits inertial behaviour characteristic of the mean.

Distribution	**Mean *T***	**Median *T***	**Gradient of log decay**	**First difference of log decay**
	yrs	yrs	yrs	yrs
(a) Single timescale	75	75	74.5	74.5
(b) Normal – narrow	75	75	76.2	69.6
(c) Normal – wide	75	75	81.3	47.2
(d) Gamma	75	72	76.8	65.9
(e) United States	35.8	40	64.1	13.2

1.3.5. Human capital

Though the easiest to conceptualise, physical assets are far from the only productive structures. Adam Smith saw society's stock of fixed capital ("of which the characteristic is, that it affords a revenue or profit without circulating or changing masters") as consisting:

> First, of all useful machines and instruments of trade which facilitate and abridge labour.
>
> Secondly, of all those profitable buildings which are the means of procuring a revenue. […]
>
> Thirdly, of the improvements of land, of what has been profitably laid out in clearing, draining, enclosing, manuring, and reducing it into the condition most proper for tillage and culture. […]
>
> Fourthly, of the acquired and useful abilities of all the inhabitants or members of the society. The acquisition of such talents, by the maintenance of the acquirer during his education, study, or apprenticeship, always costs a real expense, which is a capital fixed and realized, as it were, in his person. Those talents, as they make a part of his fortune, so do they likewise that of the society to which he belongs. The improved dexterity of a workman may be considered in the same light as a machine or instrument of trade which facilitates and abridges labor, and which, though it costs a certain expense, repays that expense with a profit. (Smith, 1776, pp. 281–282)

In modern economics the first and second of these are firmly considered produced capital, as hitherto discussed. The third hints at the idea of natural capital, value derived from the world's stock of natural resources (although Smith's notion, which focuses on human development of these resources, might be more usefully considered produced capital) (Costanza and Daly, 1992). The fourth is the origin of human capital.

The term 'human capital' would not be coined until Pigou (1928) nearly a century and a half later, and would not enter the neoclassical economic vocabulary until picked up by the Chicago School economists some time later, in particular by Mincer (1958) but soon after developed by Schultz (1961) and Becker (1962). The concept was unchanged from Smith, however: human capital could be invested in, for example via education or training, and would output value depending on the rate of return of the particular capital; from the view of the capitalist producer, human capital appeared functionally the same as produced capital. One unique aspect was that human capital also invested in itself:

> There is such a thing as investment in human capital as well as investment in material capital. So soon as this is recognised, the distinction between economy in consumption and economy in investment becomes blurred. For, up to a point, consumption is investment in personal productive capacity. This is especially important in connection with children: reducing unduly expenditure on their consumption may greatly lower their efficiency in after-life. Even for adults, after we have descended a certain distance along the scale of wealth, so that we are beyond the region of luxuries and "unnecessary" comforts, a check to personal consumption is also a check to investment. (Pigou, 1928, p. 29)

In other words, daily consumption of the necessities of life is investment in future productive potential (Perrotta, 2004; Steger, 2002). It is certainly hard to doubt the opposite, that the absence of this consumption and its consequences – malnutrition, illness – are damaging for productivity and future wellbeing. It was imagined that the resultant increase in productive potential from investment in human capital, either through upskilling or this 'productive consumption', would be reflected in higher expected earnings in the long term (Goldin, 2024).

As chapter 4 will explore in more detail, earlier efforts to estimate stocks of human capital focused on the input side of this process (they were backward-looking), adding up the sum of expenditures that were deemed to create human capital value and positing this as the sum of the stock. Kendrick (1976), for example, estimated the stock of US human capital at around 25% of US GNP based on the assumption that all education expenditure and half of all healthcare expenditure formed human capital. However deciding exactly what expenditure could be considered productive investment in human capital, particularly in the realm of personal consumption, "bristle[d] with both conceptual and practical difficulties" (Schultz, 1961, p. 8). Instead forward-looking valuations soon came to dominate, spearheaded by Jorgenson and Fraumeni (1989) who developed a method for estimating human capital as the total present value of the current workforce's expected future earnings. This method is now used by the World Bank (2021) and national statistics agencies to estimate national human capital stocks, benefiting from the widespread availability of income data and human survival functions. It is not free from speculation, however: specifying the present value of future income once again requires the use of a discount rate (World Bank, 2024). Although they are estimated in different ways, such is their confidence in the broad compatibility of the methods involved, the World Bank (2021) combine their estimates of produced, human and natural capital to form estimates of the total capital stock of nations. Human capital represents 64% of this global stock, a figure that rises in developed economies.

The dominance of human capital in the total sum of global wealth should draw attention to a significant risk in climate policy which, as noted in section 1.1.2.2, is often overlooked in the literature on transition risks and stranded assets: the prospect of stranded human capital (Lynch et al., 2024; von Dulong et al., 2023). Some may be reticent to define the risks to people's livelihoods in these terms. The idea of describing humans as capital has never been free of controversy, indeed Schultz (1961, p. 2) noted the general view that "free men are first and foremost the end to be served by economic endeavor; they are not property or marketable assets," with the exception of slavery, "and this we abhor." Others have objected to the term, describing it as dehumanising, an oxymoron, Orwellian (Joly, 2016) or an un-word (Frankfurter Allgemeine, 2005). These are all reasonable responses to human capital as a semantic description, but in the context of capital stocks, human capital is merely an estimation of the population's expected future earnings. Though assumptions naturally have to be made to reach such an estimate, what it represents is real: the life that people are able to lead is defined by their income, and the value they therefore place on their income contributes a form of economic inertia. Like produced capital, human capital is at risk of involuntary premature retirement in a rapid climate transition, and as such it would seem imperative to include it in studies of inertia and stranded capital. This will be explored in chapter 3.

A final thing to note on human capital. At some point in the transition to predominantly forward-looking valuations of human capital, the idea of personal consumption contributing to the production of human capital has dropped out of the mainstream economic understanding. This is both true in macroeconomics, where in national accounts only investment is considered to create capital and deliver future returns while consumption is instead "quite simply the end point of economic activity" (Marshall, 2017, p. 564), and it is also true in microeconomics, where the utility maximisation problem (the question of how much to save versus how much to consume) is still the dominant way of understanding consumer behaviour, neglecting the potential for consumption to be productive (Suen and Mo, 1994; Valencik and Wawrosz, 2019). 'Productive consumption' is a concept that in recent times has predominantly been taken up in development economics (Valencik and Wawrosz, 2019). Given that reducing consumption is a central target of climate policy (Dubois et al., 2019; Grubb et al., 2020a; O'Rourke and Lollo, 2015) but maximising utility and developing human capital are targets of economic policy (Reisch, 2003; World Bank, 2023), the lack of consensus over the impact of the former on the latter is a cause for concern. Chapter 4 will be dedicated to this issue, benefiting from the human capital valuation methods that will be developed in chapter 3.

1.4. Thesis overview

Four gaps in the literature, identified in this chapter, will be picked up by this thesis:

1. The financial risk associated with the stranded assets created by a rapid net zero transition – which will be necessary to meet rapidly advancing temperature targets – is poorly quantified, particularly in sectors other than energy generation.

2. A barrier to this, and to the measurement of capital more widely, is insufficient data on the lifetimes of capital assets and the exclusion of infrastructural inertia from climate models.

3. Human capital is under-represented in studies of stranded assets and economic inertia.

4. Human capital investment is poorly defined in the economic literature, hindering analysis of its turnover dynamics and of the importance of consumption to human development (of particular relevance in the context of a net zero transition).

These issues will be addressed through research organised into the three following chapters, which were written as manuscripts for publication.

Chapter 2 will create a new methodology for estimating the turnover timescales of capital assets. This will provide the basis for comprehensive data on capital lifetimes for all types of asset in the economy, with an example provided for the United States, for which the complete distribution of capital according to its lifetime will be derived for the first time. It will explore the implications for the use of this data in integrated assessment modelling to improve the treatment of inertia. This will address point 2 above.

Chapter 3 will generate new estimates for the human and produced capital at risk of being stranded in a transition to zero carbon emissions by 2050, through the creation and implementation of a new integrated assessment model. This will simulate the depreciation of capital in all 56 sectors of the economy and compare the rate at which it is naturally expected to depreciate with the accelerated rate at which it will need to depreciate to achieve the desired climate target. It will be unique in its inclusion of human capital, its coverage of all sectors, and its cautious 'at risk' framework that avoids any assumption of negative emissions. This will address points 1 and 3.

Chapter 4, benefiting from the methods developed in chapters 2 and 3, will then explore the use of the capital conservation equation for human capital, marrying the forward-looking approach used to estimate national human capital stocks with traditional backward-looking valuation methods to better understand both investment in, and the turnover dynamics of, human capital. The extent to which consumption plays a role in the process of creating human capital is currently unclear, and this is worthy of urgent enquiry given the risks to human capital value in an economic transition and the targeting of consumption by climate policy, which could extend these risks further. This will address point 4.

Chapter 5 synthesises key findings, emergent themes and areas for future research.

References and supplementary information are included at the end of each chapter. For published manuscripts, a citation for the published version is included on the first page.

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2. Heterogeneous capital stocks and economic inertia in the US economy

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Abstract

The timescales of capital investments, and therefore the turnover dynamics of capital stock, have limited representation in macroeconomic modelling. This hinders analysis of the economic inertia produced by these timescales, which is particularly important in the context of a rapid net zero transition in which vast quantities of long-lived investments may need to be prematurely abandoned. We set out to determine the minimum model that is required to accurately represent the turnover dynamics of fixed capital. We develop a quantitative framework for estimating the turnover time of fixed capital assets in the US economy, and derive the annual distribution of both total fixed capital stock and new investments across timescales. We find that these can be effectively aggregated into three major timescale components which can be easily incorporated into integrated assessment models.

2.1. Introduction

The latest evidence, presented in the IPCC's landmark Sixth Assessment Report, shows that most of the reductions in greenhouse gas emissions necessary to limit warming to 2°C need to be made over the next 20 years (IPCC, 2023). To keep within 1.5°C, as also targeted by the Paris Agreement, this deadline is halved to just a decade. This is shorter than the lifetimes of most carbon-emitting infrastructure (Fraumeni, 1997; Grübler, Nakićenović and Victor, 1999; Rincon-Aznar, Riley and Young, 2017; Jarvis, 2018), prompting concern about the likely need for many fixed capital investments to be abandoned before their expected lifetime has elapsed, at cost to both investors and workers employed in the affected industries (Mercure *et al.*, 2018, 2021; Agarwala *et al.*, 2021; Daumas, 2023). The lifetimes of fixed capital are therefore a source of inertia in the economic system (Grubb, 1997; Seto *et al.*, 2016; Fisch-Romito *et al.*, 2021), which means that an understanding of the temporal turnover of this capital is critical to understanding pathways for the inertia to and therefore the cost of, the necessary climate transition (Davidsdottir and Ruth, 2004; Mercure *et al.*, 2021).

Despite this, fixed or produced capital ('capital' hereafter) is often simulated in climate models using a single depreciation rate as if all capital turns over on a single homogenous timescale, neglecting the vast heterogeneity of capital stocks. There is also significant disagreement between models on what this depreciation rate should be, with capital effectively modelled with an average turnover of anywhere between 10 and 50 years depending on the model, indicating significant uncertainty about even the average turnover and therefore inertial contribution of capital. Given that some shorter-lived and near-end of life carbon-emitting capital will naturally depreciate on a timescale compatible with climate objectives, while some longer-lived newer capital will require extensive retrofitting or premature retirement, the heterogeneous distribution of capital lifetimes is worthy of better understanding and representation in climate and economic modelling (Jaccard and Rivers, 2007; Shalizi and Lecocq, 2009; Grubb, Wieners and Yang, 2021).

We suggest that it is the lack of available and reliable data on the distribution of capital by lifetime that has precluded accurate representation of turnover dynamics in Integrated Assessment Models (IAMs). The turnover of capital is simulated in national accounting, which relies on estimates for the mean service lives and survival functions of various types of capital asset to compile capital stock inventories (Fraumeni, 1997; OECD, 2009; Katz, 2015; Rincon-Aznar, Riley and Young, 2017). However, these estimates are seldom published, are drawn from an inconsistent array of sources, are in many cases based on guesswork or estimates extrapolated from other countries due to data being unavailable, and the methods used and assumptions made in compiling them vary significantly between countries (Fraumeni, 1997; Görzig, 2007; Rincon-Aznar, Riley and Young, 2017; Bennett *et al.*, 2020). Some attempts to characterise the heterogeneity of capital turnover dynamics have divided capital into discrete timescale groups (Jaccard and Rivers, 2007; Shalizi and Lecocq, 2009), but these groups are often arbitrarily defined (Jaccard and Rivers, 2007), and to the best of our knowledge a complete distribution of capital across all lifetimes for a national economy has not been published.

In this paper we take a new approach to estimating capital lifetimes, using 71 years of past capital stocks and depreciation data from the United States to derive turnover timescales for all 3015 assets in the Bureau of Economic Analysis (BEA) national accounts. We then reassign existing capital stocks and new capital investments to their respective timescales, and apply a standard survival function to construct an estimate for the complete distribution of capital and investment by timescale in the United States. We present evidence that this distribution is remarkably stationary, and can be accurately approximated as the sum of three discrete distributions representing fast, medium and slow capital. We provide the necessary information to replicate these distributions, enabling more complete representation of capital turnover and inertia in future research on economic inertia.

2.1.1. The survival dynamics of capital

Inertia can be defined as the resistance of an object to changes in its course, and it applies as much to economies as it does to any other assemblage of physical objects, even if the specifics of how we might represent the inertia of an entire economy may differ from that of, for example, a train. For the economy, inertia is determined not only by vested interests, mindsets, regulatory and political regimes (Seto *et al.*, 2016); it is also critically determined by the heterogenous stock of capital that comprises the economy, and therefore the investments and activities riding on this capital and the timescales over which these investments play out.

Capital investments are invariably designed to provide returns over specific amounts of time. Typically these are years, often decades, and unless the investor is willing to walk away from the returns on their investments, the creation of a fixed capital asset establishes a commitment to future activity and hence inertia. Indeed, the institutional inertia represented through vested interests, mindsets, regulatory and political regimes, as well as financial instruments used to facilitate investment, might be seen as subservient to, and in support of, the protection of future returns on investments (Foxon, 2002). Notwithstanding expensive retrofitting or premature scrapping, with consequent loss of planned returns on investment, investments with lifetimes spanning several decades restrict transition – for example, to an economy with net zero carbon emissions – to a rate which corresponds to their lifetime (Jaccard and Rivers, 2007).

Given that fossil-fuel use has grown near exponentially for well over a hundred years (Jarvis, Leedal and Hewitt, 2012), the transition to net-zero emissions within the timescales called for by the Paris process will mark a radical change in direction for the global economy. In addition to the decarbonisation of new investments, this is likely to require the removal of large amounts of existing long-lived carbon-intensive infrastructure over the next three decades (Mercure *et al.*, 2021) and/or substantial retrofitting. Davidsdottir and Ruth (2004) conclude that the rate of capital turnover is "the most important factor in permanently changing carbon emission profiles and energy efficiency". Understanding the relationship between capital investments and inertia not only allows us to identify the components which most influence progress on climate change; it can also help us assess the risk of 'stranded assets', assets which will be prematurely unable to generate economic returns, if the economy is forced to transition at rates faster than its infrastructural inertia would otherwise allow (Grubb, 1997; Jaccard and Rivers, 2007; Mercure et al., 2018, 2021).

The value of a capital asset depends not only on its projected annual productivity, but also on how close it is to its planned retirement. New assets being born through investment and old assets maturing and dying lead to a distribution of asset ages at any time, much like the demographics of human populations. Although this form of survival analysis is how asset values are compiled and tracked within sectoral national accounts (OECD, 2009), the expected lifetimes and age structure of these assets are seldom reported within that process. Disaggregation of capital by its age is a notable feature of vintage capital theory, which keeps track of capital of different vintages and is able to assign them different productivities and therefore rates of depreciation (Solow, 1960; Boucekkine, de la Croix and Licandro, 2011). However this literature takes less interest in the question of heterogeneity *within* vintages, in terms of the expected lifetimes of capital, and how this is created through the spread of investment across asset lifetimes (Barucci and Gozzi, 1998; Davidsdottir and Ruth, 2004).

Neither is it common in the economic literature, nor in much mainstream modelling of climate change, to explicitly account for the turnover of an array of pools of capital, even though this can provide critical insights into the inertia of the economy, and hence its ability to change direction. Indeed, the effects of economic inertia are invariably hidden in economic analysis by the specification of optimal investment pathways where the dynamics associated with capital turnover become embedded into idealised investment scenarios.

As highlighted by Mercure et al. (2021), the conservation equation for capital assets used in national accounting procedures defines their inertial dynamics. If K_i is the value of the i'th stock (T$), the conservation of this capital follows

$$\dot{K}_i = I_i - D_i = I_i - d_i K_i \qquad (1)$$

where I_i is the rate of investment into this stock (T$/yr), D_i is the annual depreciation of this stock (T$/yr), and d_i is the representative depreciation or decay rate (yr^{-1}) of the pool of assets comprising the stock.

Although rarely portrayed in this way, d_i is an inverse timescale, $T_i = {d_i}^{-1}$ (yrs) and describes the exponential timescale or time constant of the first order process (1) (Garrett, 2014). T_i also closely relates to the amount of time a given capital asset is expected to survive in its cohort. This is illustrated through the parallels with the mixing dynamics of physical systems which, in equilibrium where inflows and outflows balance, T_i is the expected residence time: i.e. the average time an element is expected to remain in its pool. However, this parallel extends beyond simple mixed equilibrium systems, given it also mirrors average queuing time in queuing theory as described in the widely applicable Little's law, often invoked in microeconomics (Hendijani, 2021).

The mean service life, an estimate of the "economically useful life of an asset" (OECD, 2009), is often used by national statistics agencies in the perpetual inventory method that creates national accounts, based on manufacturer estimates, tax records, analysis of price depreciation, and other sources (BEA, 2003; OECD, 2009). However, because these data are often outdated, inconsistent between countries, and not available for all assets, industries and countries (Rincon-Aznar, Riley and Young, 2017; Bennett *et al.*, 2020), using service life data to explore economic inertia poses significant challenges.

The use of service life data is further confounded by the way depreciation, D, is handled in the perpetual inventory method, where the depreciation rate d is an effective cohort-level property reflecting two features of the perpetual inventory approach. In addition to describing the turnover of assets within the cohort as determined by the assumed representative service life for the cohort and any assumed survival function around this, depreciation also relates to the rate of production of capital services from a cohort because this is modelled as the outflow of capital from an asset into production processes (OECD, 2009; Katz, 2015). This 'capital services' flow serves two purposes. On the one hand it forms part of the forward valuation of the stock, because it is the expected future flow of capital services that determines expected future productive returns, corrected to net present value assuming a particular discount rate (OECD, 2009; Katz, 2015). On the other, this outflow, just like the effects of physical depreciation, also describes the loss of capital at a rate proportional to the magnitude of the capital stock. The net effect of these various representations of the capital loss process is that actual depreciation rate of a capital stock is only partially related to any published service life data on this stock.

Mercure et al. (2021) point out that equation (1) defines both the dynamics of capital stocks and the timescale for these dynamics, and as such provides the appropriate vehicle for investigating economic inertia. Again, T_i is the time constant or e-folding time for the temporal evolution of the first order system specified by equation (1), and therefore measures the speed at which a stock of capital assets moves towards equilibrium for a given change in investment, I_i. In this respect, providing it can be estimated appropriately, T_i can be used as a representation of the inertia of a given asset class or sector, and if the full distribution of asset classes and their turnover timescales is known for an economy, these can aggregate to define the inertia for entire economies.

The turnover behaviour of entire sectors and economies is invariably approximated through the turnover of a single representative capital asset, with a fixed depreciation rate and hence turnover timescale. This is how the economy has been portrayed in most IAMs that have informed climate decision making. Capital depreciation rates in these models range between 2-10%, indicating turnover timescales for global capital of the order of 10-50 years (Table 2.1). Notably, these timescales are starting to fall outside those specified in the Paris Agreement for the full decarbonisation of the global economy, suggesting an emerging conflict between our common climate and economic objectives.

The five-fold range in turnover timescales used in IAMs, despite each of these attempting to represent the dynamics of the same global economy, suggests significant uncertainty still remains over aggregate timescales and the inertia of the global economy. Moreover, in an economy changing so rapidly – for example, to meet urgent climate objectives – that the lifetime of a substantial proportion of assets never reach their full lifetimes, a single representative timescale may not hold as an accurate description of the turnover dynamics of the stock; in this situation it may become necessary to represent a fuller range of capital stock turnover timescales and ages. It is therefore important to have sight of the full distribution of inertia amongst assets throughout the economy to investigate whether such systems can be faithfully reduced to a single representative stock, depreciation rate, and turnover timescale.

The full distribution of turnover timescales and their relative contributions to the inertia of an economy is provided by the relationship between T and K for all elements of the economy. We refer to this as the capital-timescale relationship, which we uniquely derive for the United States in this paper. Just as a survival function describes the turnover dynamics of a single asset or cohort of assets, the capital-timescale relationship describes the turnover dynamics, and therefore the inertia, of whole economies. From this we also derive the relationship between I and T, which we call the investment-timescale relationship, which describes how the annual creation of new assets is spread across timescales. We contend that these relationships are a fundamental property of economies, most crucially because they identify the spectrum of timeframes on which returns are expected on investments, and therefore how financial risk is spread through time. The specification of these relationships also fundamentally alters our view of capital, from classes of named fixed 'artifacts' to classes associated with their longevity and dynamics.

Table 2.1. Capital depreciation rates and turnover timescales in integrated assessment models.

Model	Depreciation rate (%/yr)	Timescale (years)	Source
DICE	2.0%	50	Nordhaus and Sztorc (2013)
WORLDSCAN	2.8%	36	Lejour and Planbureau (2006)
MERGE	4.0%	25	Manne and Richels (2005)
GTAP/GTEM-C	4.0%	25	Cai et al. (2015)
MIRAGE	4.0%	25	Bchir et al. (2003)
MEDIAM	4.5%	22	Weber et al. (2005)
SGM/Phoenix	5.0%	20	Wing et al. (2011)
MARKAL	5.0%	20	Strachan et al. (2008)
ENV-Linkages	5.0%	20	Duval and Maisonneuve (2009)
SAGE	5.0%	20	Marten et al. (2019)
FALSTAFF	6.7%	15	Jackson and Victor (2015)
E3ME	10.0%	10	Cambridge Econometrics (2022)
WITCH	10.0%	10	Emmerling et al. (2016)
G-CUBED	variable		McKibbin and Wilcoxen (1999)
GEMMA	variable		Jackson et al. (2014)
GEM-E3	variable		Capros et al. (2013)

2.1.2. Literature on heterogeneous capital dynamics

Where capital is disaggregated in existing literature, this is typically done by sector or by geography, reflecting the way it is reported in national accounts, but some attempts have been made to understand the relationship between capital stocks and their turnover timescales, and the inertial consequences of this. Studies attempting to characterise the inertial risks of a rapid climate transition have typically focused on specific assets comprising the economy, most commonly the energy sector (Davis, Caldeira and Matthews, 2010; Fisch-Romito *et al.*, 2021). Davis and Socolow (2014), for example, estimated that the existing stock of power plants will emit between 98-

578 $GtCO_2$ depending on their average expected lifetime, which they estimate falls in the range of 20-60 years. Other models attempt some inertial analysis by focusing on technology lifecycles (Mercure *et al.*, 2018). However, these tend to consider particular types of capital independent of the remaining economy. This neglects the interconnectivity of assets, aggregate investments and supply chains, and the inertia produced by capital throughout the whole economy (Guivarch and Hallegatte, 2011; Grubb, Wieners and Yang, 2021).

More complex IAMs have modelled some form of capital heterogeneity typically by incorporating a sectoral breakdown of the economy, modelling growth and depreciation rates for individual sectors in individual countries, such as in G-CUBED (McKibbin and Wilcoxen, 1999). While this begins to disaggregate capital from a single homogenous pool, it is of limited use to understanding the spread of inertia, as there is only limited variation in the representative depreciation rates – and therefore turnover timescales – between sectors (Mercure *et al.*, 2021). There is much greater timescale variation between types of capital than between sectors, for example between equipment and buildings. This is reflected in GEMMA, which "distinguishes between two types of capital stock: 1) buildings and infrastructure; 2) machinery and equipment, each of which is expected to have different characteristics in terms of depreciation rate" (Jackson *et al.*, 2014, p. 18). GEM-E3 similarly introduces an inertial distinction between durable and non-durable goods, in addition to a sectoral and regional disaggregation (Capros *et al.*, 2013).

A World Bank report by Shalizi and Lecocq (2009), based on earlier work by Jaccard et al. (1997) and Jaccard and Rivers (2007), highlighted the heterogeneity of capital stock and classified it into timescale groups for the benefit of modelling. In their classification Group 1 capital (lifetime 5-15 years) largely consists of consumer durables, Group 2 (15-40 years) is mostly buildings, such as factories and power plants, Group 3 (40-75+ years) is infrastructure including road, rail and power distribution networks, and Group 4 covers land use and urban form which persist for "a century or more". In their subsequent analysis they estimate that capital with lifetimes longer than 15 years, i.e. Groups 2, 3 and 4, directly influenced 41% of global GHG emissions in 2000.

Jaccard and Rivers (2007), which inspired the above, identified groups of capital disaggregated by timescale, using them to disprove suggestions that economic benefit could be gained from a delay to emissions reductions, highlighting the need to instead decarbonise long-lived capital investment in the short term as a means of avoiding the impact of capital inertia. They used a similar approach to the estimation of mean service lives by national accounting agencies, utilising Canadian technology lifespan data combined with data from trade journals, industry experts and government reports, to estimate timescales for types of capital. The authors note that "there is little in the way of firm empirical analysis establishing the natural turnover rate of either individual categories of capital stock or the weighted average of all of society's capital stock," and that "much of the recent research that has suggested benefits to delay appears to have focused on the lower part of the capital stock hierarchy: buildings and especially equipment." They represented longer-lived capital using a three-tier structure: machinery and equipment, with an estimated lifetime of 20-30 years; housing, with a lifetime of 71.5 years; and urban form, with a lifetime of 117 years.

This attention to the heterogeneity of capital stock dynamics has not become common practice in IAMs or other climate-economy analysis, and the categorisations adopted by Jaccard and Rivers (2007) and Shalizi and Lecocq (2009) based on industry data have not appeared in much further work. Grubb et al., (2021, p. 12) state that with the exception of some dedicated models, "treatment of dynamic realism in standard stylized IAMs is patchy at best". Like Jaccard and Rivers (2007), we suggest that this is heavily influenced by the lack of data on, and a framework for applying, the timescale dynamics of capital. Contrary to some of the approaches taken in the literature which focus on particular sectors or types of capital – for example, only long-lived or fossil fuel infrastructure – we are also conscious that the capital stock of macroeconomies is heavily interlinked and that both emissions and inertia are produced by capital in a broad range of sectors, with a broad range of timescales, therefore necessitating an understanding of capital inertia at the complete macroeconomic level.

The economic risk from a rapid economic transition discussed in section 1.1 cannot be estimated, and the necessary planning cannot be conducted to mitigate the risk to economies and to populations, without an accurate inclusion of capital inertia in IAMs and other climate-economy models. We propose in this paper a method for empirically deriving turnover timescales for capital assets that is not reliant on estimated service lives but rather derives directly from the continuous inventory of national accounts outlined in equation (1). We then aggregate these into a capital-timescale relationship, and discuss the results as a description of how inertia has been distributed across the US economy over time. From this we analyse the dominant modes in this relationship to derive the simplest accurate description of capital turnover.

In section 2 we will outline our method for deriving turnover times using equation (1), using data from the US. In section 3 we will aggregate these to capital- and investment-timescale relationships for the US economy, and investigate the minimum model necessary to represent these relationship in IAMs and other models that simulate capital dynamics, with evidence provided in section 4 for the effectiveness of this model.

2.2. Deriving turnover timescales for US capital assets

The US Bureau of Economic Analysis (BEA) publish detailed estimates of the total capital value of 96 private non-residential fixed asset classes in 63 industries (giving a total of 2893 sector-specific assets with a non-zero capital value), as well as 43 government-owned (federal, state and local) asset classes, 51 types of residential fixed assets, and 28 types of consumer durable goods. This provides 3015 unique asset classes describing the capital stock of the US economy – a far larger number than those for which service lives are typically provided for. For each class the BEA identify not only the current capital value K_i, but unlike many other published national accounts, they also report annual levels of investment I_i and, crucially, the annual depreciations D_i from 1947.

Given the array of definitions and deployments of depreciation in national accounts like those of the BEA it is perhaps more appropriate to define the turnover dynamics of an asset class top-down using the perpetual inventory equation (1), especially given this is how the dynamics of capital turnover will be represented in IAM simulations. If all losses of capital from an asset class are proportional to the value size of that class, then from equation (1) T_i can be estimated directly for every asset class as

$$T_i = \frac{K_i}{D_i} \qquad (2).$$

This provides direct estimates of the turnover timescale associated with each asset class including not only the physical effects of depreciation of cohorts, but also the perceived consumption of capital in value production. Figure 2.1 shows the relationship between depreciation and capital value for all 3015 BEA asset classes we consider, covering the period 1947-2018. From this we can see that, despite the complexities and heterogeneity of practice associated with specifying depreciation and value production in the BEA perpetual inventory, for practically every asset class K_i is near linear in D_i across time, suggesting that d_i and hence T_i are near constant for each class across time.

In line with equation (2) and the evidence for linearity between K_i and D_i seen in Figure 2.1, we estimate T_i using simple least squares applied to each of the 3015 asset categories, assuming that T_i does not change across each 72 year sample. Out of the 3015 regressions, only 74 (or 2.5 percent) produced regression residuals that failed a 5% threshold Anderson-Darling test for normality. Only two asset classes out of the 3015 produced statistically insignificant estimates for T_i and these were dropped from the analysis.

We evaluate our turnover timescale estimates by comparing them to the mean service lives used in national accounts to complete the perpetual inventory method. These are taken from BEA (2003) where a good match is possible; where this is not possible, mean values from other global sources quoted in Rincon-Aznar et al. (2017) are used; where no agency has a reliable estimate, the asset class is not plotted. From Figure 2.2**Figure 2.3** we can see there is broad agreement between our turnover timescale estimates based on equation (2) and the mean service lives used in various ways to define depreciations, reflecting the dominance of natural retirement at the end of service life in the turnover dynamics of many asset classes in the BEA perpetual inventory. However, there are also significant differences between the two, particularly in asset classes with mean service lives greater than 20 years. This is likely to reflect the effects of nonlinearity in the assumed survival function for certain classes (Katz, 2015), and the complex effects of capital outflows on the loss of capital through their productive use.

We hold that it is the turnover timescale T_i that more accurately reflects the inertial dynamics in each asset class compared to mean service lives, due to the quality issues with service lives raised in section 2.1, and because it is the aggregate effects of all effective forms of capital loss including natural retirement, physical deterioration, obsolescence and accidental damage. Capital is defined by the conservation equation (1) and hence it is logical for its turnover dynamics to be derived from this first order process.

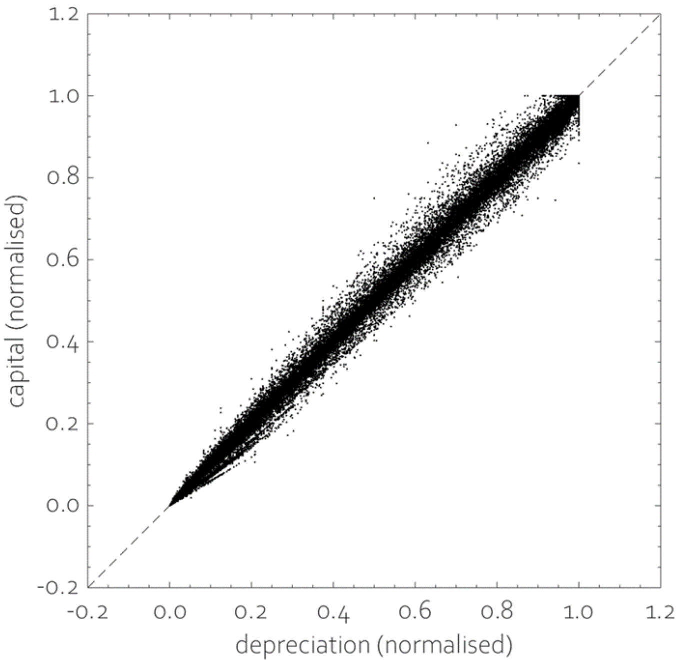

Figure 2.1. The relationship between annual depreciation and capital value for all 3015 asset classes comprising the US economy presented in the BEA database, with separate plots for each year between 1947 and 2018 (N = 217,080). Both capital value and depreciation are normalised by the historical maximum for the asset class. The 1:1 line (--) shows compliance with the linear model (2).

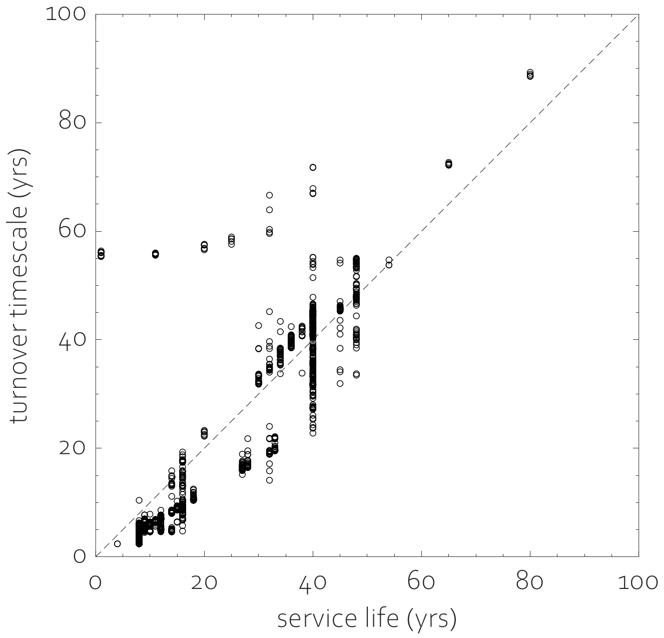

Figure 2.2. The relationship between the quoted mean service lives of asset classes, where they are available in the literature (BEA, 2003; Rincon-Aznar, Riley and Young, 2017), and the corresponding turnover timescale estimated from equation (2) using linear least squares. These were found to be strongly positively correlated, $r(2669) = .96$, $p = <.001$.

2.3. The capital-timescale and investment-timescale relationships of the US economy

The relationship between T_i and K_i for each asset class is shown in Figure 2.3, which shows discrete timescale estimates ranging from 0-90 years, but no discernible pattern beyond a clustering of the shorter timescale sectors. The method described in Section 2.2 provides a representative turnover timescale for each of the 3015 capital asset classes in the BEA account of the US economy, but like mean service lives, these invariably reflect only the first moment of a range of expected lifetimes within that class. The asset class 'Aircraft', as an example, will contain a diversity of aircraft types and models each with different expected lifetimes, and aircraft built to the same model will have a probabilistic chance of retirement over a period of years, according to a particular survival function. If we want to capture the fact that each asset class is comprised of large cohorts of elements, and that this should be accounted for in the inertial dynamics, we need to populate each asset class accordingly. To this end, the BEA, in their perpetual inventory analysis, assume symmetrical (bell-shaped) Winfrey mortality functions where discards are spread over the period ±55% of the mean service life, except for residential buildings which are spread over ±95% of the mean service life (OECD, 1993). We replicate this, using a normal distribution with the same spread to redistribute the capital value in any given asset class around our estimated turnover timescales.

Having estimated the full cohort of timescales for each unique asset class, we can now regroup capital with respect to these timescales. This is significant in reassigning capital from its familiar artefact-orientated 'asset' classification into the corresponding 'timescale', and hence inertial, class. From this, we can then assess the extent of investments made that contribute to the overall inertia of the US economy.

The result is shown in Figure 2.3. The first thing to note is that the thinness of the black envelope shows how remarkably stationary this capital-timescale relationship is. Many of the 3013 sectors (we remove 2 due to these producing negative T_i) come and go in their relative importance over the 72 years; computer hardware and software have surged in prominence, for example, while equipment for heavy industry has shrunk. However, in the timescale space this ebb and flow is lost, suggesting that the most important feature of investment in its contribution to economic inertia is not what things are called, or what they are or what they do, but rather how long they reside in the economy providing returns. It appears to be the spectrum of timescales of these returns that is preserved, which may suggest that this form of capital heterogeneity is important as a means of spreading risk and opportunities. We discuss this in Section 2.5.

We find from the capital-timescale relationship that the US economy can be approximated as the sum of three distinct distributions of timescales, which we refer to as fast, medium and slow capital (Figure 2.3). We find gamma distributions provide an acceptable summary each timescale group, and the associated gamma function parameters are presented in Table 2.2. Of these, medium capital is the largest class (57%) and has a first moment of 51 years (Table 2.2), and would seem to map well to Group 2 and much of Group 3 identified by Shalizi and Lecocq (2009). The fast capital component has a first moment of 7 years and contributes some 30 percent of all capital, paralleling Shalizi and Lecocq's (2009) Group 1. The slow group, meanwhile, dominates the distribution beyond 75 years, but making up just 13% of total capital with a large spread of timescales stretching beyond 200 years. This is dominated by real estate, but also includes some other long-lived assets that fit the description of 'urban form' used for the uppermost capital group in both Shalizi and Lecocq (2009) and Jaccard and Rivers (2007), such as sewer systems (Table 2.2), in addition to 'medium' assets that simply lived significantly longer than their planned lifetime. This group therefore maps to Group 4 and the 'urban form' group in these papers respectively, with the addition of some longer-lived real estate which they situate as part of Group 3/'Buildings', and a broader collection of legacy assets.

We derive the investment-timescale relationship directly from the capital-timescale relationship. In this case, the annual investment value at each timescale is derived by inverting equation (1), with the annual change in capital given by the between-year difference in the capital-timescale relationship. We find that this investment-timescale relationship can also be partitioned into three gamma distributions with near-identical shape but different relative allocations. These are shown in Table 2.2. In comparison to capital, investment is skewed towards shorter timescales, with 55% of total investment made in fast capital despite it only providing 30% of the resultant stock, as a result of the greater turnover of shorter-lived capital.

The first moment for the full capital-timescale distribution for the US economy shown in Figure 2.3 is 44.7 years, suggesting a representative depreciation rate on an aggregate capital stock of 2.2 %/yr, at the lower end of values currently used in IAM frameworks attempting to capture the inertia of produced capital (Table 2.1). However, if we divide total capital by total depreciations in the BEA database following equation (2) we get a representative timescale of only 16.1 years and hence a depreciation rate of 6.2 %/yr, closer to the upper end of the IAM spectrum. This difference possibly explains the lack of consensus in macroeconomics over aggregate depreciation rate values, with on the one hand observed capital stock turnovers suggesting low depreciation rates and long timescales, while on the other growth models fitted to output data suggesting much shorter effective turnover and hence higher depreciation. These effective estimates give lower turnover timescales because of growth differentially amplifying the effects of shorter timescales.

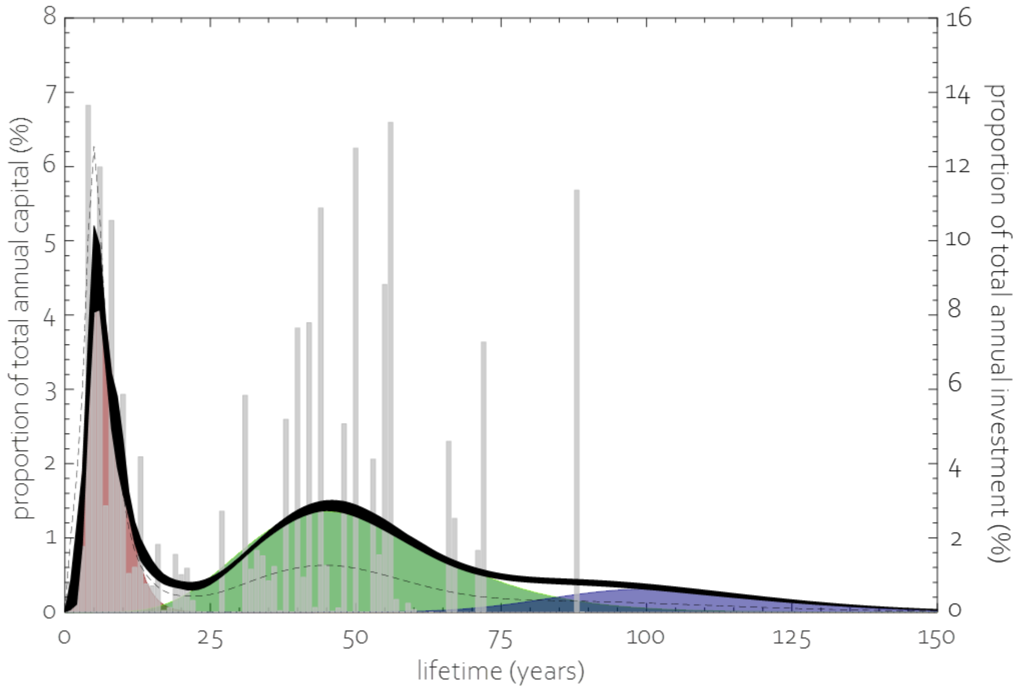

Figure 2.3. The relationship between turnover timescale and capital value. Bars represent the capital value of the 3015 BEA asset classes assigned to their timescale, T_i. Black envelope is the 95% confidence interval of the corresponding survival function with plots for all 72 years of the analysis combined, where capital value for each asset class is spread across timescales according to a Winfrey mortality function. The three coloured regions are our attempted partitioning of the survival function into constituent gamma distributions (see Table 2.2 for details). The dashed line is the corresponding relationship between turnover timescale and investment derived from the timescale-capital relationship through inverting equation (1).

Table 2.2. Partitioning of the timescale distributions shown in Figure 2.3. Each distribution is a gamma function simultaneously fitted to the overall distribution. The table reports the first moment T, shape parameter k and percent contribution to total g in the function $f\{T_i\} = g\left(\gamma(k^{-1})/\varphi^k\right) \cdot T_i^{\,k-1} \cdot e^{(-T_i/\varphi)}$ where $\varphi = T/k$. The figures in brackets are the representative timescales for the third order response estimated from the recession dynamics shown in Figure 2.4.

Parameter	T	k	g_K	g_I
Units	yrs	yrs	%	%
Fast	7.2 (5.3)	5.5	29.7	55.0
Medium	50.6 (32.1)	8.5	56.7	38.2
Slow	104.3 (91.1)	31.4	13.7	6.74

2.4. What is representative?

To explore what a minimum representative model of inertia should be, given the complete profile of capital inertia uniquely identified in the previous section, we simulate the decay dynamics of the aggregate capital of the US economy as if new investment were suddenly withdrawn. We begin our simulation with the capital-timescale distribution identified in Section 2.3, and capital is subsequently depreciated annually according to equation (1). This parallels an idealised structural shift where all new investment is diverted from 'brown' to 'green' assets with zero emissions, that are designated outside the scope of the simulation (Mercure *et al.*, 2021).

The decay profile of total capital is shown in Figure 2.4, and we find that the recession dynamics have three characteristic timescales of 91, 32 and 5 years (Figure 2.4; Table 2.2). These timescales do not perfectly align with the first moments of our capital-timescale distribution as shown in Table 2.2, likely demonstrating a dynamic effect resulting from the fact that the system is again not in equilibrium. However, the presence of three dominant modes demonstrates that the single timescales used in IAMs are inadequate when describing any transition involving declining high carbon capital stocks, and that a three-pool model for capital, as identified in Section 2.2, is more appropriate.

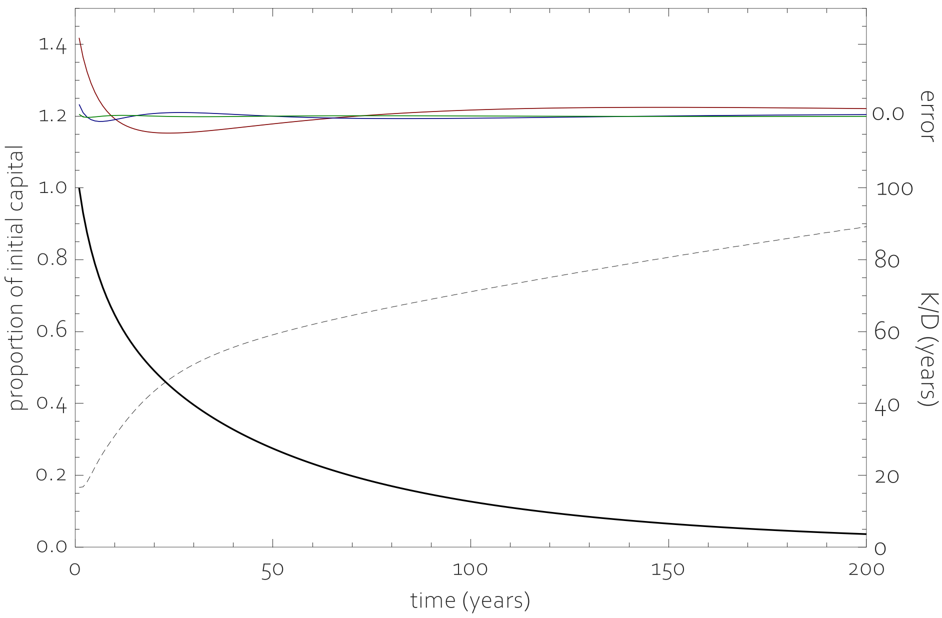

Figure 2.4. The decay response of capital given the capital-timescale relationship shown in Figure 2.3. The relationship between turnover timescale and capital value. Bars represent the capital value of the 3015 BEA asset classes assigned to their timescale, T_i. Black envelope is the 95% confidence interval of the corresponding survival function with plots for all 72 years of the analysis combined, where capital value for each asset class is spread across timescales according to a Winfrey mortality function. The three coloured regions are our attempted partitioning of the survival function into constituent gamma distributions (see Table 2.2 for details). The dashed line is the corresponding relationship between turnover timescale and investment derived from the timescale-capital relationship through inverting equation (1).(black solid), depreciating annually according to equation (1) with no new investment. The error when fitting a first (red), second (blue) and third (green) order response to the decay are also shown, and the third order time constants and gains are presented in Table 2.2. Lastly, the effective turnover timescale given by the ratio of total capital to total depreciation is also shown (dashed).

2.5. Discussion and conclusions

In this paper we have derived turnover times for capital assets in the US which, unlike estimated mean service lives which are used in conventional national accounting methods and analyses such as Jaccard and Rivers (2007), provide consistent empirical timescales for the complete US economy. Based on these, we have derived for the first time the complete distribution of fixed capital stock and investment across timescales in the US, which we call the capital-timescale and investment-timescale relationships. We found that these can be neatly partitioned into three primary timescale groups – fast, medium and slow – and have demonstrated through simple simulation that the first moment of these distributions represent the minimum model that can reliably simulate the turnover dynamics of capital. We have provided a simple method for implementing these three capital stocks, or the corresponding full spectrum of capital timescales, in IAMs.

Our results therefore give empirical backing to the idea of a three timescale-sector economy suggested by Jaccard and Rivers (2007), while also providing an updated timescale definition of these sectors based on analysis of the US economy. They highlight that, in anything other than business-as-usual growth scenarios, single timescale/depreciation rate IAMs will not adequately capture the inertial dynamics of the economy, and that a minimum of three representative stocks – one fast, one intermediate, one slow turnover – is likely required.

In this paper we have, for practical reasons, chosen to study the US as an example of a large, diverse economy which is likely to be broadly representative of developed economies, and for which capital value and depreciation data are published with a sufficiently thorough breakdown of industries and assets to facilitate the creation of a detailed timescale distribution (Fraumeni, 1997). It is also a useful economy for which to make comparisons against the service lives used in national accounting (Figure 2.2) because, as noted by Rincon-Aznar et al. (2017) the US BEA uses service lives “that are mostly based on empirical evidence” (p.25) and that are often assumed by other countries unable to produce their own estimates; for this reason the US is a common benchmark for analysis of service lives.

It is important to note that the capital-timescale structure will vary based on the nature of the economy, particularly between developed economies, where most investment simply aims to replace depreciating capital, and developing economies, where investment more significantly contributes to increasing the capital stock. Evidence is limited, but studies have shown that physical capital depreciates at a comparatively higher rate in developing countries as a result of under-maintenance, lower utilisation rates and higher time preference rates (Bu, 2006). Further research into capital timescales and inertia in other types of economies is therefore much needed. Whereas comparison of service lives between countries is challenging due to significant variations in methodology, industry and asset categorisation, and public availability of service life data (Görzig, 2007; Rincon-Aznar, Riley and Young, 2017), the turnover-time method introduced in this paper will allow comparison between any countries that publish relevant national accounts data, using a consistent method for estimating capital lifetimes.

While we have limited the scope of this paper to investigating *how* capital is distributed across timescales, with the hope that the heterogeneity of capital and its inertial implications will receive greater prominence in climate-economy modelling, we also believe that this question of *why* capital turnover is spread across timescales in the way we identify is deserving of further attention. It is an example of timescale separation, the idea that complex systems naturally self-organise to create structures with a large distribution of timescales for individual elements and processes, in order to maintain function or robustness in response to perturbation (Lesne, 2017). This has been identified at the level of the Earth system (Williamson, Bathiany and Lenton, 2016; Lenton *et al.*, 2018; Szerszynski, 2022), as well as in evolving living systems (Pocheville, 2018), and even in cellular metabolic processes (Rowland

Adams and Stefanovska, 2021). The separation of capital investments across timescales demonstrated in Figure 2.3 may, like those other systems, have emerged out of functional need – for example, the design of buildings necessarily contains multiple layers that are made up of separated timescales, from foundations through to light fittings (Brand, 1994) – or to ensure robustness; investing in capital across a range of timescales, such as investing in machines in addition to buildings, may be seen as a dynamic hedging strategy on the part of the individual investor, forming some insulation against the financial risk posed by shocks to the economy. It appears further research is needed to develop the interdisciplinary concept of timescale separation, and to explore the role and purpose of timescale separation in the economy. Certainly economies make good testing grounds for such theory development not least because of the ubiquity of the accountancy process providing much of the necessary internal state observation.

Understanding and modelling the inertial dynamics of capital is an urgent consideration, as climate change is likely to threaten the stationarity in the overall dynamics of the economy described above. Investment decisions over the past century have largely been made on the assumed stationarity of the climate, relying on investments playing out their lifetimes and delivering returns in a climate that is as predictable as it was in the past, but climate change will affect the attrition rate on capital structures requiring infrastructure planning and investment strategies to be revised (Giordano, 2012). Even where the survival of capital is not directly under threat from the impacts of climate change, the lifetime and therefore the return on investments may instead be cut short by a rapid climate policy led transition which requires the removal of active carbon-emitting infrastructure. For instance, the 2050 deadline to fully decarbonise the global economy, identified by the IPCC as necessary to avoid dangerous climate change and established in law as a target for the US, is likely to necessitate capital with remaining lifetimes beyond that timescale – our medium and slow groups – to be adapted to produce net zero carbon emissions, or to be decommissioned before that date (Jaccard and Rivers, 2007). The potential for economic impact as a result of this adaptation or loss of future returns produces a form of infrastructural inertia in the economy, with past investment decisions binding future pathways for society. This path dependence offers a powerful argument for a precautionary approach to current such decisions (Seto *et al.*, 2016; Hoepner and Rogelj, 2021) and for urgent action on those sectors with the greatest inertia (Vogt-Schilb, Meunier and Hallegatte, 2018).

Although the turnover timescale method and the capital-timescale relationship we have developed here are important for understanding these risks and how to prioritise any such retirements (Mercure *et al.*, 2021; Semieniuk *et al.*, 2021), the effects of climate change and any climate transition will reshape the survival functions of capital, taking us into uncharted territory.

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Data availability

Data will be made available on request.

CRediT authorship contribution statement

Daniel Chester: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Software, Validation, Visualization, Writing – original draft, Writing – review & editing.

Cormac Lynch: Conceptualization, Writing – review & editing, Data curation.

Bronislaw Szerszynski: Supervision, Writing – review & editing.

Jean-Francois Mercure: Conceptualization, Funding acquisition.

Andrew Jarvis: Conceptualization, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing.

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3. Stranded human and produced capital in a net-zero transition

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Abstract

The pace of the net-zero transition required to meet the Paris Agreement objectives puts the value of existing carbon-dependent capital at risk of premature depreciation. This risk extends beyond physical capital and threatens occupations and livelihoods. We quantify the current value and turnover timescales of existing global human and produced capital and compare the rate at which it naturally depreciates with that at which it would be required to depreciate to achieve climate targets. We find that achieving net-zero in 2050 by ending carbon-intensive investment in 2020 would have put up to 117 T$ of global capital value at risk. Delaying a ban on carbon-intensive investment to 2030, however, implies a risk of up to 557 T$ (37 percent of current capital), around three quarters of which is human capital. Reducing these risks could warrant intervention in both the financial and educational systems, where training for occupations that may soon cease to exist could be avoided. Other similar transformative policies to stimulate new economic capabilities in fossil fuel dependent regions are needed to ensure a just transition.

3.1. Introduction

Current estimates suggest the Paris Agreement requirement of restricting global warming to well below 2°C implies reaching net-zero CO_2 emissions globally between 2050 and 2070, while aiming for a 50% chance of not exceeding 1.5°C of warming requires achieving this by 2050, if started in 2020 (Millar et al., 2017; Holden et al., 2018; IPCC, 2018). In line with the latter, the United States, United Kingdom, and French governments, as well as the European Union as a whole, have independently adopted emissions targets to reach net-zero by 2050 (European Commission, 2018; Committee on Climate Change, 2019; The White House, 2021). The Japanese and Korean governments have also announced plans to reach net-zero by 2050, while the Chinese government has announced a target of net-zero in 2060 (United Nations, 2020). Furthermore, 194 countries have ratified the Paris Agreement and have made pledges on emissions reductions with the explicit intention to achieve this commitment (United Nations, 2015).

These objectives imply that the structure of economies must change drastically over the next 25 years as fossil fuel intensive sectors and technologies disappear and are replaced by clean-tech alternatives (Lefevre et al., 2022; Lynch et al., 2024). This economic transition is very likely to bring significant benefits to many countries, regions, and households through job creation and import bill reductions (Mercure et al., 2021). Yet for others, a transition to net-zero threatens the existence of entire communities and livelihoods as some careers, skills, and ways of living become obsolete (Green & Gambhir, 2020).

Meanwhile, in the financial world, a debate has emerged concerning the risk associated with owning carbon-dependent capital, which could be threatened by new climate policy and regulation, changing consumer preferences, and ongoing technological change (Caldecott et al., 2016; TCFD, 2017; NGFS, 2019; Bolton et al., 2020). Notably, the quantity of fossil fuel reserves valued in investment portfolios could exceed what can be used while achieving climate targets, and could thus devalue (Meinshausen et al., 2009; McGlade & Ekins, 2015, Welsby et al., 2021). Current targets could also imply asset stranding of $1.4 trillion from coal power plants alone (Edwards et al., 2022). A net-zero transition is, however, likely to not only impact the valuation of capital in the fossil fuel industry, but also capital across the economy in general, (Battiston et al., 2017; Caldecott, 2018; Cahen-Fourot et al., 2021) with value at risk in the global real estate sector alone estimated to reach up to $21 trillion (Muldoon-Smith and Greenhalgh, 2019).

Economies function by investing in the creation of productive capital assets, including skills, which in turn generate net positive future economic returns. Investments span a broad spectrum of planned lifetimes over which returns are harvested (Chester et al., 2024). The prospect that these investments could become unusable or banned before the end of their expected productive lifetime underpins our understanding of asset stranding (Kefford et al., 2018; Mercure et al., 2018a). The payback time of capital implies economic inertia, where economic agents face a range of waiting timescales during which resources are committed. This lock-in constrains their access to further finance and the associated investment opportunities (Foxon, 2002; Seto et al., 2016), hence limiting the rate at which the economy can transform. Research is also emerging into the role economic inertia plays in creating political inertia and instability (Colgan et al., 2020). Given the need to rapidly transition the global economy to mitigate climate change, understanding economic inertia is crucial. However, no comprehensive study has investigated the full spectrum of timescales that characterise the capital value at risk in pathways of emissions reduction.

Capital can be broken down into three categories (World Bank, 2021): produced capital – physical man-made economic assets; natural capital – the value embedded within natural assets; and human capital – the economic value of the workforce. Human capital is generally tied to the operation of produced capital, but its total estimated value dominates, representing 64% of global wealth and even more in developed economies (World Bank, 2021). Furthermore, the turnover of human capital is relatively slow, dictated by working lifetimes which, although highly variable across populations, have on average remained somewhat stable at around 40 years (Ausubel & Grübler, 1995; Jarvis et al., 2015). Notably, this timescale is longer than the time remaining until emissions reductions must be achieved under the Paris Agreement. This suggests a significant portion of the workforce will inevitably have to embrace the change implied by the low carbon transition within their working life.

If a transition to net-zero is faster than society's ability to re-skill existing workers, or if there is a geographic disparity between employment losses and gains, both unemployment and labour shortages could occur simultaneously through rapid structural change (Rosemberg, 2010; Markkanen & Anger-Kraavi, 2019; Green & Gambhir, 2020), particularly in the energy sector (Malik et al., 2021). Furthermore, given the tendency for related industries to cluster geographically (Arthur, 1990), entire regions could become 'stranded' (Andres et al., 2023; Spencer et al., 2018), facing the risk of post-industrial decline. This has, at least in part, precipitated calls for a 'just transition', ensuring that decarbonisation addresses existing and potential new inequalities through an equitable distribution of the benefits and burdens of the transition to net-zero (Markkanen & Anger-Kraavi, 2019). Therefore, in terms of value, turnover timescale, and social impact, human capital is probably the most important component of the inertia of the global economy, and it is therefore surprising that it has been largely absent from discussions on stranded assets.

Macroeconomic models often assume that human capital can be readily redirected into net-zero occupations (IPCC, 2018; Mercure, 2022), either because retraining barriers are low, or skills are fully fungible. However, particularly at a sectoral level, training a workforce can be a lengthy and costly program (CBI, 2020). For instance, Louie & Pearce (2016) estimate that the average cost to retrain a coal industry employee for jobs in the solar industry could be as high as $20,863 with training taking from several months up to 9 years. Meanwhile, a worker's ability to move is contingent on their regional mobility. Moreover, people identify with places and work practices, and this can act to create networks of physical and human capital that increase the degree of lock-in to a particular set of activities (Shove et al., 2012). Given the size of investments in sophisticated national education and training systems (Judson, 2002), the likely need to retrain a substantial portion of the global workforce (Bowen et al., 2018), and that many workers could be required to migrate to new locations, this risk is in urgent need of evaluation.

In this article, we aim to investigate the economic inertia facing a Paris Agreement compliant net-zero transition scenario. We develop a 56-sector view of 43 regional economies, with each sector in each region comprised of valuations of both human and produced capital. We simulate the depreciation of these capital portfolios using a population dynamics algorithm, tracking capital retirement according to its respective lifetimes while deriving CO_2 emissions. Using this framework, we explore both the carbon embedded in existing human and produced capital in addition to the size and timing of capital retirements required to achieve particular Paris compatible decarbonisation scenarios. Additionally, we aim to explore the potential impact of a delayed transition on capital stranding. The rest of this article is structured as follows; Section 3.2 will outline the construction of the capital stock dataset together with the population dynamics and early retirement algorithms. Section 3.3 describes the results of the capital depreciation simulation. Section 3.4 will discuss the implications of the simulation results, with reference to both financial stability and post-industrial decline, and Section 3.5 concludes.

3.2. Methods

Our approach seeks to be data led and as model independent as possible. We do not set out to prescribe particular pathways or transition policies. Instead, we depreciate observed estimates of existing capital stocks at observed rates, and by comparing the associated emissions to publicly declared climate objectives, we determine the total capital value at risk from premature retirement if not adapted. Given that both the capacity of any future negative emissions technology and emissions from land-use change are highly uncertain (IPCC, 2018), we focus exclusively on the carbon emissions from fossil fuel use and cement production.

Unlike previous simulations of carbon-intensive capital phase-out (e.g., Smith et al., 2019), we did not partition the economy into a limited number of activities that produce carbon emissions and the rest that does not. Instead, we take the view that all current capital is reliant on fossil fuel use to varying extents, as reflected in the different carbon intensities of sectors. As we are interested in the depreciation of currently existing capital stocks rather than any future investments, we conceptualised a two-tiered global economy going forward. This is comprised of the current 'brown' economy, tied to carbon emissions and subject to planned capital retirements in our simulation, and a new carbon-free 'green' economy, which is emissions free.

We ran simulations from two start dates; 2020 – the start of the Paris Agreement compliance period – and 2030, to assess the impact of the delayed transition we are currently enacting. Following the start of our simulations, we assumed all new capital investment is directed into the green economy (which we do not represent explicitly) so that we can track the depreciations from the current brown economy only. As no new investments are made in the brown economy, the carbon intensities of capital in each sector are assumed to be constant over time.

In the rest of this section, we first outline our construction of the global portfolio of capital stocks, their associated turnover timescales, and carbon intensities (Section 3.2.1). Then, we describe how we use this capital stock portfolio in our future capital retirement simulations (Section 3.2.2) before outlining the value at risk (VaR) framework that we use to conceptualise and communicate the threat of capital stranding (Section 3.2.3).

3.2.1. Portfolio of capital stocks

Our portfolio contains estimates of both human and produced capital. We define produced capital as the value embodied in assets, such as buildings, machinery, and other longer-lived types of durable equipment. Meanwhile, human capital is defined as the total time discounted future earnings of the workforce. This is consistent with the World Bank's income-based approach to estimating human capital (World Bank, 2021). We provide a visual overview of the construction and use of the total capital portfolio in Figure 3.1.

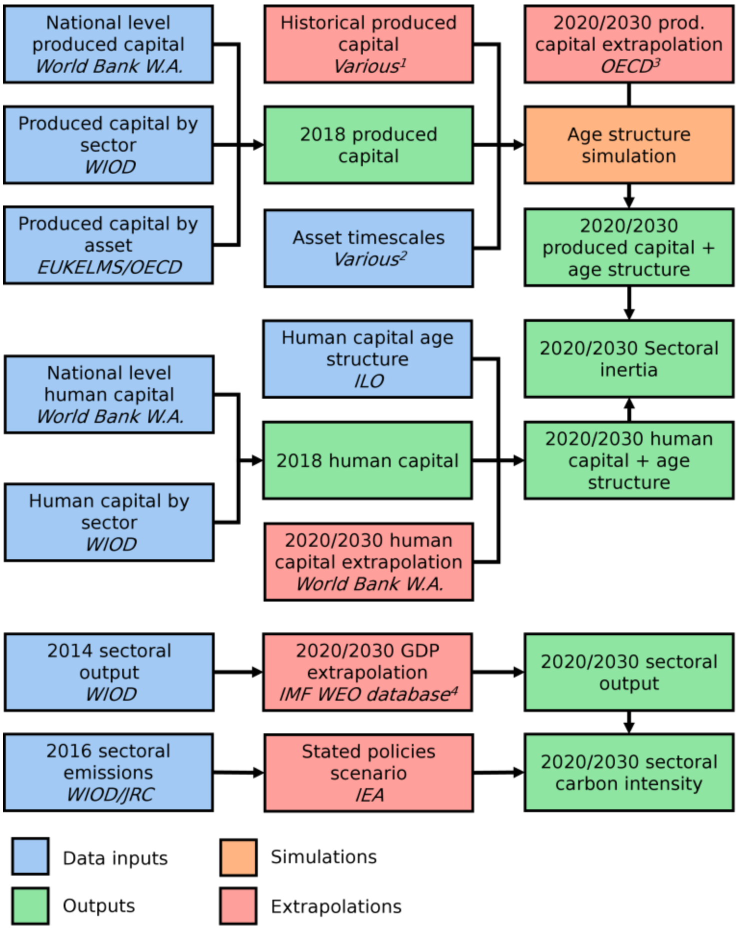

Figure 3.1. Graphical representation of the steps to create the capital stock portfolio. Data sources are shown in italics. [1] World Bank Wealth Accounts and Penn World Tables 10. [2] ONS, Statistics Canada, and Statistics Netherlands. [3] OECD Economic Outlook database. Where this is unavailable, average growth rates from the World Bank Wealth Accounts are used. [4] Covers 1980-2026. We extrapolate to 2030.

3.2.1.1. Produced capital stock

The produced capital stock portfolio is derived from the socioeconomic accounts of the World Input-Output Database 2016 release (WIOD). This provides data on produced capital stocks and labour compensation between 2000-2014 for 43 countries (Supplementary Material Table 3.4) and 56 sectors based on the ISIC Rev. 4 classification system (Supplementary Material Table 3.5), comprising around 85% of global GDP (Timmer et al., 2015). The remainder of global GDP is excluded from our analysis given it is uncharacterised in the WIOD database. For consistency across our approach, we end by rescaling our modified dataset of national produced capital to the World Bank Wealth Accounts, which provides national capital stock estimates between 1995 and 2018 (World Bank, 2021).

When simulating the depreciation of capital we have attempted to represent the full spectrum of service lives attached to both produced and human capital. We disaggregated the produced capital stock estimate in each sector into nine asset types (Supplementary Material Table 3.6) based on the ESA2010 asset classification system according to asset share data from the OECD National Accounts Statistics (OECD, 2022a) and the EUKLEMS Growth and Productivity Accounts (Van Ark & Jäger, 2017). Where asset share data for a country or sector was missing, we took the median national shares for the appropriate sector. For each asset class we define a representative service life. We interpret the service life as the economic lifetime of an asset as opposed to the physical lifetime, consistent with the OECD (2009) definition of the term. Representative asset service lives were sourced from the UK Office of National Statistics (Rincon-Aznar et al., 2017), Statistics Canada, and Statistics Netherlands (personal communication) and are sector specific. For example, the service life of machinery in the chemicals sector (ISIC code C20) is 43 years, whereas in the retail trade sector (ISIC code G47) it is 10 years. Due to difficulties obtaining country-specific data, we assumed consistent asset service lives across all countries. In order to better reflect the full dynamic range of produced capital lifetimes, each representative service life was converted to a corresponding service life distribution assuming the mortality function offered by Schmalwasser & Schidlowski (2006; see Chester et al., 2024). This then defines the age-related annual retirement profile for each asset class in each sector in each country (see section 3.2.2).

To initalise our simulations in 2020 and 2030 we simulate the turnover of produced capital starting in 1850 because of the presence of long-lived assets. We first estimated the size of the capital stock of each sector in each country in 1850 by backward extrapolating our modified capital dataset using capital stock growth rate data from Penn World Table version 10.0 (Feenstra et al., 2015). This covers the period 1950-2019, and therefore required us to assume a country specific average capital stock growth rate pre-1950 (see Supplementary Material Figure 3.4 for an overview of when different data sources were used). Again, due to a lack of data, we assumed that the relative size of sectors remains consistent over this period.

Yearly capital retirements are then based on the service lives described above. New additions to the capital stock were defined as the difference between the previous year's stock less retirements and the total expected capital stock as defined by the backward extrapolation of capital growth rates. This simulation provided estimates of capital of each vintage still active in the economy in 2020 and 2030, for each sector in each country. Since the most recent year in the World Bank Wealth Accounts is 2018, we extrapolated our produced capital stock estimates to 2020 and 2030. Between 2019 and 2023, where data was available, we grew the stock according to country specific produced capital stock growth projections from the OECD Economic Outlook No. 110 (OECD, 2022b). To the best of our knowledge, this is the only dataset that estimates the impact of the COVID-19 pandemic on produced capital stocks, which we felt was important to include when initialising our simulations. Post 2023, we assumed the stock continues to grow at the 2023 rate. For countries not in the OECD Economic Outlook database, we extrapolated using the average produced capital stock growth for each country over the period 2010-2019 in Penn World Table version 10.0 (Feenstra et al., 2015). Due to a lack of sufficiently disaggregated growth projection estimates, we assumed no structural economic change in our extrapolation i.e. sectoral relative shares remain constant.

Finally, we derived sector-specific turnover timescales for produced capital, representing the economic inertia implied by capital in each sector, by calculating the weighted (by relative size of each asset type) average service life of capital in each sector. This reflects the fact that a sector like real estate, comprised of mostly dwellings, will have greater economic inertia than a sector that is made up of shorter-lived assets. We provide a visual representation of this process in

Supplementary Material Figure 3.5. These sector turnover timescales were then used in the subsequent forward simulations of planned capital retirement.

3.2.1.2. Human capital stock

Although the economic value embodied in the labour force is the largest component of the capital stock in most countries (Lange et al., 2018), most national accounts do not include estimates of the stock of human capital, including the World Input-Output Database socio-economic accounts that form the basis of our analysis, which only contain sectoral labour compensation data. Furthermore, the Jorgenson-Fraumeni lifetime earnings approach to estimating human capital used by the World Bank generally assumes a representative working life when integrating to estimate human capital, much like representative service lives and depreciation rates are used when characterising produced capital. However, as with our produced capital analysis, we want to account for the fact that, like its produced counterpart, human capital expresses a very broad range of service lives in any economy through the range of working lifetimes of its participants. In order to attempt to capture this, and its impacts on the economic inertia in our analysis, we approximate the age-related net recruitments and retirements in a workforce through the first difference of the International Labour Organisation (ILO) 1990–2010 workforce participation rate data (see Figure 3.2). We then sample from these age-related distributions to derive working lifetime distributions (see Figure 3.2) over which we aggregate time discounted future wages mirroring the World Bank method (Jorgenson & Fraumeni, 1989; Lange et al., 2018; World Bank, 2021). Due to limited data availability, we were only able to construct US and global working life distributions. We therefore scaled the China stock to the global distribution, and the EU stock to the US distribution, on the basis that economies at a shared level of development will likely share labour market characteristics. Again, in absence of more disaggregated data, we assume median wage varies with age following the profile of earnings in the United States based on Kiersz et al. (2020) and Ruggles et al. (2024). Finally, we repeat the disaggregation of the age-human capital distribution into its net recruitment and retirement components to derive the age-related retirement profile used in our forward simulations (Figure 3.2).

Total present day human capital stocks were sourced from the World Bank Wealth Accounts, which provide country level estimates of the human capital stock between 1995 and 2018 from which we select the US, China and EU stocks, and sum all countries for the global stock. Again, we rescale these estimates to those of the World Bank to be consistent with our produced capital data, and we extrapolate to 2020 and 2030 by growing the estimates at the median rate observed in the World Bank Wealth Accounts over the period 2010-2018. These were disaggregated into the 56 sectors using the share of labour compensation in the WIOD for the period 2000-2014. Unlike produced capital, we do not need to spin up the present-day age structure of human capital from 1850 because this derived from the analysis detailed above.

3.2.1.3. Carbon intensities

During rapid decarbonisation, some parts of the economy will be more exposed to stranding than others. We measured this exposure through the carbon intensity of each sector, similar to the approach used by Battiston et al. (2017). The carbon intensity was also used to project future sectoral emissions in the simulation of capital depreciation. Emissions data were provided by the Joint Research Centre of the European Commission for the period 2000-2016 and are fully consistent with the sectoral and regional classification adopted in the WIOD (Corsatea et al., 2019). They were then extrapolated to 2020 and 2030 according to the stated policies scenario in the IEA World Energy Outlook database (IEA, 2021). Sectoral GDP data was provided by the WIOD and was scaled to the IMF World Economic Outlook Database: October 2021 which covers the period 1980-2020 and provides projections until 2026. We linearly extrapolated these estimates to 2030. We calculated carbon intensities for each sector by dividing the total sector emissions by sector GDP.

3.2.2. Simulations

We considered two sets of forward simulations. The first simply explored the amount of carbon associated with the 2020 and 2030 global stocks of produced and human capital. The second explored any *additional* removals of capital required to reduce these annual emissions to a level consistent with recent interpretations of net-zero policy, where annual emissions decline linearly to net-zero in 2050 (UNEP, 2021). This provided 4 scenarios that are described in Table 3.1. In all scenarios, future investments creating new capital were not considered given the study aim is to evaluate the size of the *existing* capital at risk in 2020 or 2030 in a rapid transition. As a result, there was an implicit idealisation that all future investment was made into a separate green economy which was net-zero compliant.

When no early retirements are considered, starting in 2020 (or 2030), produced brown capital was depreciated by annually ageing the stock and retiring capital again using the mortality function described by Schmalwasser & Schidlowski (2006), with the mean age of retirement set to the produced capital turnover timescale of the sector. The full distribution of service lives for produced capital is shown in Figure 3.2. For human brown capital, we assumed that in 2020 or 2030, value is distributed with age according to the discounted expected future wages of the currently existing workforce, as described above (Figure 3.2). Thereafter, we incremented retirements by annually ageing this population and removing human capital in line with its age-related retirement profile (Figure 3.2, Figure 3.3). This forms the basis for the Planned Retirement Scenario (PRS).

In each year both human and produced capital were pooled and the i'th sectoral GDP output, y_i, , was then calculated according to each sector's productivity, A_i, and total (human + produced) capital, K_i,

$$y_i = A_i K_i \qquad (1)$$

where A_i is estimated total factor productivity for the i'th sector. These productivities were derived from the start date values of K_i and y_i (provided in Supplementary Data) and were assumed constant post start date because they relate to legacy capital. Labour was represented explicitly through human capital and not as a separate factor of production. We note that the linearity implied in (1) is borne out in the World Bank estimates of GDP and total capital (World Bank, 2021; Jarvis and King, 2024). Emissions from each sector were then estimated by multiplying annual GDP values by the estimated sectoral carbon intensities described above.

To quantify the amount of capital that must be actively retired from the global capital portfolio to restrict emissions to a net-zero pathway, the predicted total emissions in any year were compared to the desired linear decline pathway leading to net-zero in 2050. Then an amount of capital, human and produced, was retired to reduce emissions to the desired level. Here, capital was prioritised for retirement according to its carbon intensity and age relative to service life (see Figure 3.2). The rationale for these selection criteria was that it is likely that capital with a higher carbon intensity would be retired first, as would capital closest to its end of service life. These two criteria were applied simultaneously following the multicriteria selection method of Ehrgott (2005). Retiring the highest carbon intensity and closest to end-of-life capital first minimises the total retired capital, thus also implicitly minimising the capital at risk value for any given pathway to net-zero. This strategy also maximises the time available to find solutions to avoid asset stranding. These additional retirements were incremented on top of the planned retirements detailed above, tracking sectoral capital values and ages accordingly. We refer to this retirement strategy as our Accelerated Retirement Scenario (ARS).

Uncertainty was estimated in our simulations by incorporating the effects of uncertainties in our initial sectoral values of capital, GDP, emissions, and in turn our estimates of carbon intensities and productivities, and performing a Monte Carlo analysis for each scenario ($n = 1000$) with these values randomised within specified ranges. Uncertainty in our starting values for global capital was derived from the standard deviation of the three available 2014 global produced estimates; WIOD, World Bank Wealth Accounts, and Penn World Tables (± 36 T$). Uncertainties in global GDP were taken from the standard deviation of the eight available global estimates presented in Jarvis & King (2024) (± 15 T$/yr). For industrial emissions, we replicated the 1σ confidence level reported in the Global Carbon Project (± 0.5 GtC) (Friedlingstein et al., 2022). The relative uncertainties in the sectoral carbon intensities and productivities were assumed to be the same as their global counterparts, which were estimated from GDP and emissions data using method of moments.

Table 3.1. The four scenarios we simulate, allowing us to compare the outcome of our Accelerated Retirement Scenario (ARS) to the Planned Retirement Scenario (PRS). For each scenario, we run four regional simulations: Global, China, United States, and European Union.

Scenario	**Transition start date**	**Capital retirement scenario**
PRS2020	2020	Planned Retirement Scenario
ARS2020	2020	Accelerated Retirement Scenario
PRS2030	2030	Planned Retirement Scenario
ARS2030	2030	Accelerated Retirement Scenario

3.2.3. Value at risk

The magnitude of capital stranding likely to occur in a net-zero scenario depends on many factors. This includes whether low-cost fossil fuel producers increase their production to reserve ratio to undercut higher cost producers (Mercure et al., 2018), whether capital can be retrofitted to be made compliant with new regulations (Zhang et al., 2021), and whether displaced workers are able to migrate to new regions or sectors to take-up new employment. The latter is particularly uncertain as workers may or may not be able to move to jobs in other sectors because of skill gaps or to other places due to inhibited spatial mobility. Furthermore, displaced workers may be able yet unwilling to move to different sectors or places due to place and job attachment. Even when workers do move, new jobs could be less well paid or less secure (Foden et al., 2014; Baran et al., 2020).

To attempt to accommodate these uncertainties, we do not make any assumptions about which capital can or will be adapted to be net-zero-compliant. Instead, we determine estimates of the value size of all potential early capital retirements, which we refer to as 'value at risk' (VaR). Similar approaches have been used by Dietz et al. (2016) and Battiston et al. (2017). By estimating VaR we avoid grappling with the broad spectrum of possibilities surrounding the potential to reduce this risk - both positive and negative - by focusing on the upper bound of this spectrum, the total portion of the economy that would need to be retired prematurely if nothing were done to make capital compatible with net-zero objectives.

VaR is the sum value of all prematurely retired capital in the year it is retired, discounted at an annual rate from the start year of the transition. We apply a discount rate of 6% and 1.5% to produced and human capital respectively, in line with what is typical in other studies (e.g., Lange et al., 2018; Semieniuk et al., 2022), to reflect the net present value of these retirements.

3.3. Results

Figure 3.2shows the aggregate service life distribution of produced and human capital. Human capital makes up 67% of global capital in 2020 with a range of expected service lifetimes centred around a mean of 28 years. This compares to a mean working life of 38 years (Figure 3.2), reflecting the historical trend (Ausubel & Grübler, 1995). The difference in these timescales is largely attributed to the time discounting within the human capital estimate along with the nonlinear age-median wage relationship we have assumed. Produced capital, meanwhile, is distributed around a mean lifetime of 46 years across the 56 sectors which is also consistent with the literature (Chester et al., 2024). From Figure 3.2 we conclude that there is a significant portion of both human and produced capital that turns over on timescales greater than the time remaining to achieve net-zero by 2050.

Figure 3.3 shows various limiting trajectories of total capital retirement globally, with and without carbon budget constraints, and with stringent climate policy action taking effect in 2020 or delayed until 2030. We estimate that, if no new investment was made in carbon-intensive capital from 2020 onwards, depreciating the current capital stock without early retirements results in an additional 444-763 GtCO_2 being released to the atmosphere by 2100. Simple projections of future growth suggest that delaying this action until 2030 increases the carbon commitment to 697-1038 GtCO_2.

Figure 3.3 also shows the trajectories for both total carbon-dependent capital and cumulative emissions consistent with achieving the 2050 net-zero objective. Again, we consider this capital in isolation from the green economy, investment in which we assume will continue and indeed grow significantly to replace retired existing brown capital. Here, following the ARS, a transition starting in 2020 has little impact on human or produced capital prior to 2040 through retiring near end-of-life, high carbon capital. Post 2040, by comparison, ever more capital must be retired from the carbon-dependent brown economy as both the proportion approaching retirement age and the sectoral carbon intensity fall as a result of prior retirements. In essence, the lower hanging fruit is picked first, and increasing quantities of capital are at risk of early retirement as the 2050 target nears and fewer emissions are removed per unit of capital retired. However, the ARS does not capture the fact that in practice, capital at risk later in the transition will benefit from greater time to adapt or otherwise mitigate the risk, and the transition will benefit from learning-by-doing (Farmer & Lafond, 2016; Matthews et al., 2018). Continued technological innovation, along with growing economic and political pressure, may result in actions that lower the VaR of early retirements or lessen their financial impact.

Figure 3.3 shows the trajectory of human capital distributed according to age during the 2030 transition shown in Figure 3.3. By 2050, the average age of the global workforce in the brown economy has risen from 28 to 50 years by curtailing recruitment at the start of the scenario. As a result, the final wave of enforced retirements from the carbon-dependent economy occurs relatively uniformly across the age profile.

Figure 3.3 shows the effects of the early retirements on the portion of remaining carbon-dependent brown capital in selected sectors relative to the business-as-usual case (PRS). The sectors shown are those which are retired first; these are predominantly sectors which have high carbon intensities, such as the electricity, transport and industry sectors. It is important to note that these sectors do not necessarily disappear but are instead progressively decarbonised as net-zero compatible assets in the green economy replace their carbon-dependent counterparts. However, the carbon savings from retirements in these sectors are not enough to meet the net-zero objective and so ever larger amounts of the remaining medium carbon intensity sectors become exposed. This assumes that the removal of the existing oil, gas and coal supply capital and its replacement with a net-zero supply does not fully decarbonise all other existing capital. Given the way capital inventories are compiled with the inevitable overlap of sectoral definitions, we believe this assumption correctly reflects the recalcitrant nature of residual emissions and the way they are distributed within the global economy. Furthermore, by using production-based emissions when defining sectoral carbon intensities, we are tying the carbon dependency of capital directly to their own fossil fuel combustion and not that of other sectors. We do not include the possibility that net-negative emissions technologies could reduce the risk exposure of existing capital with residual emissions, given that the deployment and effectiveness of those technologies remains speculative (McLaren, 2020).

Table 3.2 shows the global aggregate estimates of VaR for both human and produced capital, and the carbon emissions associated with presently existing capital in both planned and accelerated retirement scenarios. Table 3.3 provides similar estimates for three major economies: the United States, the European Union, and China. The ranges provided reflect uncertainties in our capital, GDP and emissions data and represent a 95% confidence interval around our results, as described in Section 3.2.2. Our PRS carbon emission estimates of 444-763 $GtCO_2$ and 697-1038 $GtCO_2$ reflect the global quantity of "committed carbon" in 2020 or 2030 respectively (Davis & Socolow, 2014). Unlike other such estimates in the literature - such as 658 $GtCO_2$ by Tong et al. (2019), who assume a "single reference lifetime of 40 years for all electricity-generating units", and 716 $GtCO_2$ by Smith et al. (2019), in a scenario where they also assume a 40-year lifetime for "energy and industrial capital" - our estimates include carbon committed through human capital. One might therefore expect our estimates to be higher; that they are not likely reflects the 15% of GDP not accounted for in our model, which represented around 26% of emissions in 2020.

If all future carbon-dependent investments were terminated in 2020, we estimate that achieving net-zero in 2050 would have required the early retirement of up to 117 T$ of capital value globally, or 11% of all capital in use in 2020. Achieving this target in individual economies would have required early retirement of 0-28 T$ of capital value in both the United States and China (0-10% of each country's 2020 capital), and 0-22 T$ of capital value (0-11% of 2020 capital) in the European Union.

Crucially, delaying an effective ban on new carbon-dependent capital investments until 2030 increases the total VaR substantially. Total VaR is 63-557 T$ (4-37% of 2030 capital) globally, 12-130 T$ (3-34%) in the US, 1-215 T$ (0-41%) in China, and 8-95 T$ (4-36%) in the EU. Therefore, even modest delays now make wait-and-see policies on decarbonisation considerably more costly in both absolute and VaR terms, especially for human capital, with a 10 year delay requiring the early retirement regime to be over 6 times as aggressive (Table 3.2 and Figure 3.3). Through making the financial penalties so much higher, delaying would also serve to further undermine the appetite to make the necessary transition away from brown capital investments. Moreover, the impact of a delayed transition is not spread equally. In per capita terms, VaR in the US (35-394 T$ per billion people) is vastly greater than in the EU (19-190 T$/bn ppl), China (1-153 T$/bn ppl) and the global average (8-71 T$/bn ppl), with the value at risk dependent on the size of the existing carbon-dependent capital stock in each country, as well as its age and sectoral composition (younger, longer-lasting and more carbon-intense assets generally contributing more value at risk).

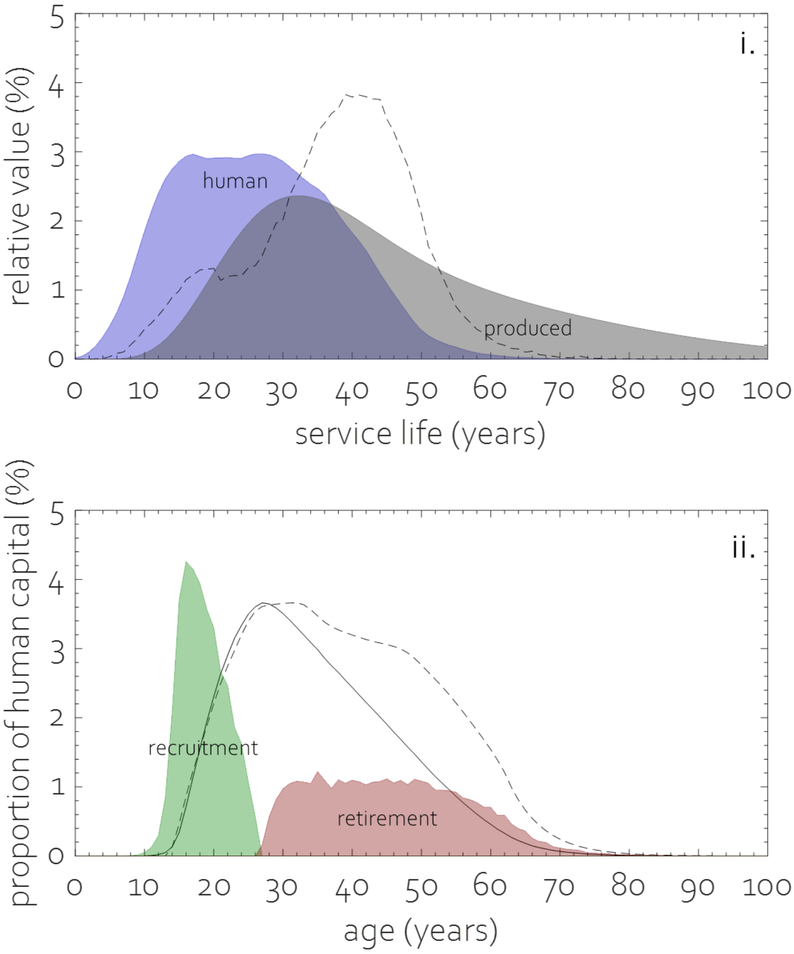

Figure 3.2. i. The distribution of relative value of human and produced capital with respect to the service life of that capital (see Sections 3.2.1.1 and 3.2.1.2). The working life of people is also shown (dashed). **ii.** A disaggregation of human capital with respect to workforce age (solid line) into net recruitment and retirement. The recruitment and retirement distributions give rise to the human capital service life shown in i. Also shown is the International Labour Organisation (ILO) global participation rate with respect to age 1990-2020 used to derive human capital and the working life estimates (dashed).

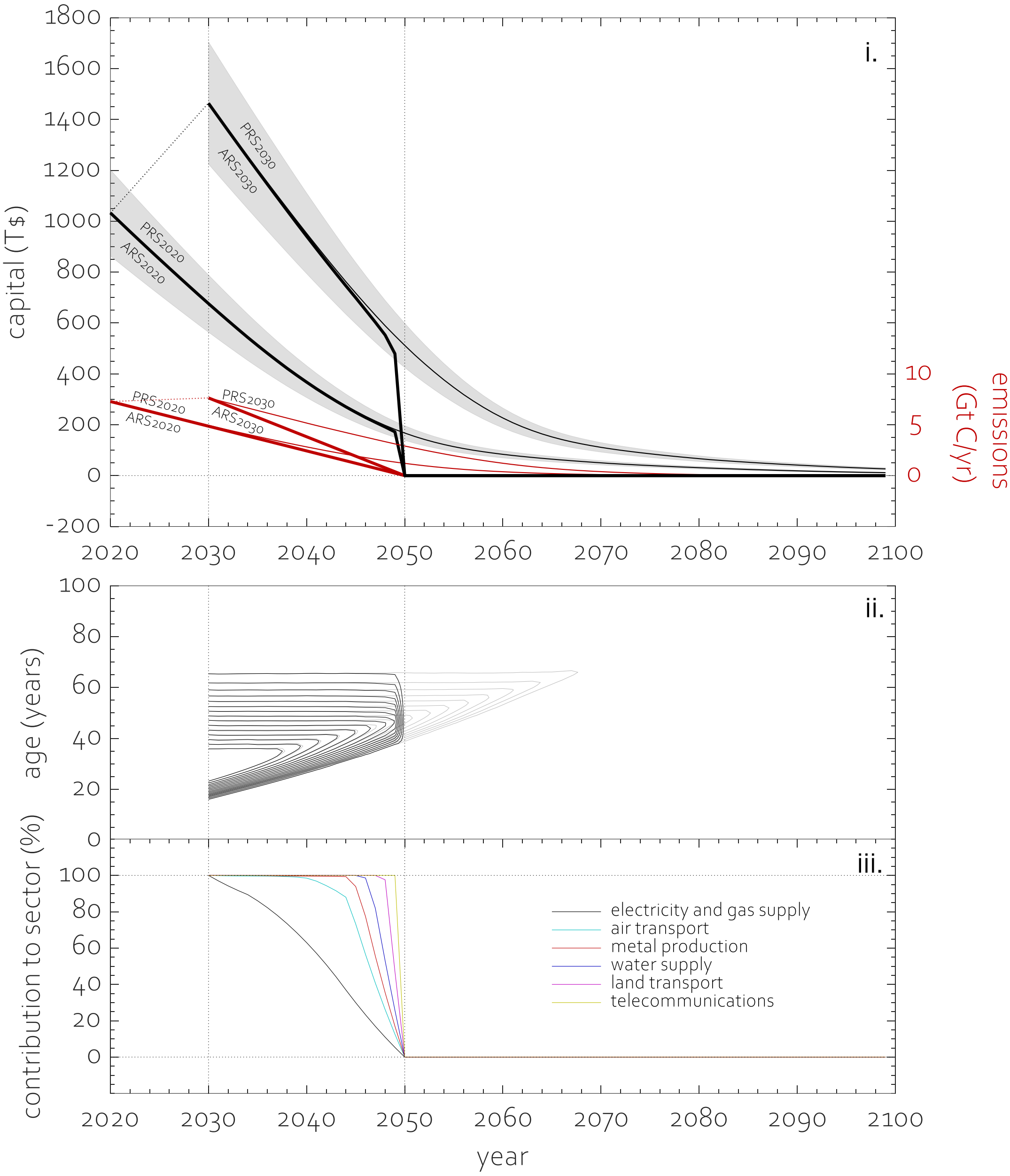

Figure 3.3. i. The evolution of total capital (black) and emission rate (red) for the ARS (2020–2050 and 2030–2050 net-zero) scenarios (thick) and their associated PRS (business-as-usual) conditions (thin). Uncertainties are 95 percentiles. **ii.** The evolution of global human capital age distribution for the ARS2030 (black) and PRS2030 (grey) scenarios. Contours represent 10 % increments of the overall stock of human capital. **iii.** Relative decrease in the capital value size of selected sectors for the ARS2030 scenario. See Methods for details.

Table 3.2. The cumulative end of century budgets for both carbon and capital Value at Risk (VaR) of early retirement for the four global scenarios shown in Figure 3.3.[1]

Start year	Scenario	Carbon added post 2020 or 2030	Capital Total	Capital Human	Capital Produced
		Gtc	T$ (% of start value)		
2020	PRS	121-208	0	0	0
	ARS	117	0-117	0-69	0-48
			(0-11)	(0-10)	(0-14)
2030	PRS	190-283	0	0	0
	ARS	148	63-557	45-399	18-158
			(4-37)	(4-38)	(4-35)

Table 3.3. The value of capital Value at Risk (VaR) of early retirement necessary to achieve a 2050 net-zero target in three major economies.

	2020 start (ARS2020)			2030 start (ARS2030)		
Country	Total	Human	Produced	Total	Human	Produced
	T$ (% of start value)			T$ (% of start value)		
China	0-28	0-19	0-9	1-215	1-169	0-45
	(0-10)	(0-9)	(0-15)	(0-41)	(0-41)	(0-39)
USA	0-28	0-18	0-10	12-130	9-99	3-31
	(0-9)	(0-9)	(0-11)	(3-34)	(3-37)	(3-29)
EU	0-22	0-10	0-11	8-85	5-53	3-32
	(0-11)	(0-9)	(0-14)	(4-36)	(4-38)	(3-33)

[1] *Post-publication note:* The ranges shown in Tables 3.2 and 3.3 are 95% confidence intervals.

3.4. Discussion

Our simulations show that the global value at risk of stranding in a net-zero transition may be much larger than what has been previously reported (Battiston et al., 2017; Caldecott, 2018; Mercure et al., 2018a). This is principally because of our consideration of human capital while previous studies focus only on produced capital. Our 'at risk' framing reflects the fact that significant portions of this risk could be mitigated through the way future investments in the net-zero economy are designed and implemented. In this sense, VaR is a maximum value of potential stranded asset exposure, and realised devaluation could be significantly reduced by a range of redemptive strategies. For instance, the VaR embodied in residential properties could be mitigated through the retrofit of insulation and electrification of heating (Muldoon-Smith & Greenhalgh, 2019). Meanwhile, human capital VaR could be mitigated through retraining and relocation, allowing displaced workers to take employment in the green economy.

The worst-case nature of VaR should not be confused with the uncertainty ranges given in our estimates of VaR. As noted in Section 3.2.2, these reflect uncertainty in the data used in our simulations, including uncertainties in our initial sectoral capital stocks, GDP and emissions, and therefore our sectoral carbon intensities and productivities. These are substantial and they result in wide ranges in our results. This is largely a consequence of poor availability of detailed, up to date data, particularly for capital stocks where we have needed to make extrapolations to the starting dates of our simulations. Data on the age structure of presently-existing capital is also limited, necessitating a retrospective simulation to construct this as described in Section 3.2.1.1. Further understanding of VaR and the inertia of economies requires the development, or publication where they already exist, of detailed sectoral and regional capital stocks and their age structure, which would allow the uncertainty in our results to be reduced significantly (Chester et al., 2024).

As noted in our discussion of Figure 3.3 in Section 3.3, a small share of total retired capital is responsible for most of the required emissions reductions, demonstrated by the markedly non-linear difference in capital trajectories between ARS and PRS in Figure 3.3, despite the linear decline in emissions over the same period. Like Tong et al. (2019), this leads us to conclude that the electricity, transport, and industry sectors offer the most cost-effective premature retirements. This encourages a strategy of targeting ambitious near-term climate policy in these sectors given their high rate of emissions per dollar of capital, reducing overall VaR and allowing more time to mitigate risk in less emissions-intense sectors, as discussed in the previous section. This will, however, require greater attention to be given to the challenge of residual emissions than at present (Buck et al., 2023).

Mitigating VaR will not be a trivial task. For produced capital, 'lock-in' and path dependency might make it particularly difficult to reduce VaR through retrofitting in some sectors, including the real estate sector (Muldoon-Smith & Greenhalgh, 2019) which, with a significantly lower than average capital turnover rate, is particularly vulnerable to stranding. Moreover, for human capital, as highlighted in Section 3.1, displaced workers face several barriers to moving jobs. This includes not only training and educational barriers, but also barriers in the housing market, where workers from post-industrial regions could be priced out of more affluent regions undergoing rapid growth in the green economy (Lux & Sunega, 2012; Martin et al., 2016). The mobility of workers is also impacted by place (Svobodova et al., 2021) and job (Baran et al., 2020) attachment. Given achieving net-zero by 2050 appears to expose very significant proportions of major economies to these risks, it appears critical that decision-makers consider this in the design of policies to redeem as much of current capital into the net-zero economy as possible, particularly human capital.

A systemic devaluation of human capital as a source of financial, political, and socioeconomic instability has not been substantially debated, and our results suggest that serious consideration should now be given to this issue. In practice, this corresponds to sizeable social groups whose occupations become exposed to the possibility of rapid obsolescence. This is where the accumulated value from either direct investment in training or through accumulated experience operating in carbon-dependent sectors, could be lost as it is not necessarily replaced by the skills and experience needed to operate a net-zero economy. This also suggests that many regions dependent on carbon-intensive capital could be at risk of post-industrial decline (Lynch et al., 2024; Snyder, 2018) as industry disappears and communities lose their livelihoods and identities (Baran et al., 2020). This significantly threatens any pursuit of a just transition. Identifying areas and communities at particularly high risk requires more regionally disaggregated approaches.

Despite the substantial threats posed by such devaluation, we argue this is no reason for inaction on climate change. This is not least because of the physical risks that climate change poses, to not only the financial sector but also to global biodiversity, human health, and livelihoods (TCFD, 2017; IPCC, 2018; NGFS, 2019). Furthermore, there is growing evidence to suggest that tipping points in the solar photovoltaic and electric vehicle transitions might have already been or are about to be reached (Lam & Mercure, 2022; Barbrook-Johnson et al., 2023; Nijsse et al., 2023), where climate policy is no longer needed to ensure rapid low carbon technology diffusion. Meanwhile, a low carbon energy system is likely to offer substantial cost savings over a fossil fuel-based system even when climate damages are ignored (Way et al., 2022).

Instead, a debate needs to quickly emerge on how to manage and plan not just investment in produced capital, but also skills, careers, and the labour force in general. Given the significant inertia that exists in the economy and the development and lifecycle of human capital in particular, it is possible that both unemployment and labour shortages could arise simultaneously in a rapid low-carbon transition. When allied with the considerable complexity in identifying retirement and redemption regimes that minimise these capital losses, planning in this space is likely to be challenging.

3.5. Conclusions

Significant portions of capital are at risk of premature depreciation in a net-zero transition and, whilst largely excluded from previous studies of stranded assets, human capital dominates the total value at risk. We find that even a modest delay to the end of carbon-intensive investment increases the VaR by a considerable extent, from a maximum risk of 117 T$ in 2020 to 557 T$ in 2030. The VaR framework we use highlights the uncertainty surrounding what capital will be stranded and what capital could be recovered through retrofits of produced capital or workers finding new employment. It is, therefore, a method to communicate the absolute maximum value at risk in the transition and the realised value could be less.

The substantial value at risk in a transition to net-zero is no justification for the obstruction of climate mitigation policy. We instead argue that prompt action to advance the transition – by ending investment in carbon-intensive capital and retiring capital in the most carbon-intensive sectors – is needed to minimise VaR. Obtaining more precise estimates of capital stranding in a net-zero transition will require a greater awareness of the fungibility of human capital; understanding the barriers and challenges that impact labour mobility. Approaches with greater spatial disaggregation will be needed to identify specific regions at high risk of post-industrial decline and socioeconomic instability deriving from capital stranding.

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Data availability

All data that support the findings of this study are included within the article (and any supplementary information files). The code that supports the findings of this study is openly available at the following DOI:
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CRediT authorship contribution statement

Daniel Chester: Conceptualization, Methodology, Visualization, Formal analysis, Data curation, Writing – original draft, Writing – review and editing

Cormac Lynch: Conceptualization, Methodology, Visualization, Formal analysis, Data curation, Writing – original draft, Writing – review and editing

Jean-Francois Mercure: Conceptualization, Methodology, Writing – original draft, Writing – review and editing, supervision, project administration, funding acquisition

Andrew Jarvis: Conceptualization, Methodology, Visualization, Formal analysis, Writing – original draft, Writing – review and editing, supervision, project administration, funding acquisition

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Supplementary material

Table 3.4. A list of the countries included in the study.

Countries	
Australia	Latvia
Austria	Lithuania
Belgium	Luxembourg
Brazil	Malta
Bulgaria	Mexico
Canada	Netherlands
China	Norway
Croatia	Poland
Cyprus	Portugal
Czechia	Republic of Korea
Denmark	Romania
Estonia	Russian Federation
Finland	Slovakia
France	Slovenia
Germany	Spain
Greece	Sweden
Hungary	Switzerland
India	Taiwan
Indonesia	Turkey
Ireland	United Kingdom
Italy	United States of America
Japan	

Table 3.5. A list of all sectors included in the study, and the associated produced capital turnover timescales and carbon intensities in the global 2020 simulations (see Methods). Tables containing initial data for all simulations are available in the supplementary data.

Sector Code (ISIC)	Sector Name	Produced capital lifetime (yrs)	Carbon intensity (Mt CO2/ Million $)
A01	Crop and animal production, hunting and related service activities	31.4	64.6
A02	Forestry and logging	29.2	8.3
A03	Fishing and aquaculture	30.5	2.0
B	Mining and quarrying	38.5	2.0
C10-C12	Manufacture of food products, beverages and tobacco products	35.4	56.1
C13-C15	Manufacture of textiles, wearing apparel and leather products	37.6	24.8
C16	Manufacture of wood and of products of wood and cork, except furniture; manufacture of articles of straw and plaiting materials	37.3	3866.9
C17	Manufacture of paper and paper products	35.0	26.8
C18	Printing and reproduction of recorded media	37.2	13.9
C19	Manufacture of coke and refined petroleum products	32.2	59.2
C20	Manufacture of chemicals and chemical products	33.5	156.0
C21	Manufacture of basic pharmaceutical products and pharmaceutical preparations	23.6	46.2
C22	Manufacture of rubber and plastic products	34.7	8001.7
C23	Manufacture of other non-metallic mineral products	36.6	9.2
C24	Manufacture of basic metals	30.6	112.1
C25	Manufacture of fabricated metal products, except machinery and equipment	31.4	383.3
C26	Manufacture of computer, electronic and optical products	23.5	46.4
C27	Manufacture of electrical equipment	24.8	11.5
C28	Manufacture of machinery and equipment n.e.c.	32.0	589.8
C29	Manufacture of motor vehicles, trailers and semi-trailers	26.7	26.0
C30	Manufacture of other transport equipment	32.4	2679.9

C31_ C32	Manufacture of furniture; other manufacturing	34.8	13.1
C33	Repair and installation of machinery and equipment	38.4	1067.2
D35	Electricity, gas, steam and air conditioning supply	37.6	1099.3
E36	Water collection, treatment and supply	38.2	22.0
E37-E39	Sewerage; waste collection, treatment and disposal activities; materials recovery; remediation activities and other waste management services	33.9	77.4
F	Construction	34.9	119.9
G45	Wholesale and retail trade and repair of motor vehicles and motorcycles	40.2	154.1
G46	Wholesale trade, except of motor vehicles and motorcycles	39.1	127.2
G47	Retail trade, except of motor vehicles and motorcycles	42.1	69.6
H49	Land transport and transport via pipelines	38.5	39.6
H50	Water transport	36.6	2291.8
H51	Air transport	32.6	56.7
H52	Warehousing and support activities for transportation	41.9	471.9
H53	Postal and courier activities	32.6	374.8
I	Accommodation and food service activities	40.9	124.1
J58	Publishing activities	36.6	167.4
J59_J60	Motion picture, video and television programme production, sound recording and music publishing activities; programming and broadcasting activities	30.2	342.1
J61	Telecommunications	31.1	7.2
J62_J63	Computer programming, consultancy and related activities; information service activities	31.6	40.0
K64	Financial service activities, except insurance and pension funding	34.2	71.7
K65	Insurance, reinsurance and pension funding, except compulsory social security	35.5	78.0
K66	Activities auxiliary to financial services and insurance activities	38.6	49.3
L68	Real estate activities	66.4	51.0

M69_ M70	Legal and accounting activities; activities of head offices; management consultancy activities	38.9	4.6
M71	Architectural and engineering activities; technical testing and analysis	41.9	5.8
M72	Scientific research and development	29.2	26.6
M73	Advertising and market research	36.2	34.6
M74_ M75	Other professional, scientific and technical activities; veterinary activities	35.5	42.7
N	Administrative and support service activities	35.4	570.7
O84	Public administration and defence; compulsory social security	33.9	12.0
P85	Education	41.4	172.2
Q	Human health and social work activities	41.9	197.6
R_S	Other service activities	35.4	1932.7
T	Activities of households as employers; undifferentiated goods- and services-producing activities of households for own use	32.4	33.1
U	Activities of extraterritorial organizations and bodies	27.0	25.2

Table 3.6. A list of the produced capital assets included in the study.

Asset Type	**Description**
Communications equipment	Hardware used for communication
Computer software and databases	Computer programs and files of organised data
Computing equipment	Information and communication technologies
Cultivated biological resources	Livestock and plantations of trees
Other Machinery and Equipment	Machinery and equipment not elsewhere classified
Research and development	Creative work to increase the knowledge stock
Dwellings	Buildings used for residential purposes
Other buildings and structures	Buildings and structures other than dwellings
Transport Equipment	Equipment used for moving people and things

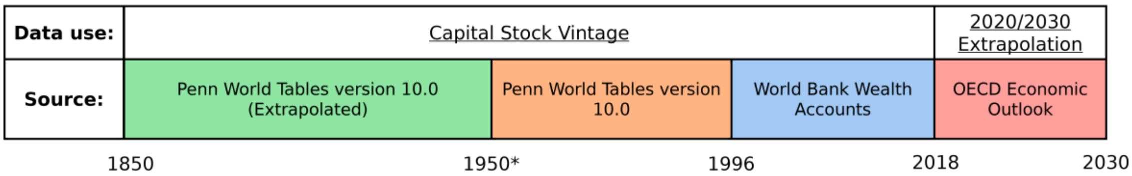

Figure 3.4. Visual representation of the data sources used to construct the regional and sectoral produced capital stocks between 1850 and 2020/2030 (not to scale). Data in the capital stock vintage period (1850-2018) are used in our simulation of the age structure of produced capital (Section 3.2.1.1). They are extrapolated to 2020 and 2030 to form the initial sectoral and regional capital stocks for our forward simulations (Section 3.2.2). *The start date of Penn World Tables data varies by country and is either 1950, 1960, or 1970.

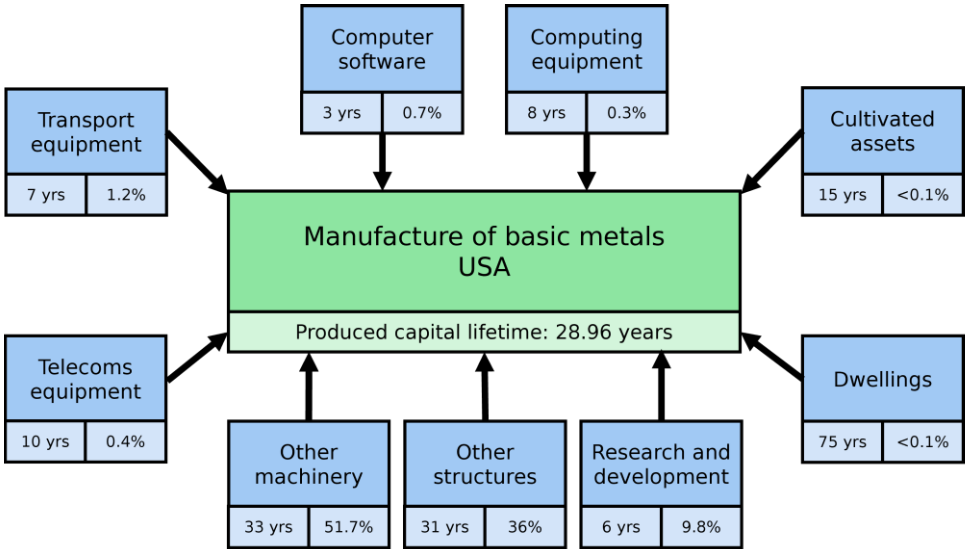

Figure 3.5. Example of the relative asset shares and service lives in the Manufacture of basic metals sector in the USA.

4. Are we consumers?

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Abstract

A consensus has long been held in national accounts that consumption – which accounts for around three quarters of economic output – solely serves current utility and is therefore an end point of economic activity, while investment creates capital which facilitates future output. However, in addition to the produced capital that conventionally results from investment, human capital is increasingly a feature of national accounts and this, by definition, must also be created by investment of output. Using available data on human and produced capital, and the standard backwards-looking account for capital inventories, we show that the scale of this investment is substantial – typically around twice that in produced capital – and the proportion of output potentially left over for entirely unproductive consumption once this is accounted for is at most small. This leads us to conclude that most of what we have traditionally seen as consumption is in fact 'productive consumption' – as conceived by early theorists of human capital, but at a greater scale than they imagined – consisting of short-lived intermediary investments leading to the creation of people's ability to operate in the future, across a broad range of timescales and with varying degrees of productivity.

4.1. Introduction

Both within economics and wider society it is taken as fact that people are consumers. This view is formalised in national accounting systems which, savings aside, partition the measured output of the economy between either investment or consumption, and the management of this partitioning is often understood to underpin economic decision making. The classical and neoclassical economics that has come to dominate that decision making extend this thinking to a belief that the behaviour of economic agents can be characterised as a continuous endeavour to maximise consumption through their investment decisions. Despite few people actually believing in such a rational, perfectly informed world, the picture this theory paints of people striving to quench ever expanding immediate needs and wants through consumption has become so pervasive that it is hard to imagine that people are anything but consumers. This view particularly comes into focus when people's apparent appetite to consume is blamed for the destruction of our planet.

By all accounts this consumption is a real phenomenon. Money is spent on goods and services, and the material input required for the production of these goods and services is driving the transgression of planetary boundaries (Sala et al., 2020; Tian et al., 2024). Individual consumers cannot necessarily be blamed for this, of course: there are structural drivers to overconsumption (heterodox, particularly Marxian, economists argue that overconsumption is rooted in overproduction, which is necessary to maintain corporate profits and prevent crises of capital accumulation (Akbulut, 2021; Curran, 2017; Pirgmaier, 2020), while advertising and the influence of business actors in politics serves to induce demand and create a social logic of consumerism (Jackson, 2016)). That consumption is so problematic and yet so endemic to capitalist economies increasingly leads sustainability researchers and activists to explore alternative economic systems entirely (O'Neill et al., 2018). The stakes are high therefore: the extent of consumption, and the distinction between investment and consumption activity, needs to be well defined.

This distinction initially appears relatively clear cut. Investment uses current output to create economic structures that persist into the future and, hopefully, produce future returns of more output. In contrast, consumption is the use of output to exclusively "satisfy current needs and wants" (Bannock & Baxter, 2011) without any implication for future periods. Framed in this way, unlike investment, consumption is "quite simply the end point of economic activity" (Marshall, 2017), affecting the forward evolution of the economy only through the demand it creates. The literature on productive consumption, however, challenges the notion that consumption plays no active role in generating future outputs, arguing instead that the satisfaction of current needs also plays into and simultaneously increases the productive potential of labour, both in the present and the future. This remains a key concept in development economics (Valencik & Wawrosz, 2019), especially in developing countries (Daitoh & Nishimura, 2021), reintroduced by Steger (2002) who cited empirical evidence suggesting a positive link between three forms of productive consumption – nutrition, health and education – and growth in both labour productivity and output. He hypothesised that consumption may either increase the stock of human capital or increase the efficiency of labour[2]. In contrast to the conventional narrative around consumption, productive consumption "acknowledges that a large part of human behaviour is related to the future" (Valencik & Wawrosz, 2019, p. 127) and that, just like investment in produced capital, consumption can be "focused on a long-term strategy of use of current

[2] Productive consumption in this form is distinguished from its earlier usage by Mill (1848) and Ricardo (1821), later developed by Marx (1867), who simply argued that consumption of means of subsistence by productive workers is productive consumption because it produces (surplus) value for their employers; it was not considered to add to the individual's long-term productive capacity.

income for the acquisition and use of assets, allowing for them to increase the current value of future income" (Valencik & Wawrosz, 2019, p. 127). Steger (2002) thus reframed the utility maximisation question as one dependent on the extent to which consumption is productive rather than to the extent of consumption versus investment, coining "net cost of consumption" to refer to "consumption less the human-capital-enhancement effect of consumption". According to Perrotta (2004, p. 2) "to say that an increase in human consumption increases productivity seems obvious", but yet "it is hard to find a full theorization of this principle in the main streams of economic thought".

If productive consumption does indeed lead to changes in future labour productivity and "increase the current value of future income" (Valencik & Wawrosz, 2019, p. 127), then this suggests it is an investment in human capital. This is by no means a new idea, in fact it was central to the thinking of early advocates of human capital such as Becker (1962), Mincer (1958) and Schultz (1961), and Pigou foresaw this when observing that;

"there is such a thing as investment in human capital as well as investment in material capital. So soon as this is recognised, the distinction between economy in consumption and economy in investment becomes blurred. For, up to a point, consumption is investment in personal productive capacity." (Pigou, 1928, p. 29)

Quantifying this investment in human capital is not straight forward however. Schultz (1961, p. 8) noted that while produced capital formation can be estimated in a relatively uncontroversial fashion by measuring the expenditures made to produce capital assets, human capital formation requires one to "distinguish between expenditures for consumption and for investment," a distinction which "bristles with both conceptual and practical difficulties". He speculated that while sometimes consumption could be assigned either to only satisfying current needs or to investment in the productive potential of labour, most consumption has both effects, making estimation of investments into human capital using a similar method as produced capital difficult and subjective. Nonetheless, human capital stocks began to be constructed using modelled accumulation of historical expenditure on education, training and healthcare, and in some cases nutrition and leisure activities (Steger, 2002; Suen & Mo, 1994; Valencik & Wawrosz, 2019). Kendrick (1976), for example, defined US human capital investment as the total of all education expenditure and half of all healthcare expenditure, and estimated it at ~25% of GNP in 1969, making it at least equivalent to the size of investments in produced capital. By implication, this significantly reduced the portion of US output that could be attributed exclusively to pure consumption.

In recognition of the importance of the value-producing investments that are collectively accumulated in people, the landmark 2021 World Bank Changing Wealth of Nations (CWON) report elected to develop simultaneous estimates of both physical and human capital. However, because of the conceptual complexities of defining past investments in human capital, they elected instead to use the income approach developed by Jorgenson & Fraumeni (1989) to generate their human capital estimates (World Bank, 2021). Unlike investment-derived (backward-looking) estimates of human capital stocks, the income approach is forward-looking, estimating human capital as the present value of the current workforce's expected future earnings (Fraumeni & Christian, 2020; Jorgenson & Fraumeni, 1989). This method has increasingly dominated human capital studies, in part motivated by the availability of robust income statistics at the national scale (World Bank, 2021).

Although there are significant regional differences, the World Bank estimates suggest that human capital dominates national wealth portfolios, far outweighing produced capital stocks. By implication, so too must the size of investment made in its creation must outweigh the creation of produced capital stocks, and given the quantities involved, therefore dominate national expenditure. If true, this would significantly erode the portion of output left over for unproductive consumption, suggesting instead a much more significant overlap between investment in human capital and consumption than historically thought (or, in Steger's (2002) terms, a much lower net cost of consumption). The adoption of forward-looking human capital valuation therefore has the unexplored potential to answer the longstanding debate about the true extent of productive consumption.

Using forward-looking valuations to estimate the size of past investments in human capital is not necessarily a radical leap. In the produced capital stock valuation mandated by OECD practice, convergence is assumed between the forward- and backward- looking valuations of capital (OECD, 2009).

"The central economic relationship that links the income and production perspectives to each other is the net present value condition: in a functioning market, the stock value of an asset is equal to the discounted stream of future benefits that the asset is expected to yield, an insight that goes at least back to Walras (1874) and Böhm-Bawerk (1891)." (OECD, 2009, p. 32)

The development of human capital accounts raises the question of whether the same can be said for human capital valuations. This question appears underexplored. Such an assumption of course requires the economy to be dynamically stationary such that all future returns materialise, and although that is clearly in error[3], given it underpins produced capital inventories, it seems reasonable to similarly explore investments in human capital through this lens. For example, if we accept the forward-looking human capital valuations of the World Bank and assume a stationary economy in line with OECD mandated practice on wealth accounting, then perhaps we can apply backward-looking inventory methods to these human

[3] Capital valuations across the entire economy are threatened by the climate crisis, for example (Chester, Lynch et al., 2024).

capital accounts in order to infer levels of investment in this human capital. Although the results will rest heavily on the imperfect assumption of convergence between the forward- and backward-looking perspectives, they will at least reflect current wisdom within the wealth and general accounting communities.

In this paper we attempt a valuation of historical investment in both produced and human capital – and thus determine the scale of consumption – by marrying the forward- and backward-looking approaches to measuring this capital. In Section 4.2 we generate an estimate for the overall turnover timescale and hence depreciation rate of produced and human capital, and we then use this in Section 4.3 to estimate the proportion of national output required to have been historically invested to create the stocks of produced and human capital in the G20 countries estimated by the World Bank from 1995-2018. This leads us to explore what it means for most of what is currently characterised as consumption to be considered investment in human capital, albeit with varying degrees of productivity, in Section 4.4. Section 4.5 reflects on the limitations of our findings and areas for further research, and Section 4.6 concludes.

Finally, before we proceed, perhaps it is also useful to reflect on why we would want to challenge the consumption narrative given its apparent widespread acceptance as a description of human behaviour, its alignment with the real and measurable loss of planetary resources, and the well-examined structural drivers that give rise to it? First and foremost our motives are scientific, trying to understand the dynamics of the economy and correct any mis-classification of economic activity, even if any correction is simply categorical and set within the norms of accountancy practice. However, as we will attempt to unpack in our discussion of the results in Section 4.4, we see wider utility in reviewing our understanding of consumption. Given that a predominant focus of ecologically-minded economic policy is reducing consumption, for example, it is vital to understand the extent to which consumption is productive and therefore explore the effects of reducing consumption on future human potential. Moreover, given the way that 'investors' seem to be attributed more agency in our understanding of the economy than 'consumers', the classification of economic activity may not only be categorical but also carry important normative implications.

4.2. Methods overview

Investment-driven estimates of the annual turnover of produced capital stocks traditionally lean on the conservation of capital defined by the perpetual inventory method (OECD, 2009). Here annual changes in capital value, ΔK, of a given stock are determined by

$$\Delta K = I - D = I - dK \qquad (1)$$

where I is the annual investment into this stock ($\$/\mathrm{yr}$), D is the annual depreciation of this stock ($/yr), and d is the representative depreciation or decay rate (yr^{-1}) of the pool of assets comprising the stock. Here we aim to apply equation (1) to *both* produced and human capital stocks to estimate levels investment required to account for the annual changes in the World Bank capital wealth data based on known depreciation rates.

For produced capital this is no more than exercising the same backward-looking inventory approach used to create the World Bank stocks. For human capital it applies an assumption that the forward-looking World Bank stocks can be equated to past investments and retirements in a similar backward-looking fashion to produced capital, reliant, of course, on the idea that the economy is stationary and the expected returns on this capital always materialise. The seemingly radical equivalence we draw between produced and human capital is not without epistemological challenges, and this is one, but it is an approach that has precedent (Judson, 2002) and we feel that with all due cognizance of the limitations (discussed in Section 4.5), we believe valuable insights can be gained from it. Perhaps as a result of human capital turnover rarely being put in these terms (despite backward-looking valuations being central to original theories of human capital as discussed in the previous section), or the novelty of national accounts-compatible human capital stock estimates now being available (and routinely added to produced capital to estimate total national capital stocks), we feel that equation (1) has been under-utilised for analysis of human capital, and in particular its potential to reveal the levels of historical investment implied by available human capital data has been overlooked. Perhaps another barrier to such an analysis is available estimates of the representative depreciation rate of human capital (Jones & Chiripanhura, 2010), which we will now explore.

4.2.1. Turnover of produced and human capital

Given estimates of K and ΔK, we can produce estimates of I for both produced and human capital if the representative depreciation rate, d, is known for each stock. In this section we will derive our own values of d to enable us to estimate I. This is a necessary and worthwhile endeavour, but our methods and findings regarding I can be well understood without this section; if you are willing to take our estimates for d as read, feel free to proceed to Section 4.2.2.

As we transition from single assets to entire economies the retirement dynamics of produced capital are assumed to tend towards being geometric (OECD, 2009), and hence d becoming a constant, representative of the aggregate depreciation rate of a given pool of capital (Abadir & Talmain, 2001; Chester et al., 2024). Perhaps what has precluded the use of the capital conservation equation in human capital evaluations is a lack of consensus over the rate of human capital depreciation, or over the idea that it depreciates exponentially (Arrazola & Hevia, 2004; Dinerstein et al., 2022; Weber, 2008, 2014). As a result, human capital is often neglected in studies of capital depreciation (Chester, Lynch et al., 2024). However, not only do people leave the workforce when they retire, taking their productive capacity with them, they also can suffer premature retirements through ill health and accidents. They also tire more easily with age, although often they are able to compensate for this through increasing skill. They also have the capacity to forget acquired skills, or the skills they have can become obsolete, hence the need for refreshment training (Judson, 2002). These capital survival processes might be described by an array of 'survival functions', just as they are for produced capital, and as with produced capital, we might assume that when aggregated to the scale of entire economies these decay processes tend toward being geometric, described by representative depreciation rates. It is also valuable to appreciate that d is the inverse of the expected turnover timescale of a stock, $T = d^{-1}$ (Chester et al., 2024), where T reflects the average amount of time a unit of capital spends in the pool of the stock before being retired. As such, T is a measure of the working lifetime of capital in years (Chester et al., 2024). This is perhaps a more intuitive way to picture the turnover of human capital, though it is crucial to note the difference between the lifetime of the stock of *human capital* value, which we are describing here (a function of earning potential, which will change over the working lifetime of any given worker), from the length of an average working life.

For produced capital we are able to utilise the same values of d used in the construction of the World Bank capital stocks which will form the backbone of our investment analysis (see next section). These are provided by the Penn World Tables (PWT), the World Bank's source of produced capital stocks (Feenstra et al., 2015; World Bank, 2024). PWT allocate capital to one of 9 asset classes and depreciate them at different rates, but in their dataset provide annual produced capital depreciation rates on a nationally aggregated basis, which we assume as our estimate for d. These are shown in their timescale form T in Table 4.1, ranging from 18.2 years (China) to 32.8 years (Australia). To reflect the difficulty of estimating capital stocks and their depreciation, we adopt an uncertainty range for our produced capital depreciation rates based on the standard deviation of each country's 1995-2018 annual depreciation rate estimates.

For human capital, however, because the World Bank capital stocks are constructed from future wages rather than through the use of equation (1), we are required to look elsewhere for human capital depreciation rates. In response to the lack of consensus in the literature over such rates, and our requirement for data which is individually applicable to the G20 countries (in addition to global estimates) and ideally updated at annual intervals over a 24-year period – richer data than are currently available in the literature – in this paper we derive our own estimates of the human capital representative depreciation rates rather than screening for published values.

We start by constructing a pool of human capital that reflects the likely age structure of currently existing human capital based on a combination of workforce participation rates and average earning profiles (Figure 4.1i). This gives us two options for determining T. We can compare the rates of entry and exit from this pool (investment and depreciation of capital respectively) to estimate the average service life of capital – the average amount of productive time spent in the economy – or we can simulate the turnover of this pool with no new investment (i.e. with equation (1) reduced to $\Delta K = -dK$) which will reveal a representative depreciation rate through the initial relative decline in capital, which reflects the aggregate turnover dynamics of that pool. Ideally the service life and representative depreciation rate should be aligned (through $T = d^{-1}$), but because mapping between the spectrum of turnover timescales in a pool of capital and its representative timescale is complex and we are mindful of the real world limitations of these methods (see Section 5), we compare both methods and use the average difference between their outcomes for each country as a measure of uncertainty in our human capital depreciation rate estimate.

We construct our dynamic inventory describing the turnover of human capital as follows. Following Chester, Lynch et al. (2024), we estimate net recruitments to and net retirements from a given workforce through the first difference of the relevant International Labour Organisation (ILO) 1995–2018 age to workforce participation rate data (Figure 4.1i). For some G20 countries these data are missing for some years; we linearly interpolate to fill these gaps (for China only two years are available and we apply the average of these for all years). We then sample each of these two distributions to derive an estimate of the average working lifetime for this workforce (retirement age – recruitment age) on the assumption that there is no correlation between net recruitment and net retirement age and that the distribution of their sampled difference is representative of working lifetimes. From this we aggregate time-discounted future wages over these working lifetimes using available data on median US (Kiersz et al., 2020; Ruggles et al., 2024) and UK income by age (Francis-Devine, 2023; ONS, 2023). This produces an estimate of the age distribution of human capital (Figure 4.1i). This approach is consistent with, and effectively reverses, the income-based World Bank method for human capital valuation based on Jorgenson & Fraumeni (1989) (World Bank, 2021), with the advantage that it yields a full distribution of human capital with respect to workforce age. Now that our distribution represents the value of human capital at each age rather than the rate of workforce participation, the mean of the sampled lifetimes of capital is the mean service life of human capital – a measure of T – rather than the average time a worker spends in the workforce.

We then repeat the first step, differentiating the now human capital-age relationship with respect to age to get the depreciation rate-age relationship shown in red in Figure 4.1ii. We then simulate the future turnover of our human capital portfolio with no creation of new capital, only depreciation, which we conduct by annually aging the stock and removing capital at the rate implied by the depreciation function for that age. The pool of human capital ages and shrinks over time (Figure 4.1ii) and is near-zero after around 50 years (Figure 4.1iii). We derive an estimate of the representative depreciation rate, d, of the entire human capital stock from the first difference of the log of its simulated depreciation. We take just the first years estimate from this simulation as it relates closest to the pool of human capital we are interested in given in time that pool becomes depleted in younger capital. The average of these for each G20 nation (inverted in the form T) is shown in Table 4.1, alongside the average service life estimates.

We are reassured that the depreciation timescales and service lives we have derived for human capital are remarkably similar for each country, as expected, with the exception of China and Saudi Arabia (Table 4.1). Depreciation timescales for all countries average around 30 years, which is notably shorter than average human working lifetimes which have hovered at around 35-40 years throughout modern history (Ausubel & Grübler, 1995; Eurostat, 2024), but human capital depreciates at a disproportionate rate relative to retirement from the workforce for the reasons explored above. China and Saudi Arabia exhibit similar human capital depreciation timescales to other countries but their service lives are over a decade longer; these outliers are most likely a reflection of the poor data quality in these countries.

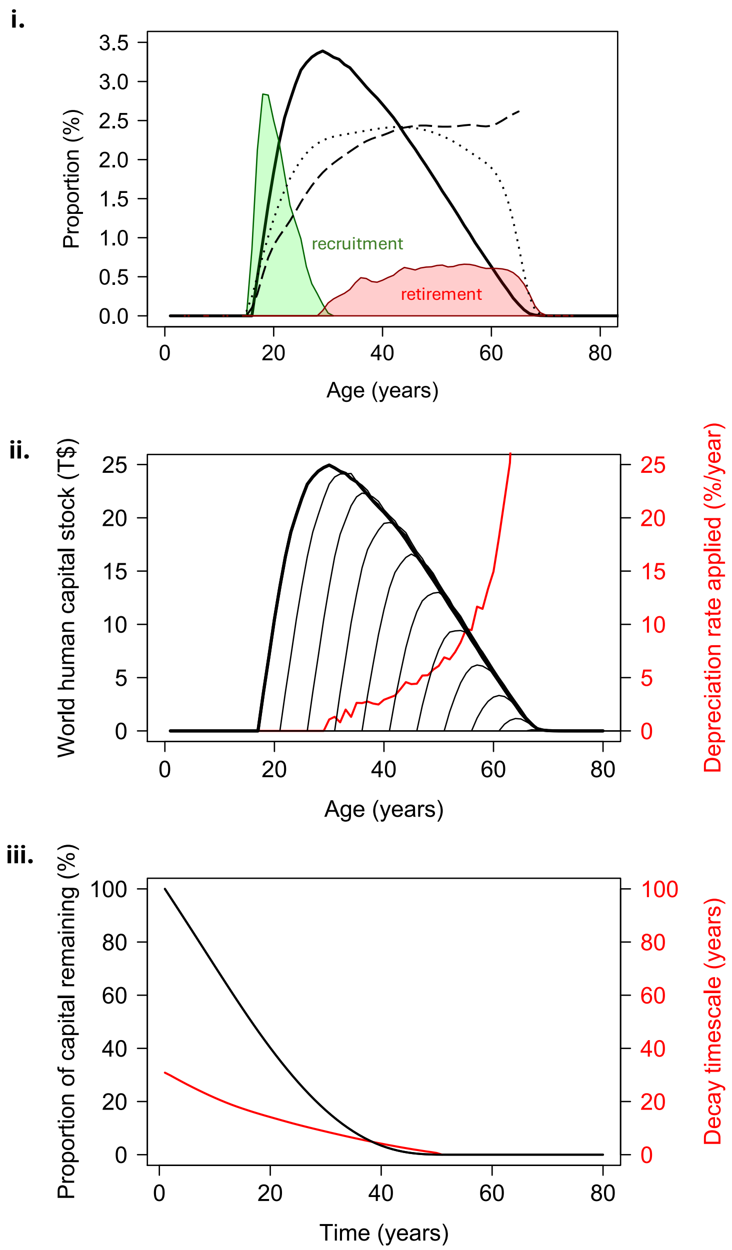

Figure 4.1. i. The distribution of human capital with respect to workforce age (solid line), disaggregated into net recruitment (green) and net retirement (red) likelihoods per Chester, Lynch et al. (2024). Also shown are the distributions of workforce participation (dotted line) and average earnings (dashed line) with age which are used to construct the human capital distribution. **ii.** The distribution of the global stock of human capital 1995-2018 (thick black line) with respect to workforce age, and its evolution over time in our depreciation simulation shown at 5-year intervals (thin black lines). The depreciation rates used to depreciate the capital at each age is shown in red. **iii.** The depreciation of the total stock over time from the depreciation simulation (black line). The first difference of the log of the total stock in year zero – the instantaneous depreciation rate – is taken to be the turnover timescale of the capital (30.9 years). Although not relevant for this purpose, the onward evolution of this timescale is shown in red for reference.

4.2.2. Implied investment in produced and human capital

Rearranging the capital conservation equation 1 gives the size of the annual investments in capital creation, I, as

$$I(t) = K(t) - (1 - d)K(t - 1) \qquad (2).$$

We source annual estimates of produced and human capital stocks 1995-2018 from the World Bank CWON report (World Bank, 2021), while d is established in section 4.2.1 above. To reflect uncertainty in our data and analysis structure we perform a Monte Carlo analysis ($n = 10^3$). Here uncertainty in the World Bank capital stocks themselves is estimated from the standard deviation of the three available capital stock estimates (WIOD, World Bank Wealth Accounts, and Penn World Tables) as per Chester, Lynch et al. (2024). Uncertainty in the representative depreciation rates of these stocks, d, is described in Section 4.2.1. Because equation 2 is in effect a high pass filter, hence amplifying noise in the WB human and produced capital time series data, our estimates of I also include an amplification of the annual variability in the WB capital stock data. Finally, we compare our annual investment estimates to the World Bank constant (2018) GDP (MER) series 1995-2017 to evaluate the proportion of output being accounted for by produced and human capital investments. Here uncertainty in the GDP data is taken from Jarvis & King (2024) who compare eight available constant global GDP estimates.

4.3. Results

Our resulting estimates for the average annual investment in produced (I_p) and human (I_h) capital over the 1995-2017 period for the global economy and for the G20 countries are summarised in Table 4.1. Investment in human capital is typically around twice the amount of investment in produced capital, which is reflective of the relative size of their stocks (global human capital is 1.41-2.74 times the size of global produced capital over this period, while investment in it is 1.19-3.58 times greater), but both show significant variation between individual countries. Coupled with the cautious approach we have taken to uncertainty in our methods and the high pass filter effect discussed above which contribute to wide country-specific confidence intervals, we find that total annual capital investment (produced and human) may vary from as little as a third to over four times national output, though this ratio typically falls between 0.5 and 1. We briefly suggest here a number of theories for this variability, and for the apparent paradox of greater than 100% of output being invested (a scenario which our results suggest is more likely than not in China, India and Indonesia), but further discussion of methodological issues and uncertainty can be found in Section 4.5.

First, the conservation equation and our comparison to national GDP assume a closed system in which there are no gains or losses to the national capital stock beyond creation and natural depreciation of capital, but in reality capital and investment are able to cross national borders, both through foreign direct investment and through the movement of physical capital and workers. This is a weakness of our method: net inflows of capital investment will inflate estimates of investment in proportion to national GDP, and net outflows will have the opposite effect. Our global analysis, on the other hand, is not subject to these effects and here we see total investments account for 83 percent of output on average. Capital stocks can also increase not through investment but through one-off endowments, for example workers leaving the subsistence economy and entering paid employment, as the former is poorly captured by capital stocks and GDP estimates. Even the global economy is not a closed system therefore, but the effect of this is likely to be more pronounced at a country level than globally, and more pronounced in developing economies.

While these effects may explain some of the outliers in Table 4.1, significant differences exist in the portion of output spent on investment even between economies at a similar level of development and with a similar balance of payments. These differences might enlighten us to the state of each economy and economic policy being pursued there. Some countries appear to be habitually low investors in both human and produced capital, for example the United Kingdom whose investment of 0.22 and 0.18 respectively languish behind comparative economies for decades (Dibb & Jung, 2024). We also note a broad inverse correlation between investment levels and productivity (also included in Table 4.1) which suggests that countries with low productivity may be compensating for this with increased investment; countries which are doing neither, such as the UK and Japan, appear to be suffering the consequence of this through stagnating growth.

Depreciation rates (taken as T^{-1} from Table 4.1) will also factor into the level of investment. High turnover capital such as Chinese produced capital (average lifetime 18.2 years) will naturally require replacement at a faster rate. In this way greater depreciation demands greater like-for-like investment to sustain the same levels of capital.

While the differences between countries are interesting, our most notable finding is that total investment ($I_p + I_h$) accounts for most, if not all, of output expenditure globally – our most reliable geography – and in most countries. Figure 4.2 demonstrates our uncertainty in the exact amount, but the most likely outcome is that investment forms 83 percent of total GWP, suggesting net-consumption is of the order of just 17 percent, with an 18 percent chance that it could actually be zero.

This is as intuitive as it is radical: if a quarter to a third of annual output is invested in produced capital, and human capital is also constantly being created and forms a stock twice the size, investment in capital must dominate output. Where does this leave consumption? We are conventionally told that consumption forms the majority of output expenditure – such is the basis of the rational optimiser. Instead, our results indicate that the share of output invested in human capital accounts for most of the share that is typically attributed to consumption, which would seem to leave little to no room for consumption. Thankfully the theory of productive consumption gives us a way to reconcile this contradiction, but the evidence presented here leads us to a radical conclusion: that almost all consumption is productive and hence investment. That to consume is, for the most part, to invest.

Table 4.1. Average annual investment in produced and human capital as a share of GDP, 1995-2017, average capital timescales (T) used to depreciate capital (equation (2); $d = T^{-1}$), average human capital service lives for comparison (see section 4.2.1), and average total factor productivity (the average ratio of total capital to output) for reference. All are best estimates, with 95 confidence intervals shown in brackets.

Country	Investment share of output			Capital timescales (yrs)			Productivity (%)
	Produced	Human	Total	Human		Produced	
				Depreciation timescale	Service life	Depreciation timescale	
Argentina	0.18 (0.14 — 0.23)	0.39 (0.31 — 0.5)	0.57 (0.46 — 0.71)	28.7 (27.5 — 29.9)	29.8 (28.5 — 31.1)	31.3 (24.9 — 42.4)	12.8 (9.4 — 17.6)
Australia	0.37 (0.29 — 0.47)	0.57 (0.44 — 0.72)	0.93 (0.76 — 1.16)	28.2 (27.5 — 28.9)	28.8 (28.1 — 29.5)	32.8 (26.5 — 42.8)	7.1 (5.2 — 9.7)
Brazil	0.25 (0.19 — 0.33)	0.63 (0.47 — 0.84)	0.88 (0.67 — 1.15)	27.8 (26.8 — 28.9)	28.9 (27.8 — 30.1)	21.0 (16.2 — 30.0)	8.6 (6.3 — 11.8)
Canada	0.29 (0.23 — 0.36)	0.62 (0.5 — 0.77)	0.91 (0.75 — 1.1)	29.6 (28.8 — 30.4)	30.4 (29.6 — 31.3)	28.0 (26.0 — 30.4)	6.4 (4.7 — 8.8)
China	0.66 (0.53 — 0.82)	2.73 (2.19 — 3.39)	3.4 (2.78 — 4.15)	39.4 (29.2 — 60.9)	29.2 (23.1 — 39.4)	18.2 (16.3 — 20.6)	4.5 (3.3 — 6.2)
France	0.25 (0.19 — 0.31)	0.37 (0.29 — 0.47)	0.61 (0.49 — 0.76)	25.7 (24.9 — 26.5)	26.5 (25.7 — 27.3)	29.4 (25.0 — 35.8)	8.3 (6.1 — 11.4)
Germany	0.25 (0.2 — 0.32)	0.36 (0.29 — 0.45)	0.61 (0.51 — 0.74)	29.1 (28.2 — 30.0)	30.0 (29.1 — 31.0)	27.6 (25.3 — 30.4)	8.3 (6.0 — 11.3)
India	0.72 (0.51 — 0.99)	1.77 (1.23 — 2.46)	2.5 (1.96 — 3.18)	30.3 (28.8 — 32.0)	32.4 (30.6 — 34.3)	21.3 (13.1 — 56.1)	10.2 (7.5 — 14)
Indonesia	0.51 (0.4 — 0.64)	0.7 (0.54 — 0.9)	1.21 (0.96 — 1.51)	30.5 (29.2 — 32.0)	32.1 (30.6 — 33.8)	22.4 (18.1 — 29.3)	7.5 (5.5 — 10.2)

Italy	0.23 (0.18 — 0.29)	0.22 (0.18 — 0.28)	0.45 (0.37 — 0.55)	27.0 (26.2 — 27.9)	27.9 (27.0 — 28.8)	27.1 (24.5 — 30.1)	10.1 (7.4 — 13.8)
Japan	0.23 (0.18 — 0.29)	0.25 (0.2 — 0.32)	0.48 (0.39 — 0.6)	27.8 (26.9 — 28.8)	28.8 (27.8 — 29.9)	24.0 (21.3 — 27.5)	9.4 (6.9 — 12.9)
Mexico	0.24 (0.19 — 0.3)	0.29 (0.23 — 0.36)	0.53 (0.43 — 0.64)	29.8 (28.7 — 31.0)	31.0 (29.8 — 32.4)	28.0 (23.9 — 33.8)	12.1 (8.9 — 16.6)
Russia	0.35 (0.24 — 0.49)	0.46 (0.36 — 0.58)	0.81 (0.62 — 1.04)	26.0 (23.4 — 29.3)	29.3 (26.0 — 33.5)	32.0 (25.4 — 43.3)	6.9 (5.0 — 9.4)
Saudi Arabia	0.28 (0.2 — 0.39)	0.26 (0.13 — 0.41)	0.54 (0.34 — 0.79)	26.4 (20.8 — 36.3)	26.8 (21.0 — 37.1)	21.2 (13.9 — 44.6)	14.4 (10.6 — 19.8)
South Africa	0.19 (0.13 — 0.26)	0.33 (0.23 — 0.45)	0.52 (0.37 — 0.7)	37.1 (37.0 — 37.3)	26.5 (26.4 — 26.5)	18.9 (13.4 — 32.0)	13.8 (10.1 — 18.9)
South Korea	0.39 (0.31 — 0.5)	0.54 (0.42 — 0.69)	0.93 (0.75 — 1.16)	28.1 (27.1 — 29.2)	27.1 (26.1 — 28.1)	20.9 (16.9 — 27.4)	10.0 (7.3 — 13.7)
Turkey	0.23 (0.18 — 0.3)	0.08 (0.07 — 0.11)	0.32 (0.26 — 0.4)	27.8 (26.9 — 28.7)	28.7 (27.8 — 29.7)	20.1 (16.0 — 26.9)	33.0 (24.1 — 45.1)
United Kingdom	0.18 (0.14 — 0.22)	0.38 (0.31 — 0.47)	0.56 (0.46 — 0.68)	29.2 (28.2 — 30.3)	30.3 (29.2 — 31.5)	27.0 (24.9 — 29.4)	9.9 (7.2 — 13.5)
United States	0.26 (0.2 — 0.35)	0.62 (0.47 — 0.82)	0.89 (0.68 — 1.14)	29.4 (28.3 — 30.6)	30.6 (29.4 — 31.8)	25.6 (19.8 — 36.1)	6.9 (5.0 — 9.4)
World	0.28 (0.21 — 0.37)	0.58 (0.44 — 0.76)	0.87 (0.67 — 1.11)	29.7 (28.6 — 30.9)	30.9 (29.7 — 32.2)	24.1 (18.4 — 34.9)	8.1 (6.0 — 11.1)

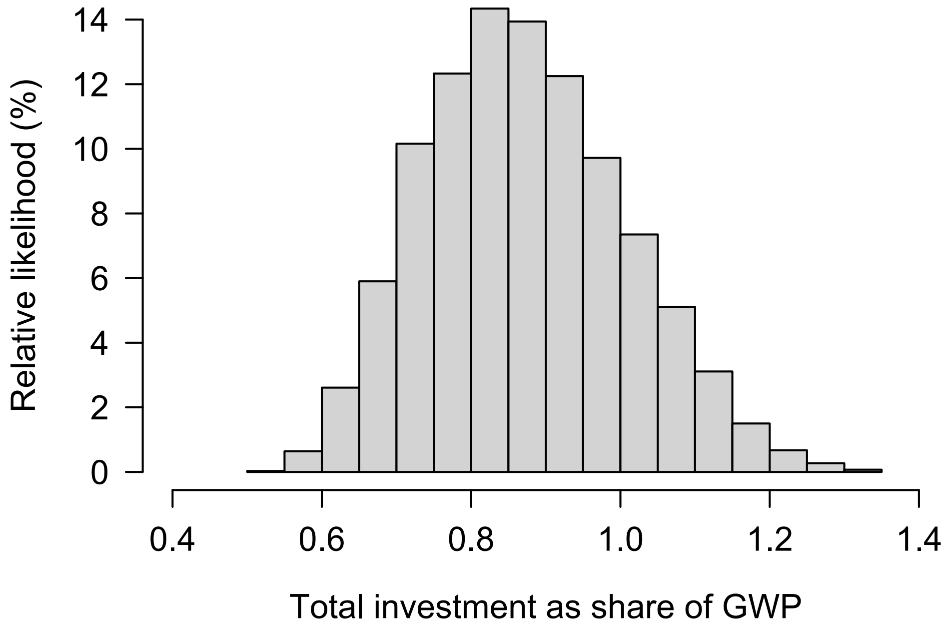

Figure 4.2. Monte Carlo estimates for the average annual global investment in produced and human capital as a share of gross world product (GWP). 95% confidence intervals are reported in Table 4.1.

4.4. Rethinking consumption as investment

Our findings not only support Pigou's statement that "up to a point, consumption is investment in personal productive capacity" but encourage us to radically reconsider where we consider the 'point' of distinction to be: almost all consumption, in fact, appears to be investment in personal productive capacity. How can we understand this, when consumption so typically manifests as an immediate expenditure? We suggest that investment in human capital largely takes the form of shorter-lived intermediary expenditures, invariably mislabelled as consumption because their ultimate productive purpose is obscured from immediate view. The literatures on consumption behaviour and social capital highlight many forms of consumption that have long-term effects on the consumer/investor, but which are not recorded as investment in mainstream economics and national accounting. These typically centre on healthcare, education and nutrition, as discussed in Section 4.1, but more unexpected examples abound: Suen & Mo (1994) note that "children [and expenditure on them] contribute to parents' satisfaction, as well as income security at old age" (Ehrlich & Lui, 1991), while clothes are valued for career concerns, not just personal satisfaction (Hamermesh et al., 2002). The latter, indeed, can exemplify well the value of positional goods: value derived not just from their direct utility but by their relative scarcity and social signalling (Frank, 1985; Schneider, 2007). A cup of coffee, indeed, may seem like a trivial, short-term act of consumption, but it provides energy for other tasks that may themselves produce or further stimulate production of human capital value. Human capital theory would suggest that the average increase in wages over the course of a working lifetime measures the return on this investment, although likely imperfectly given this investment is rarely restricted to the individual but likely benefits others and vice versa through network interactions.

In many cases these intermediary investments will contribute to a chain of investment that ultimately result in the creation of human capital. For example, fuel for a car will facilitate the buying of groceries which in turn facilitates the cooking of a meal, which provides energy for study or work; similarly the aforementioned cup of coffee can amplify all of the above. In some ways this is a natural continuation of the idea that capital is "nothing but the complex of intermediate products which emerge at the various stages on the roundabout journey of production" (Böhm-Bawerk, 1891), but acknowledges that one final outcome can be the production of value embedded in human beings. This makes any specific estimation of the human capital impact of any given unit of consumption near impossible, not least because these investments also invariably interact with and rely upon produced capital to realise their value, as well as other human capital and potentially natural capital, reminding us that produced and human capital are not separable, non-interacting stocks. Humans are intensely networked, and their human capital value is largely derived from their connection to other productive structures, from baristas to teachers and from computers to cars; investment in ownership or proximity to any of these may develop (or hinder) their human capital value. The compartmentalisation of different types of capital into separate stocks is necessary to enable any form of valuation – this challenge presents itself within stocks as well as between them, for example it is difficult to suggest that the value of cars is unrelated to roads, or that trains are unrelated to their tracks, any more than they are to their drivers – but it is a crude tool that, viewed in this light, the idea of consumption is clearly stretching to its limits.

What of immediate needs then, and Steger's intertemporal trade-off? If we only invest do we not service our needs, which keep us going from one day to next? Our findings encourage us to ask in response: what is the difference between an immediate need and a short-lived investment (required to fill a space vacated by the depreciation of previous short-lived investments?). Our bodies and our minds are not static but are continually evolving entities – with philosophers left to ponder what it is that truly remains (Mix, 2022) – and we survive (and thrive) by continually replacing and adding to ourselves. On some level this is just maintenance, but even maintenance can be considered investment, it is simply a matter of timescales – in this case short-lived investments which will need imminent replacement, as compared to delayed gratification achieved through longer-term investments (indeed as Schultz (1961) noted even in the early days of neoclassical human capital theory, consumption can sometimes achieve both at the same time, or its effects can be hard to distinguish). This is just as true in the realm of produced capital. Physical structures are invariably a composite of many component parts with widely varying lifetimes needing continual replacement to keep the overall structure functioning, each of which can be considered investments over heterogenous timescales (Chester et al., 2024). However, in conventional accounting a dividing line is drawn between investment in capital, which lasts a year or more, and consumption, which disappears quicker and therefore need not bother capital stock inventories – a line which is arbitrarily imposed by the annual or quarterly accounting cycle[4]. Brand (1994) writes about the 'shearing layers' of buildings in the timescale space, with components lasting anything from days through to centuries, resulting in continual evolution of the overall structure through what appears on the surface as maintenance of individual layers (be it replacing lightbulbs, furniture or windows). This 'timescale separation' seems to be a necessary feature of structures at all scales (Szerszynski, 2022) and the human, in all its biological and sociological complexity, is perhaps the perfect example.

This is not to suggest, of course, that all consumption behaviour is rational and long-term maximising investment. These intermediary investments have effects, often

[4] Although convenient for accounting, the year is an arbitrary timescale with no particular significance to the spectrum of service lives of productive structures in the economy (Sombart (1902), indeed, argued that the very concept of capital, and its definition as productive assets lasting more than one year, emerged from the introduction of accounting rather than the other way round).

multiple, of varying magnitudes and varying timescales; some, such as tobacco or recreational drugs, may indeed have negative effects on long term human capital formation despite potential short term benefits (although these same investments may also make some positive contributions to human capital development, in particular alcohol, which is a popular catalyst for the formation of social relations and networks (Demant & Järvinen, 2011)). Some of these effects may be unexpected, and some may have collective impacts. Long-distance holidays or private automobile use may boost the human capital of one person, but through its impact on the climate, contribute towards the restriction of opportunities for all, indeed as just discussed they will inevitably affect other types of capital through the networked interactions. In a world where it were possible to measure the size of these investments, their conversion through other intermediaries and their long-term effects through future wages, it would be possible to estimate the return on investment (ROI) and therefore productivity of these investments, but realistically their vast interlinkage renders this impossible. Even in lieu of such a quantitative analysis, based on the evidence presented in this paper we believe that attempts to draw a fixed distinction between investment and consumption, or between consumption which creates human capital value and that which does not, are not fit for purpose and proliferate unhelpful narratives. Instead the questions worth asking are to what *extent* does any form of consumption create future value, over what timescale, and for whom?

This represents a significant shift in our perception of consumption and utility maximisation and may encourage a reconsideration of the approach of public policy towards consumption. The literatures on human capital and productive consumption encourage the pursuit of policy to increase productive consumption – in contrast to what they see as 'unproductive' consumption – as a means of building prosperity, tackling inequality (Dinda, 2014b) and delivering green growth (Dinda, 2014a). Our findings, which suggest that almost all consumption is productive to some extent, make a case for placing much greater value on consumption as a whole. A blindly negative approach to consumption can lead to good ideas being rejected, for example a recent publication on minimum income welfare payments by Bartik et al. (2024, p. 7) argues that because the effect of these payments is largely to increase consumption, and recipients do not see a short-to-medium-term increase in earned incomes, "the long-term effects on consumption or financial outcomes may be small," seeming to overlook the long-term effects that consumption itself can have. This is something we recognise intuitively at an individual level: many people would acknowledge that even an hour spent watching television can be relaxing, restorative and even educational. There can be value in almost anything we do, it is all a matter of degree.

A critical question is how to reconcile this with the real and urgent need to reduce consumption of the earth's natural resources. While the sustainable consumption and green growth literatures have largely emphasised efficiency and technological innovation as the predominant solution, aimed at reducing the material throughput of consumption activities without requiring significant reductions in their overall level (Lorek & Spangenberg, 2014), others have argued that a decoupling of material use from economic activity on this scale is not feasible (Jackson (2016), for example, calculates the need for a 130-fold improvement of efficiency by 2050 if the population and the global economy were to continue growing and global incomes were to reach parity with the EU). The latter category have a greater challenge. Can consumption (investment in human capital) be reduced in absolute terms without impacting future human potential and therefore future human wellbeing? For their part, advocates of degrowth are likely to respond by arguing (a) that according to some models, consumption losses (and therefore reductions in human capital) can be compensated by increases in social capital (networked human capital) formed through increased leisure and wellbeing activities (Bilancini & D'Alessandro, 2012; Heikkinen, 2015), (b) that a long term reduction in incomes in the Global North will not necessarily lead to a reduction in social welfare if policies such as a universal basic income or universal basic services are pursued (Kongshøj, 2023), and (c) that the long term effect of growth-induced climate change will be to reduce incomes in any case so a managed reduction should be pursued (Sekulova et al., 2017). These analyses are not constructed with an explicit acknowledgement of the potential link between consumption and human capital creation, however – perhaps due to greater reticence to engage with the human capital framework among heterodox economists – so we conclude not only that this link needs much greater study, but also that research into alternative economic pathways may need to recalibrate its assessment of the long term effects of consumption.

Finally, a note on nomenclature. While this paper is motivated by simply ensuring the appropriate characterisation of economic activity on a macro scale we are mindful that the term used to describe it has significance in its own right. As highlighted in Section 4.1 the words 'consumption' and 'investment' convey very different meanings, not just in economic theory but also in the public imagination. Choice, for example, appears to be a key attribute of consumption as currently conceived (though in reality heavily constrained and coerced by structural forces), but if it has no direct effect on the forward evolution of the economy then the leverage of that choice is somewhat restricted; in contrast investment by definition shapes the future, and hence appears to assign the investor more agency over that future than consumption. Though investment comes in many forms – not all effective nor long-lasting – and the growth it fosters can lead in many different directions, it feels fair to assert that consumers are perceived to be undertaking less 'productive' activity, and to be asserting less agency over their (and the economy's) future trajectory than investors. Describing the act of consumption as a form of investment, and people as investors rather than consumers, may help disabuse the notion that people are passive consumers and encourage us to cast light on the choices they make through the futures they create with their investments. This reflection is not undertaken by the existing productive consumption literature, perhaps largely because the types of consumption they identify as performing an investment function (education, healthcare, training) largely represent expenditure by institutions, while the remainder of consumption – which this paper begins to bring into the sphere of investment – is very heavily led by the individual.

4.5. Cautions and limitations

Making use of the availability of human capital stocks – now often provided aggregated with produced capital to produce total national capital stocks – we have applied a unified perpetual inventory method to capital turnover, drawing what we feel are natural conclusions from the increasingly equal standing being given to produced and human capital in national accounts. We emphasise that our results should be taken as merely instructive; the vast uncertainties in, and discrepancies between, the investment estimates shown in Table 4.1 highlight the limitations of our approach and the care we have taken to factor in appropriate uncertainty to our assumptions. The challenges of preparing and interpreting our results are discussed here in detail.

4.5.1. Methodological limitations

Our human capital distribution and the depreciation rates we derive from it are useful but imperfect approximations. For a start, we are reliant on limited data, limiting the countries for whom this analysis is possible and requiring us to interpolate both the annual workforce participation rate and earnings-age distribution from data provided at 5-year age intervals. To estimate distributions of recruitment and retirement by age, we are required to assume that all net change in the human capital stock before and after the maximum workforce participation rate consists of entirely either recruitment or retirement respectively. In our net recruitment or net retirement estimates – and, therefore, our service lives and depreciation rates – there is no representation of additions to human capital later in life, nor early removals, both of which we know occur either through people joining or leaving the workforce or through gaining and losing knowledge, particularly lifelong learning over the course of a career. As such our human capital depreciation is *net* depreciation over working lifetimes, with some investment and therefore some depreciation missing from our model. Nonetheless as an approximation of the dynamics of human capital – exhibiting a broad compatibility with the established capital stocks methodology – we feel that this method is sufficient for the purpose of estimating an overall depreciation rate for human capital.

The process of reversing equation (1) using assumed depreciation rates also amplifies noise, leading to somewhat variable estimates of investment, which we average over the 1995-2017 period to improve reliability. This has a particularly notable effect around the 2008 financial crisis where GDP briefly declined in many countries, causing our model – on account of its assumption of continued depreciation at fixed rates – to conclude that investment in human capital was in fact negative for a year (in the US, for example) or two (in the UK). This may be an expression of mass unplanned depreciation of human capital through early retirement and skill loss from unemployment caused by the market crash (Coile & Levine, 2011) – a story that is likely repeated by the Covid-19 crisis which our data do not cover, and at risk of repetition as discussed later – falsely attributed to the investment side of the equation, but nonetheless this should encourage a healthy caution over our investment estimates in and around negative growth scenarios.

As a result of the various limitations and assumptions discussed here and in Section 4.3, and the uncertainties embedded in the capital stocks and GDP data we are working with, we find significant uncertainty in our results. Even notwithstanding the particular challenges of defining and measuring human capital discussed in the following section, national accounting is far from an exact science and relies on widespread estimation and assumption to compile and maintain capital stocks (Boskin, 2000), particularly around capital lifetimes and depreciation rates for which data are surprisingly scarce (Chester et al., 2024; Rincon-Aznar et al., 2017), so it is only appropriate that we exercise a degree of caution when adopting these stock data.

4.5.2. Shortcomings of the human capital framework

In this paper we have fully embraced the idea of humans as capital and adopted an income-based definition of human capital which replicates the method most used by the literature and by institutions such as the World Bank. In doing so we feel we have taken this idea to its logical conclusions and demonstrated that even on the most conventional terms, if humans can be partially represented as a form of capital, then consumption must be leading the creation of this capital. While we felt it important to work with orthodox assumptions to demonstrate this in the most powerful and uncontroversial form possible, it is important to acknowledge that an approach which measures human wealth as future wage potential – in other words, the value of humans to imagined future employers – comes with practical and ethical limitations.

Most notably, using average wages to estimate human capital neglects or misallocates a vast array of skills and activities that are not rewarded in monetary terms in capitalist economies but which undoubtedly add to the wellbeing and potential of the individual and of society, for example care, domestic work, parenting, and voluntary/charity work. In some cases this labour may effectively be rewarded in the form of wages earned by other members of their household, in others the economic benefit may be entirely unfelt by the individual, or there may be no such benefit at all. Crucially, of course, much of this is highly gendered and racialised so the effect of its omission is disproportionately felt. The omission of domestic or otherwise unpaid work has been a long-standing criticism of national accounts (Beneria, 1999; Miranda, 2011) and most notably of GDP (DeRock, 2021), but it has particular significance here because it would suggest that the large estimates for human capital creation in Figure 4.2 are, in fact, likely to be highly conservative estimates of the value of human wealth created annually. In addition to the need for alternatives to GDP as a measure of societal welfare (Bergh, 2009; Costanza et al., 2014; Michaelson, 2023) there is a need for alternative forms of forward-looking valuations that capture the full breadth of human output, and were we able to use those here it is likely that our total values of annual human capital investment would be higher (though not necessarily higher as a proportion of GDP, if the definition of GDP also changes). By recognising that humans are continually investing in the productive capacity of the economy, our analysis takes some important first steps towards a more developed understanding of the true scale of human activity.

Our analysis relies on the assumption of broad equality between forward- and backward-looking valuations of capital which, as noted in Section 4.1, is an assumption based in common practice for produced capital. This assumes for example an idealised 'competitive market' in which gross operating surplus equals capital input, in other words where the market value of capital equals its replacement cost (OECD, 2009), but naturally not all investment takes place in an idealised environment. Estimates of costs can be wrong, and assets may not yield expected returns (represented through a discount rate in forward-looking valuations), leaving sizeable discrepancies between forward and backward-looking capital valuations. Typically it is assumed that any such cases will average out at the scale of asset classes, sectors and national geographies, but systematic changes in investment practice and the nature of the economy can lead to widespread revaluations of capital which skew the forwards-backwards comparison, potentially precipitating financial loss to investors (Zenghelis et al., 2018). This is a key criticism levied by post-Keynesians who argue that volatility in the utilisation of capital will invariably make these assumptions uncertain i.e. "the past is irreversible and the future is unknowable" (Hart & Kriesler, 2015, p. 322). This is a known challenge for produced capital which both creates and suffers from inertia in the economic system (Chester et al., 2024), but it is perhaps an even greater challenge for human capital (Chester, Lynch et al., 2024). This is because methods of estimating human capital based on future earnings potential, often using current and historical lifetime wage profiles, rely on an assumption that the skills and knowledge currently demanded by employers will continue to be demanded in future. There are many circumstances in which this has historically not been true, and could foreseeably not be true in the near future, for example due to the impacts of an unmanaged transition to avoid climate change, or due to displacement by artificial intelligence (Ernst et al., 2019). It is well understood that avoiding climate change calls for a wholesale transformation in the nature, the purpose, and most likely the scale of the economy (IPCC, 2022) and if, as is likely, this transition takes place on a shorter timescale than the remaining working lifetimes of most workers, they are potentially at risk of becoming stranded human capital in a similar manner to the 'carbon bubble' of physical stranded assets (Chester, Lynch et al., 2024).

A perhaps even more significant assumption underpins our entire approach: that the same perpetual inventory method (PIM) can be applied to both produced and human capital. While PIM is well-established for tracking produced capital accumulation – where assets have relatively observable prices, standardised depreciation rates, and tangible forms – its extension to human capital is novel. Unlike physical assets, human capital is embodied in individuals and cannot be directly observed or traded, making its valuation dependent on indirect proxies such as earnings or education levels, and likewise it is subject to depreciation patterns that are non-linear, heterogeneous, and influenced by social, institutional, and biological factors (skill obsolescence, health decline, labour market shifts) that introduce different dynamics from produced capital. As noted elsewhere, there is little consensus on the exact allocation of costs of, and valuation of returns to, human capital investment. Applying the same methodological framework to both forms of capital risks obscuring important differences in how these assets are accumulated, utilised, and maintained. Some would conclude that doing so is therefore inappropriate. However, as Goode (1959, p. 148) argued, when assessing the challenges of treating humans as capital it is easy to overlook the vast difficulties and inconsistencies in the valuation of *produced* capital that we are already accustomed to:

Admittedly, many conceptual and measurement problems are raised by an attempt to broaden the definition of capital and investment. Difficulties of imputation and allocation of costs and of valuation of returns have no doubt weighed heavily in the decision to exclude human capital from existing statistics. I suggest, however, that we are inclined to exaggerate the difference in difficulty of compiling estimates of the two kinds of capital formation. Because of the wide use of statistics of physical capital formation, we sometimes forget that certain of the assumptions and methods underlying the estimates are debatable. (Goode, 1959, p. 148)

We argue that for all the differences in the properties and dynamics of produced and human capital, equation (1) – which simply states that capital is the subject of investment and depreciation – is a defining characteristic of all capital. The increasing availability of national stocks of human capital provided alongside produced capital stocks implies mainstream acceptance of human capital and therefore of this characteristic. Our analysis proceeds on this basis. Our results should be interpreted with an abundance of caution – as should all analysis which uses capital stocks, given the vast assumptions made in their construction – but they are still able to offer broad insights.

Finally, in the previous section we suggested that reframing consumption activity as investment may be a helpful correction to the prevailing economic narrative, reclaiming some agency and power on the part of the 'consumer' who is otherwise portrayed as partaking in 'unproductive' activity. However the question of agency is a contested one. As a form of capital, human capital creates value through its daily use, typically not for the individual but extracted by their employer and remunerated to a certain extent through wages. For the individual, returns on investment in their human capital come in the form of greater skills and increased payment by employers in the long term. Investment in human capital – particularly in the forms it is conventionally perceived – comes from a variety of sources beyond the individual, not necessarily motivated by long-term benefit to them but by the potential to extract more value (indeed there is an increasing trend of private employers claiming ownership of human capital by imposing post-employment constraints that seek to keep knowledge, gained through training and experience, within their company (Stone, 2001)). So to what extent do we invest, or are we instead invested *in*? Moreover, to fully assign agency, we have to assume that individuals are making free choices, and in reality there are widespread structural forces that determine people's economic activity, encompassing the cultural, social, economic, technological, geographic and political (Poças Ribeiro et al., 2019; Shaw & Clarke, 1998), and shifting consumption patterns is not easy, as the climate crisis is starkly demonstrating (Girod et al., 2014). As highlighted in Section 4.1, quite how much agency people can be said to have in their choices is a worthy debate and one that has long persisted with no easy answers (Bianchi, 1998). Changing the language we use will not change the reality of consumption – how and why it is conducted, and by whom – but as scientists we should be aiming for accurate categorisation at all times, especially when the object of study is so central to contemporary policy debates, and has a clear influence on public perception of the economy and their own economic activity.

These are all important issues to have in view and are each worthy of greater study, but we nonetheless feel that our results and conclusions – based on a simple first-order analysis of capital turnover in line with conventional accounting assumptions – offer a valuable new perspective on the role of consumption in the economy which warrants further discussion.

4.6. Conclusions

We are not without our criticisms of human capital, both in its conceptualisation and its execution, as the previous section exposes. We have embraced it, however, to make a critical point: if we are to believe that the human capacity for productive labour fits under the definition of capital and the size of this capital stock can be inventoried alongside produced capital, as per the World Bank's efforts, then we similarly have to believe that it undergoes both investment and depreciation, and the scale of these reveals some profound truths.

Our investigation began with the latter, because although human capital depreciates – both through retirement from the workforce and the loss or obsolescence of acquired skills – rarely is the capital conservation equation applied to it, and thus the survival dynamics of this capital (particularly the overall depreciation rate) are poorly understood. Through an analysis of available workforce participation and earnings data we have been able to advance this understanding and, armed with estimates of the rate of human capital depreciation and therefore the historic depreciation of World Bank human capital stocks, we have then been able to estimate the annual investment required to create the World Bank's national human capital stocks.

Finding that this approaches or even sometimes exceeds total output, we conclude that the conceptual framing of consumption may be due a re-evaluation. Our proposition, that this expenditure should be viewed as investment in human capital, challenges the conventional dichotomy between investment and consumption and offers a pushback against the idea that humans are passive, often wasteful, consumers. It seems that almost everything they do may help form their future self, both directly and indirectly and to varying degrees; by switching to a framework of investment we may begin to interrogate the productivity and therefore returns on these investments. This also challenges the idea of production as a one-way flow from producers to consumers; given the role of human capital as a factor of production, and of consumption in producing human capital, the flow must instead be cyclical, and arguably one that ‘consumers’ have more agency in than our nomenclature currently implies.

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5. Discussion

I have found out what economics is; it is the science of confusing stocks with flows.

Michał Kalecki *(Robinson, 1982)*

This thesis set out to understand how investments produce capital (produced and human) spread across a spectrum of expected lifetimes, and how these lifetimes restrict the ability of the economy to undergo systematic transition. This was motivated by the rapidly closing window in which globally impactful and irreversible climate change can be avoided, and growing fears in the financial sector (and therefore the sphere of politics) that the necessary speed and scale of policy change to achieve this threatens a substantial – but still largely undefined – portion of global capital value.

Our understanding of capital lifetimes is advanced by the introduction of a method to derive turnover timescales for capital in chapter 2, utilising available investment or depreciation rates to estimate the average time all capital assets spend in the economy. This new abundance of data encourages us to briefly abandon our object-focused view of the economy and instead view it solely through the lens of time using the timescale distribution of capital in the United States presented in chapter 2. From this we immediately get a picture of value flowing through the economy at all timescales, from the very short (which, at timescales less than a year or two, is typically dismissed as consumption) to the very long, all contributing to the functional richness of the economy. It is possible that the slow, low return structures are necessary to facilitate the shorter, more volatile whims of the economy, and perhaps vice versa, as chapter 4 demonstrates in the case of human capital. Many of these perspectives – of capital as a flow, or of the functional richness of the system, for example – borrow more from ecology than from economics. They, along with other emergent themes and topics worthy of further study, will be explored in this chapter.

This chapter will first highlight the key findings and contributions of this thesis, particularly in relation to the questions set out in section 1.4, before moving on to a discussion of interesting themes that emerge from this work and potential areas of future study.

5.1. Key findings

The work presented in this thesis has defined the relationship between the size of capital investments and the lifetimes of these investments, and explored the way in which this relationship defines the inertia of the economy to major changes through the risk of asset stranding. Through the application of a systems dynamics approach to capital stocks it has been able to characterise the lifetimes of, and therefore the inertia produced by, capital throughout the whole economy – a significant advancement on the previous literature which has typically focused only on the most polluting sectors, or assumed uniform lifetimes for all capital, ignoring the heterogeneity of capital in the real world and the need for a complete transition of all aspects of the economy to meet climate targets.

Chapter 2, *Heterogeneous capital stocks and economic inertia in the US economy*, provided a review of the treatment of capital across major integrated assessment models. It introduced a method for estimating the lifetimes of any capital stock for which annual values of total stock, and either investment or depreciation, are provided in national accounts. It then used this method to estimate the lifetimes of over 3000 classes of capital asset in the United States and combined them, by applying a survival function, to form continuous capital-lifetime and investment-lifetime distributions for the US economy. Finally, it investigated the decay dynamics of the capital-lifetime distribution to demonstrate that the US economy can be summarised as the sum of three groups of capital categorised by timescale – fast, medium and slow – and provided a simplified three-sector method for the representation of capital inertia in integrated assessment models (where modelling the full dynamics of capital is not feasible).

Chapter 3, *Stranded human and produced capital in a net-zero transition*, developed a new integrated assessment model which represents the turnover of capital at all timescales, tracking the ages and remaining lifetimes of all presently existing capital disaggregated by sector. It used available data and retrospective modelling to estimate the age distribution of currently existing produced capital assets, and manipulated data on human workforce participation to estimate a similar distribution for human capital. It then simulated the expected business-as-usual depreciation of these assets, on a global basis and for the US, EU and China. This was repeated with scenarios for a transition to net zero by 2050, in which capital is progressively removed to maintain necessary emissions trajectories. This revealed that up to 117 T$ of global capital value – 11% of all existing capital – would now be at risk if investment in carbon-emitting capital had been ceased in 2020, which increases dramatically to 557 T$ – 37% of existing capital – if this is delayed until 2030.

Finally chapter 4, *Are we consumers?*, exploited the potential for the conservation equation for capital identified in chapter 1, typically used to measure stocks of produced capital, to be used retrospectively on published stocks of human capital to provide more detail on the turnover dynamics of human capital in comparison to produced capital, and particularly to identify how stocks of human capital are created from economic output. It explored in more detail the method used to estimate age distributions of human capital in chapter 3, and performed simple decay simulations of existing human capital stocks to derive both service lives and depreciation rates for human capital in 20 example economies, finding that within each economy these timescales are broadly similar. Through application of the backward-looking conservation equation, it then found that the share of GDP output allocated to the creation of human capital is significantly larger than that to produced capital, often leaving little to no output for consumption, leading it to explore the idea that almost all of what is conventionally considered consumption may be more accurately considered investment in human capital.

5.2. Emergent themes and future work

5.2.1. Stranded assets: next steps

The global capital value at risk of premature retirement in an economic transition aimed at meeting agreed climate objectives is larger than previously identified in the literature (section 1.1.2.1), especially if policy action is delayed and therefore more new long-lived carbon-emitting capital is commissioned. The primary reasons for this significant difference in results are as follows:

- Despite chapter 3 being branded an investigation into pathways towards net zero – for maximum relevance to policy and to the contemporary political discourse, which has largely settled on net zero as a catch-all for Paris-compliant climate policy – the idea of negative emissions was ruled out of the scenarios investigated, largely reflecting uncertainty in the ability of this technology to be rolled out in such a restricted timeframe (section 1.2.3). Rather than being allowed to continue, residual (hard to eliminate) emissions therefore must be removed from all sectors, often at significant cost.
- The 'value at risk' framework assumes a worst-case scenario in which all presently-existing capital must be removed from the economy before the 2050 deadline, and therefore none is able to be retrofitted to be compliant with a ban on emissions, or permitted to continue as residual emissions by the use of negative emissions technology. This is a useful counterpoint to the dominance of optimistic assumptions in other models which serve to justify weak climate action (section 1.2.3), but in practice some of this risk will be avoidable.
- Human capital is a novel addition to this model. This significantly advances the study of inertia by considering the risk to human livelihoods directly alongside the risk to capital. By including these livelihoods in the total monetary value at risk – by all means, defining human value in monetary terms is controversial in itself – the resultant at-risk figures are larger and

inconsistently defined with reference to the literature. Moreover, similar to produced capital, a worst-case scenario is assumed where no human capital is able to become net zero compliant and avoid being stranded.

A worthwhile priority for future development of this research would be reconciliation with the existing stranded assets literature on some of these topics. Rather than entirely dismissing negative emissions, for example, a range of scenarios for the deployment of negative emissions technology could be introduced and the resultant effect of these, and the residual emissions they would permit, on the overall value at risk would be highly instructive (the ability to roll out negative emissions technology on a sufficient scale is, of course, a reflection of inertia in itself (section 1.1.2.3), modelled in the form of induced innovation (Pasqualino *et al.*, 2024); future work should could seek to combine this inertia with that of capital turnover). Likewise, existing analysis on the current sectoral extent of zero-carbon retrofitting and the potential for further retrofitting could be included in future models, which would further elucidate how much risk, and where, can realistically be expected to play out. These issues could be reflected through marginal abatement costs, for example (Grubb *et al.*, 2024; Harmsen *et al.*, 2021; Vogt-Schilb *et al.*, 2018).

A notable inconsistency in this thesis, not hitherto discussed, is that the capital-timescale relationship derived in chapter 2 is not deployed in the model created in chapter 3, despite the important role that chapter 2 identifies for this tool in integrated assessment models. Rather than include a detailed representation of all timescales of capital at an aggregated all-sector level, the focus of the model was instead on a sectoral breakdown of capital. As full capital-timescale relationships were not available for individual sectors, a unique representative timescale was instead estimated for capital in each sector and a simple retirement function assumed based on this timescale. The analysis in section 1.3.4 suggests that this compromise may be an appropriate approximation, but only if sectoral capital is more restricted in its timescale range and defined by a dominant mode, compared to the overall economy which is multimodal and therefore less likely to have its inertial dynamics accurately represented by a single timescale (chapter 2). This has not been established – at least not for all sectors – and it should therefore be taken up as an urgent focus of future work. If single timescales are found to not be representative of sectoral capital, then models seeking to capture transition dynamics would benefit from the inclusion of a full timescale distribution of capital for each sector (Figure 2.3) or a small selection of representative timescales to define subsets of this capital (Table 2.2).

Finally, while much of the focus of the stranded asset literature is rightly on quantifying stranded assets – as has been shown, this task is far from complete – there are further questions to answer about how, and to what extent, stranded assets produce inertia to climate policy, and how this inertia can be overcome. Who bears the burden of the capital valuation losses? What influence do they exert over politics as a result? Malm and Carton (2024) begin the process of understanding the political economy of asset stranding, which benefits from a conceptualisation of capital not just as a physical good, but as a social process (Mair, 2022). This field of study could benefit from further analysis based on the theory of 'capital as power', which understands capital as a form of power not only over markets but also society at large, "including the ability to shape political will, environmental conditions, international relations, norms, beliefs, arts, education" (Nitzan and Bichler, 2009; Vastenaekels, 2024, p. 4).

5.2.2. We are not consumers: next steps

Chapter 4, as a scientific study, is imperfect. It uses back-of-the-envelope calculations with a very wide margin of error to demonstrate the potential of a novel mode of analysis and to make a fundamental observation about the mis-attribution of economic activity. It is not shy about the limitations of this analysis – they are discussed in detail in section 4.5 – and while they should not detract from the important message that is ultimately conveyed, they define relevant areas for future research. More generally, the aim of the chapter is to re-introduce the idea of productive consumption to the economic discourse, and to inspire a new area of research into the role of consumption in producing human capital. This section will not repeat the various practical limitations of the study which could be refined by future research, as these have already been covered, but will outline some questions that chapter 4 leaves unanswered.

Most crucially perhaps, what are the mechanisms by which everyday consumption creates human capital value? The creation of human capital through education and training, for example, is well established, but the suggestion that almost all forms of consumption lead to an increase in human productive potential newly introduces a vast array of activities to the sphere of investment, some of which are intuitive (food and exercise, for example) but many of which may not be.

Some consumption, indeed, will not be positively productive. Some activities worsen life expectancy or the capacity to perform work, which will negatively affect an individual's expected future earnings. The entertainment industry's increasingly ruthless targeting of users' attention, including children, is evidenced to be worsening attention spans (Alghamdi and Aljabr, 2024; Yakob, 2021). But often it is not clear cut: many activities have both positive and negative effects, with different effects sometimes emerging over longer time periods. What is positive for one person may not be positive for the next, or what may be positive in some quantities may be destructive in more. Will it ever be possible to quantify the relationship between an element of consumption and the human capital it produces? Can a coherent theory of productive consumption be created without this quantification? Does such a theory really give individuals more agency, as chapter 4 suggests, if the benefits to be gained from any given form of consumption remain hard to determine? And to what extent do individuals have agency over what they consume anyway? Such choices are inevitably framed by their socioeconomic context, and the creation of human capital value is inevitably dependent on the networks and structures in which any individual is embedded and contributing to. Structural and network-based analysis of human capital creation of this nature is a ripe area for future research.

A critical challenge to the rethinking of consumption, particularly in the context of this thesis, is the role of consumption in environmental degradation. This was identified in section 1.3.5. If consumption is a vital ingredient in the development of people, but also responsible for a damaging level of throughput of planetary resources, what is the ideal policy response? If an act of consumption benefits the individual but harms the collective, does that (or should that) impact the productivity of the consumption?

Finally, as discussed in section 4.5.2, defining human worth on the basis of wage earnings (and therefore the importance of human activities through the monetary value they produce) presents moral and conceptual complexities. The narrowly-defined scope of human capital has emerged out of accounting necessity but it, like all economic tools, reflects and in turn projects the normative values of its user and the society it is representing. A focus on wage earnings in this way is not entirely inappropriate: the society in which we live is one that values and requires money (at least to a certain point) for its inhabitants to survive and flourish. Chapter 4 embraced a conventional definition of human capital both to make use of available data and to simulate the potential loss of livelihoods in a rapid transition, which would have a very real impact. However alternative quantitative approaches that broaden what is seen to be of benefit to individuals and society, and may therefore change estimates of human capital value or perceptions of its loss (and, in turn, how policy is constructed and alternative futures are imagined), would be a worthwhile development. Until or in lieu of that development, use of the term 'human capital value' needs to be highly caveated.

5.2.3. Everything flows

Let us return to chapter 2, and to some wider themes that emerge from this research. When viewed solely through the lens of turnover time (Figure 2.3), the economy appears as a continuous spectrum of investments entering and leaving the system at different rates. Chapter 2 demonstrated that the trick to understanding capital lifetimes, seemingly having eluded economists and statisticians all these years, is to recognise that they are turnover rates, in other words, that capital is a flow.

How can a stock be a flow? These terms are so embedded in economics and system dynamics that it can seem natural to think of them as mutually exclusive. They are, however, deeply dependent on the perspective from which one approaches the system in question. To early geologists the rock strata appeared solid and permanent, but it was soon realised that rock – itself merely an aggregate of minerals – is "seething, creeping, crushing stuff" (Clark *et al*., 2022, p. 205), an expression of vast flows over geological time (indeed, only around 1% of it is in the rigid form we are used to, most of it beneath the crust is fluid even from a human perspective). We use the term 'concrete' to evoke the image of solidity in everyday conversation, but even concrete deforms under pressure and appears transitory with enough perspective (its Latin root *concrescere*, to grow together, lent itself to Whitehead's 'concrescence', the dynamic process of parts coming together to form a whole which underpins much of modern physics) (Clark *et al*., 2022; Doan, 1960).

If our human bias towards the timescales of the Earth system lead us to arbitrary conclusions, then perhaps the same is true of the economic system. When we abandon the content of investments and consider only the timescales, there is no rational distinction between those which last longer than one year and those which last less, between (fixed) capital, circulating capital and consumption. The construction and replacement of bridges and tunnels over the course of centuries, and the consumption of food and drink on a cycle measured in hours, equally flow through the economy providing returns over defined periods of time. As hinted at in chapter 1, the accounting cycle is merely a construction for the benefit of human capitalists, its annual view of capital turnover a relic of a period in economic history where production was dominated by the agricultural cycle.

Our understanding of the economy, and of society, may be improved by stepping back from the tempting perspective of human daily (and annual) life and instead observing how everything we see around us flows through this dynamic, ever-evolving planet, as argued by Clark and Szerszynski (2020) in their book *Planetary Social Thought*. Similarly, Russell (2001) observes that the complexity of species turnover on local spatial and temporal scales disappears at the level of geological time, where only origination and global extinction of species are left as relevant variables, giving species, too, the appearance of a flow. The universality of turnover timescales suggests that any resource can be considered a flow if it has measurable inflows and outflows, thus consisting of a pool rather than a collection of individual artefacts.

A barrier to this, and particularly to the comparison of flows across disciplines in the spirit of planetary thinking, is that "turnover is defined, measured, and modeled in many different ways depending on the discipline [and] the scale of measurement" (Russell, 2001, p. 377). A unification of approach to turnover dynamics across the social and natural sciences would therefore be of great benefit (especially in the interdisciplinary study of timescale separation, introduced in the next section), and might help encourage adoption of the idea of capital as flow introduced in chapter 2.

5.2.4. Timescale separation

This leads us to a related topic, introduced in section 2.5: the question of *why* the economy, like many other systems, is comprised of structures spanning a vast range of timescales, but with preferences for particular timescales (Figure 2.3). From a systems perspective, what does the economy (and the connected system it purports to serve, society) gain from this separation across timescales?

A better question may be: what does any system gain from timescale separation? Again, this is a question that appears in different ways and is given different answers across disciplines. It is one that finds relevance in almost all systems (human and non-human), however, and there may be critical commonalities in the processes involved. Indeed Szerszynski (2022, pp. 206–207), in considering timescale separation a form of infrastructuring, explores "the possibility that infrastructuring might be a more-than-human, planetary phenomenon: not just that human infrastructures depend on natural systems that underpin them and make them possible, but also that human-centered infrastructuring might simply be a variation on a more general phenomenon in the ongoing self-organization of planets". Timescale separation is certainly easy to observe at the planetary level (Figure 5.1). Edwards (2002) speculates that the role of human infrastructure in this, working at the scale of decades and centuries, is to mediate between long geophysical timescales of millennia or more and human (and animal) timescales of hours, days and years, in an attempt to "create an ordered and predictable artificial nature for modern societies" (Szerszynski, 2022, p. 197). This suggests that timescale separation may in fact be a manifestation of (Carney, 2015)'s tragedy of the horizon.

Interestingly, timescale separation can even be seen *within* the structures that comprise the economy: a house, for example, despite having a single estimated service life, is in fact a composite of many substructures each with their own lifetime (from walls to lightbulbs), combining to create a timescale distribution that looks remarkably like that of the overall economy (Figure 5.2). Perhaps this is a coincidence, or perhaps it speaks to an emergent behaviour of this type of system.

The hypothesis that dynamic systems naturally evolve in ways that separate their processes across timescales is speculative and worthy of significant further study, both to establish the universality of this phenomenon and its motivations. In the specific case of the economy this would be particularly instructive given the influence of its timescale distribution on its inertia, potentially pointing at unforeseen effects of changing this distribution, which chapter 2 highlights is highly stationary. In the interest of inspiring – but not presupposing – this further study, four potential theories to explain the observed emergent tendency towards timescale separation are explored below (but these are by no means exclusive, and are at this stage mere speculation).

First, as Szerszynski (2022) cautions, it may simply be an accidental feature that does not play a significant causal role. The separation of the earth system into various subsystems and processes with different physical properties and characteristic timescales can, he notes, be attributed at least in part to the gravitational processes that guide the creation of planets and the effect of differentiation in temperature and pressure on the nascent planet. The earth system is not alone in being sensitive to its initial conditions; perhaps the timescale separation observed in other systems is similarly an all but inevitable result of their nonlinearity. Likewise, Wong et al. (2023) suggest that timescale separation, while not an accident, is simply a by-product of functional selection happening at different speeds (from fast reactions to slow system adaptations), naturally resulting in the emergence of multi-timescaled architectures.

Second, separation of timescales may optimise (or be necessary to facilitate at all) the functioning of the system. The economy is perhaps where this effect is seen most clearly through the role of infrastructure: the efficiency of fast turnover structures is dependent on the presence of slow ones through the provision of transport and communication systems, for example. Though perhaps harder to observe, Szerszynski (2022) cites similar effects within the hydrosphere and biosphere. Rivers, for example, distance their processes across timescales – the effects of constant erosion, solution, deposition and bed-armouring combining to produce slow, long-term changes to the land surface – to create a more ordered environment for flowing water (Rodriguez-Iturbe and Rinaldo, 1997). This optimisation role is comparable to the role of longer-lived structures that can often be observed forming in dissipative systems as a result of thermodynamic processes that work to increase dissipation (Prigogine, 1969). A common example is Bénard cells, which form when a shallow liquid is heated from below, and some of the convective energy flow is naturally diverted into creating an infrastructure of long-lived, hexagonal convection cells which result in a faster change in temperature than would otherwise be achieved (Schneider and Kay, 1994). Similar principles have been applied to study the distribution of resources through human systems (Jarvis *et al*., 2015).

Third, timescale separation may benefit the robustness of a system. It is in this sense a systemic form of hedging, allowing processes and structures operating at particular timescales (particularly ephemeral ones) to be "selected out" without endangering the wider system. This is a well-established part of investor behaviour (Harris and Shen, 2006), but is also an important consideration in assessing the health of ecosystems (González, 2023) and can even be observed at the cellular level, where recent research suggests that what is often assumed to be 'noise' may instead be an adaptive spread of frequencies that improve the ability of a cell to resist external perturbations (Rowland Adams and Stefanovska, 2021).

Finally, it may benefit adaptability. To some extent this an extension of the need for robustness: "living systems evolve robustness to fast transient changes (homeostasis), and adaptation to sustained (directional) changes" (Lesne, 2017, p. 64). Pocheville (2018) discusses the need for adaptive processes to be spread across timescales – perhaps all timescales – to facilitate species adaptation and therefore evolution. This is also an important theme in the economic system, as this thesis has demonstrated: the ability of an economy to adapt to changes is constrained by the turnover of the existing structures within it. This is not just true for systemic changes like a climate transition, but also for the take up of technologies, for example, which often require the old technology to be phased out at its natural rate (Figure 1.3).

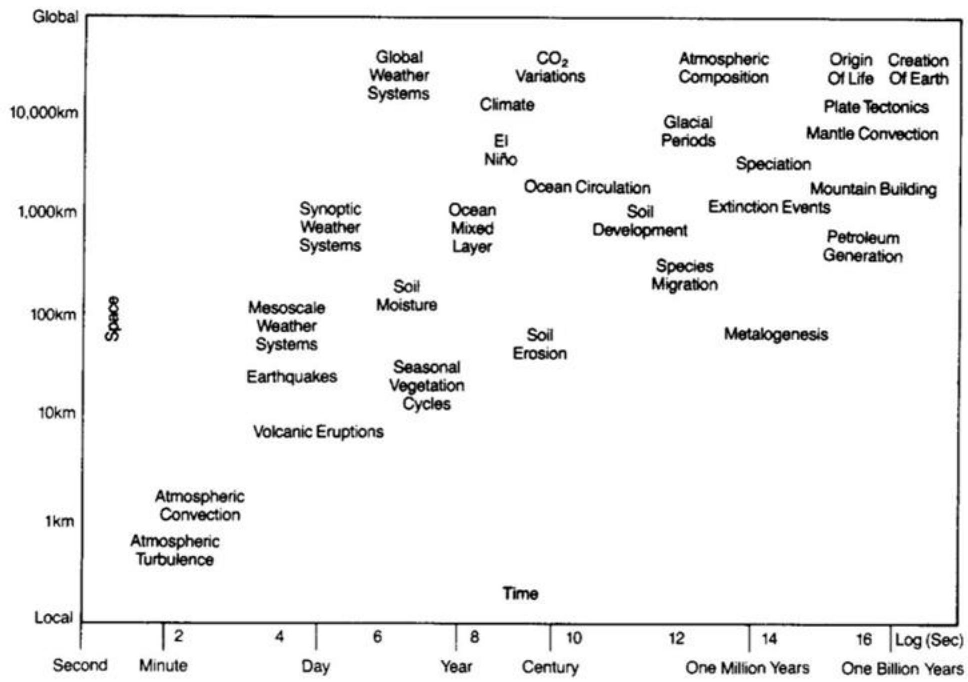

Figure 5.1. Characteristic space and time scales of earth system processes. Reproduced from Dutton (1987), based on a similar figure in NASA (1986).

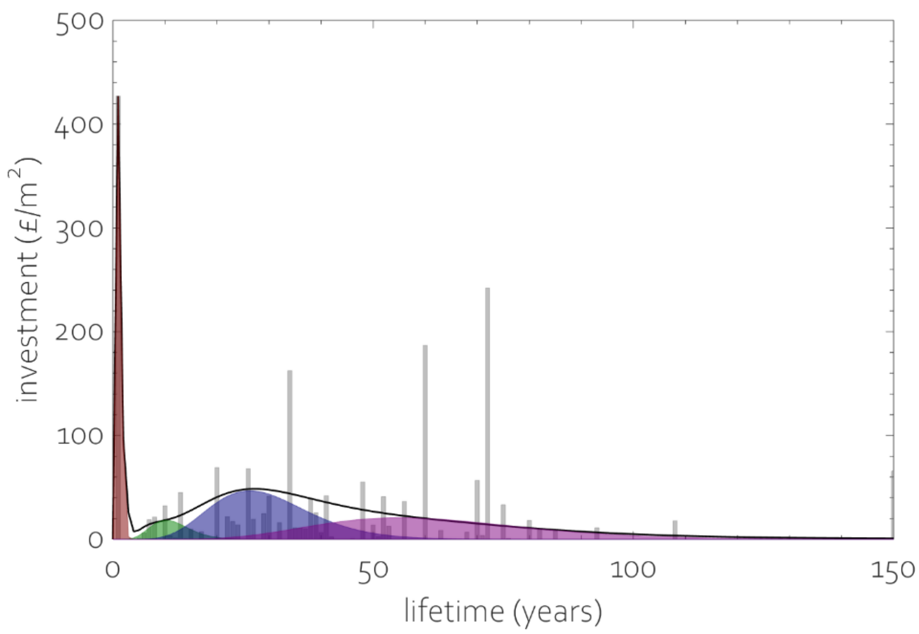

Figure 5.2. The investment-timescale distribution of residential buildings. Reproduced from Feiruzi (2024).

5.2.5. Economic growth

An underappreciated stylised fact of the global economy is that, in spite of unprecedented global events and far-reaching changes in individual economies over the past century, GDP growth has been maintained reasonably consistently at around 2.5-3% per year (Figure 5.3). This represents a growth timescale of 0.025^{-1}-0.03^{-1}, or 33-40 years. Jarvis *et al*. (2015) were among the first to observe that the growth rate of the economic system bears a resemblance to the average lifetime of the productive structures that comprise the system, particularly noting the 2.4% yr^{-1} growth rate of global primary energy and the roughly 40-year lifetime of energy infrastructure. Chapter 2, taking a deeper dive into the lifetimes of these productive structures, demonstrates that these lifetimes are, like GDP growth, historically stable, unlike the sectoral classifications used in the accounting process. While they are also heterogeneous – more than most economic models account for – their centre of mass is nonetheless around 40-45 years (Figure 2.3).

The connection in timescales between the growth of the economy and the lifetimes of its constituent parts seems unlikely to be by accident, and the mechanisms and underlying drivers of this emergent behaviour are worthy of greater investigation. Jarvis *et al*. (2015) argue that it may be necessary for productive structures to turn over at a similar rate to the evolution of the system to allow for the required update of innovation. The growth of systems creates problems, so systems attempting to maintain growth have to solve these 'diminishing returns to scale' effects by reconfiguring themselves. The rate at which they must do this transforming is the rate at which they create these problems, which is the rate at which they grow.

But why at this rate in particular? This may be where the correlation with human working lifetimes is significant: as noted elsewhere, the average lifetime of workers in the economy has also hovered at around 35-40 years throughout modern history (Ausubel & Grübler, 1995; Eurostat, 2024; Chap.3&4). It is only during their working life that individuals are able to direct resources and manipulate the economy in their interest, and capital investments which give returns on the scale of a working lifetime are able to provide wealth and economic security to the individual investor (Jarvis, 2018; Jarvis *et al*., 2015). While some seek fast returns on short-lived investments, most productive structures provide returns over working lifetimes, with relatively few – largely residential properties and government-funded infrastructure – lasting beyond human timescales (Figure 2.3). Indeed, investors are likely to be restricted to investing over working lifetimes by the availability of finance; lenders are rarely willing to provide payback periods beyond 30 years when contracts are with individuals (Mercure, personal communication, October 9, 2020). This is reinforced by discount rates, as discussed in section 1.2.2, which construct a preference for investments on human timescales by valuing returns to the present generation more than those to future generations (indeed 3% yr^{-1} is a common social discount rate, for example in the UK Treasury's Green Book).

In short, 2.5-3% yr^{-1} growth appears tied to capital turnover which has historically been at the same rate, and which in turn seems to emerge from the ubiquity of individualistic investment practices, secured against human working lifetimes. This observation does not, however, seem to feature in mainstream economics. It is worthy of greater attention, and these links are should be studied further, not least given the centrality of economic growth to the priorities of policymakers worldwide and the effects that structural changes in the timescales of capital, through asset stranding for example, may have on the wider economy.

This is of particular relevance to the pursuit of degrowth, the topic of a rapidly growing field of research and activism which argues that continued economic growth in high-income countries may not be sustainable, achievable or socially beneficial (Kallis *et al*., 2025). If growth is indeed connected to rates of capital turnover and investment practices, then any attempt to drag the global economy away from its current long-run growth rate may require radical changes in investment horizons and, as a result, longer-lasting productive structures. This may have other benefits: investment on intergenerational timescales spreads wealth across generations, undoing the temporal injustice that features so heavily in the climate crisis (see chapter 1). It would also begin to reconnect the horizons over which we make investment decisions with those of the ecological systems these decisions perturb, which may facilitate better stewardship of the natural world and, in the words of Mélenchon again, “end the dictatorship of short-termism” (Mélenchon, 2021).

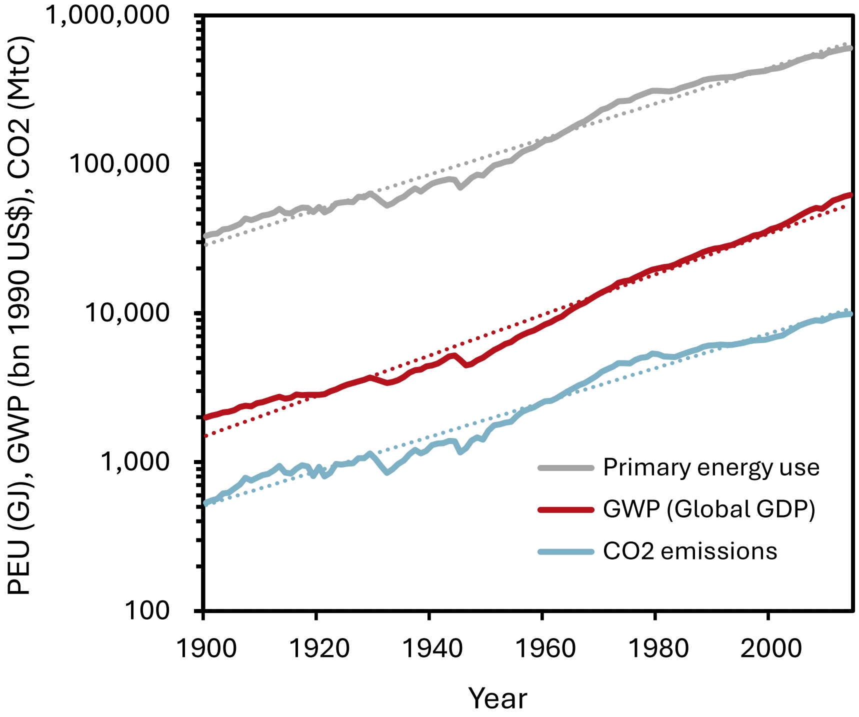

Figure 5.3. The long-run growth of the global economy is remarkably consistent: Gross World Product grew on average 2.9% yr^{-1} between 1900-2014, while growth in primary energy use and CO_2 emissions both averaged 2.4% yr^{-1}. Adapted from a similar figure in Jarvis *et al*. (2012) and Jarvis *et al*. (2015) using data from De Stercke (2014) and Friedlingstein *et al.* (2024).

Those who do not move, do not notice their chains.

Rosa Luxemburg *(date unknown)*

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