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.[1–3] A policy debate has emerged over whether such substantial financial loss affects market valuation and stability.[4–6] Here, we quantify the current value of existing global human and produced capital, sector by sector, and compare the rate at which it naturally depreciates with that at which it would be required to depreciate to achieve climate targets. Comparison allows us to determine the human and produced capital value at risk across the economy by sector. We find that stopping the production of carbon intensive capital and the training of carbon intensive occupations in 2020 allows a better than 50 percent chance to achieve a 2 °C target. However, achieving net-zero in 2050 implies capital value at risk approaching 50 T$, three quarters of which is human capital. We conclude that intervention in both the financial and educational systems may be warranted in order to reduce these risks, where training a workforce for occupations that may soon cease to exist could be avoided.

Introduction

The Paris Agreement requirement of maintaining warming 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 before 2050.[7–9] In line with the latter, the UK and French governments and the European Parliament have independently adopted emissions targets that reach net-zero in 2050.[10–12] The Japanese and Korean governments have also announced plans to reach neutrality by 2050, while the Chinese government has announced a target of net-zero in 2060.[13] Lastly, 189 countries have ratified the Paris Agreement and have made pledges on emissions reductions with the explicit intention to achieve this commitment.[14]

As a direct consequence of these objectives, a debate has emerged in the financial world concerning the risk associated with owning carbon-dependent capital, which could be threatened by new climate policy and regulation, changing consumer tastes and ongoing technological change.[4,5,15,16] 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.[17,18] Capital value at risk (VaR) could not only be in fossil fuel supply activities, but also in real estate, transportation and across industry in general.[2,3,19]

The economy grows by accumulating long and short-lived productive capital assets and skills, alongside an increasing diversity of methods and products, generating net positive economic returns. What threatens the economic value of longer-lived produced capital, and the economic activities it is associated with, is the prospect that it could become unusable or banned before the end of its expected productive lifetime.[1,20] The payback time of capital in general implies economic inertia, where economic agents face a range of waiting timescales during which resources are committed, constraining their access to further finance and the associated investment opportunities,[21,22] hence limiting the rate at which the economy can transform. Despite the crucial nature of economic inertia, no comprehensive study has yet been made on the full spectrum of timescales that characterise the capital at risk in plausible pathways of emissions reduction.[23–25]

Although human capital is generally tied to the operation of produced capital, it also dominates total capital value, particularly in developed economies.[26] Furthermore, the turnover of human capital is relatively slow, dictated by working lifetimes which, although highly variable across populations, on average have remained remarkably stable at around 40 years.[27,28] This turnover timescale is longer than the time left until emissions reductions have to be achieved under Paris, implying a significant fraction of the workforce will inevitably have to embrace change within their working life. As a result, in terms of both value, turnover timescale and social impact, human capital is probably the most important component of the inertia of the global economy, and it is surprising therefore that it has been largely absent from discussions on stranded assets.

A transition to net-zero could adversely affect the labor force by creating both unemployment and labor shortages through rapid structural change, if progress is faster than society can train or re-skill new and existing workers, or if there is a geographic disparity between current and new employment opportunities[29–31]. This has precipitated calls for a 'just transition' where the structural change associated with a shift to net-zero is fostered in ways that maximise the opportunities for those on lower incomes.[29] It is often assumed in economic models and scenarios that human capital can be readily redirected into net-zero occupations[7], 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[32,33]. 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.[34] Furthermore, given the substantial investments in sophisticated national education systems[35], and that a large proportion of the global workforce is likely to require substantial retraining to avoid becoming at risk of obsolescence,[36] or may possibly even be required to migrate to new geographical locations, this risk is in need of urgent evaluation.

To characterise the economic inertia facing plausible net-zero transition scenarios we develop a 56 sector view of the global economy, with each sector comprised of standard valuations of both human and produced capital (see Methods). For each sector and component we specify a 'service life' (for produced capital), or a 'working life' (for human capital). These determine the aggregate turnover timescale and hence depreciation rate for that component if it were to operate as planned, which range from years (machines and equipment) to decades (structures, houses and careers). We ascribe CO_2 intensities to each sector according to their fuel use (not including embedded carbon to avoid double-counting). We forward simulate the depreciation of these capital portfolios using a population dynamics algorithm that tracks capital retirement according to its respective lifetimes, and derive CO_2 emissions trajectories that we compare to desired carbon budgets. We then explore prioritising capital retirements in ways that meet carbon budgets, and calculate the VaR of both human and produced capital according to those scenarios.

Stranded human and produced capital

Figure 1i shows the aggregate lifetime distribution of produced and human capital for the 56 sectors of the global economy. Human capital makes up 77% of global capital in 2020, centred around expected mean working lifetimes of 38 years. Produced capital, meanwhile, is distributed between mean lifetimes of approximately 15 to 70 years across the 56 sectors. It is worth noting these timescales are approximations of the first moments of the aggregate survival function of all the assets comprising a sector, and that this distribution will necessarily show significant variation about the first moment, as we will see for human capital. From Figure 1i we conclude that, on average, the turnover of a large fraction of produced capital is substantially faster than that of human capital, and is therefore more adaptable to, and potentially less at risk from, a rapid net-zero transition, than human capital. In contrast, built commercial structures, including energy infrastructure, turn over at a similar rate to human capital on average, whilst residential buildings have representative turnover timescales approximately twice that of human capital, highlighting the inflexibility these type of investments engender.

Figure 1ii shows the distribution of working lifetimes estimated as the difference between the recruitment and retirement probabilities inferred from global workforce participation rate data (see Methods). This again has a mean of 38 years, but is highly asymmetrically distributed about this mean, with a 95 percentile range of 15 to 52 years. Because of this asymmetry and the overriding importance of human capital, we assume human capital is similarly distributed in the forward simulations.

Figure 2i shows various limiting trajectories of total capital retirement globally, with and without carbon budget constraints, and with and without delay for stringent climate policy action. The assumed interpretation of current net-zero policy is a linear decline in annual emissions to zero by 2050, which is associated with adding a further 160 GtC net to the atmosphere post 2020. 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 238 – 263 GtC being released to the atmosphere by 2100. Given the current understanding on the likely sensitivity of global temperature to cumulative emissions,[37] this would represent 1.4 to 1.8 °C of warming, i.e. a better than 95 % chance of keeping below 2 °C, but a worse than 50 % chance of keeping below 1.5 °C. Delaying action by just 5 years increases the carbon commitment by a further 70 – 105 GtC, suggesting additional warming of up to 0.2 °C, hence taking global temperature increase beyond the 2 °C guardrail. From this we infer we are currently at a critical threshold where keeping significantly below 2 °C is achievable without reliance on speculative negative emissions technologies providing all future investments are effectively carbon free.

Figure 2i also shows the trajectories for both cumulative emissions and total carbon-dependent capital consistent with achieving the 2050 net-zero objective. Here, early retirements are prioritorised with respect to the carbon intensity of a sector and closeness to planned retirement age of a given stock. Not only are these obvious criteria for selecting early retirements in pursuit of a net-zero objective, they are most likely to minimise VaR when attempting to achieve the net-zero objective. Prioritorising capital retirements like this means a lot of the budgetary overshoot can be met without significant impacts on human or produced capital prior to 2040 through retiring near end-of-life, high carbon capital. However, post 2040 ever more capital has to be retired from the carbon-dependent economy as both the proportion approaching retirement age and the sectoral carbon intensity fall as a result of prior retirements. It is commonly believed that decarbonisation becomes progressively easier through learning-by-doing,[37,38] and this would certainly apply to the vast net-zero compatible investments implied in this simulation. However, for the balance sheet value of early retirements of existing capital, our results highlight the opposite because the lower hanging fruit will have already been picked.

Figure 2ii shows the trajectory of human capital distributed according to age during the transitions shown in Figure 2i, where some occupations in the carbon-dependent economy necessarily have to become phased-out to meet the net-zero objective. By 2050, the average age of the global workforce in the carbon-dependent economy has risen from 28 to 50 years due to 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. Here the modal retirement age decreases from its current value of 65 (Figure 1ii) to 50 in the 2040's (Figure 2ii).

Figure 2iii shows the effects of the early retirements on the portion of remaining carbon-dependent capital in selected sectors relative to the business-as-usual case. These sectors do not necessarily disappear, but are instead progressively decarbonised as net-zero compatible assets replace their carbon-dependent counterparts. Not surprisingly, the more carbon intense sectors in the carbon-dependent economy, such as energy supply and transport, disappear first in this simulation. However, the carbon savings 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 may correctly reflect the recalcitrant nature of residual emissions and the way they are distributed within the global economy. Furthermore, through using production-based emissions when defining these sectoral carbon intensities we are tying the carbon dependency of capital directly to their own fossil-fuel combustion and not that of other sectors (see Methods). We do not include in our analysis 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.[39]

Table 1 shows the aggregate estimates of the early retired total value and VaR for both human and produced capital, and Suppl. Table 1 provide this broken down by sector. Here VaR is approximated as the product of early retired value and how close to planned retirement age this early retirement is, attempting to reflect whether or not an investor has had their expectations on returns fully met (see Methods). We estimate that achieving net-zero in 2050 if all future carbon-dependent investments were terminated in 2020 requires early retirement of 312–476 T$ of capital value, ~36% of all capital currently in use, with 65% of this being human capital. When accounting for the relative age of these early retirements we find the VaR is around one fifth of the total retired value (27-42 T$), again 65% of this being human capital. Therefore, even in this minimum VaR trajectory, we observe very substantial human capital retirements of 28-42% of the 2020 total stock of the global economy (Table 1). Delaying until 2025 before an effective ban is in place on new carbon-dependent capital investments increases the total capital retirements and VaR by around 100% (687–991 and 154-232 T$ respectively). Therefore, even modest delays now make wait-and-see policies on decarbonisation substantially more costly in both absolute and VaR terms, especially for human capital, with a 5 year delay requiring the early retirement regime to be approximately twice as aggressive (Table 1 and Figure 2i).

Managing transition risks

Even though our results are relatively coarse, due to the necessary global focus and the nature of our sectoral disaggregation, our coverage is comprehensive and data-led and, as a result, the values we find for VaR are substantially larger than what has been previously reported[1–3,40], principally because of our including consideration of human capital. We frame the capital values we estimate as being ‘at risk’ to distinguish them from actual early retirements, reflecting the fact that significant portions of this risk could be mitigated through the way we design and implement future investments in the net-zero economy. However, given achieving net-zero by 2050 appears to expose very significant proportions of the global economy to these risks, it appears critical that decision-makers properly engage in that design process in order to redeem as much of current capital into the net-zero economy as possible, especially the 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 ranges of occupations become exposed to the possibility of rapid obsolescence, where the accumulated value either from direct investments in training, or through accumulated experience operating in carbon-dependent sectors at risk, could be lost as it is not necessarily replaced by the skills and experience needed to operate a net-zero economy. We may well be experiencing similar levels of devaluation as a result of covid-19, and a debate needs to quickly emerge on how to manage and plan not just investment in produced capital, but also skills, careers and the labor force in general, as we enter the net-zero transition faced with the spectre of forced early retirement ages. Given the significant inertia that exists in the economy in general, and the development and lifecycle of human capital in particular, it is possible that both unemployment and labor shortages could arise simultaneously in a rapid low-carbon transition. When allied to the considerable complexity in identifying retirement and redemption regimes that minimise these capital losses, planning in this space is likely to be challenging.

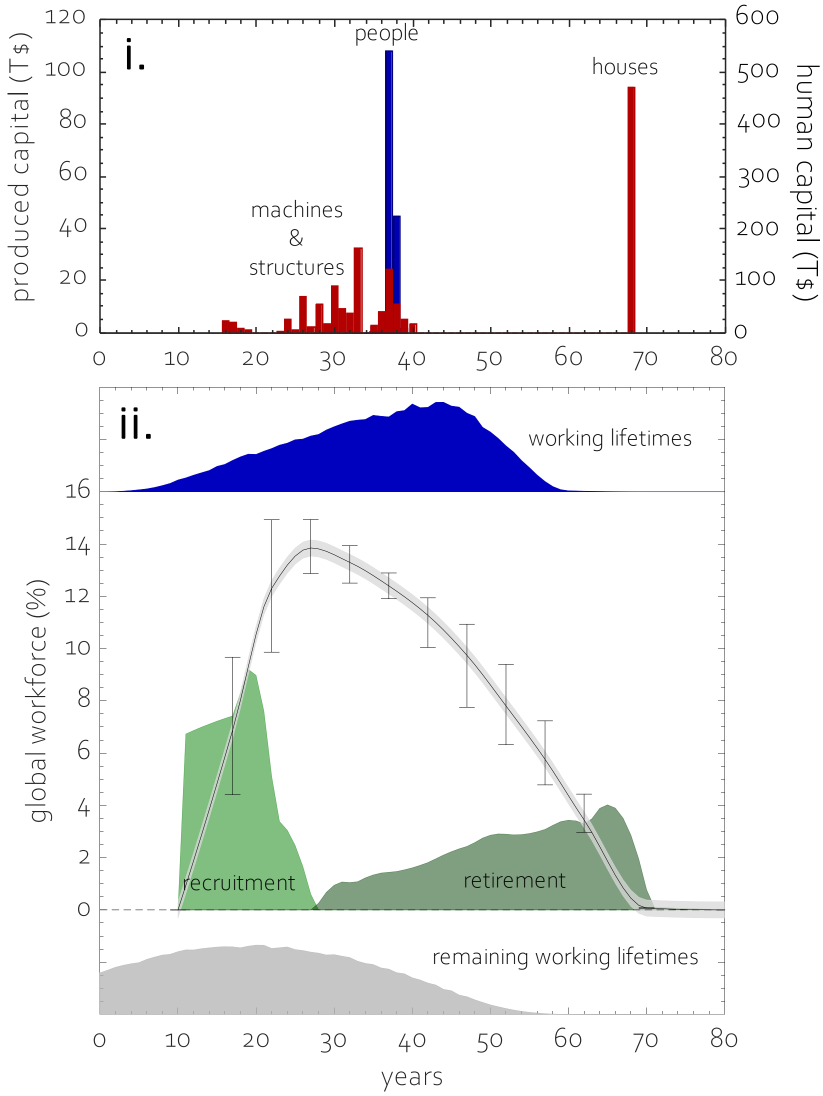

Figure 1. i. The distribution of global capital value with respect to aggregate turnover timescales across a 56 sector representation of the global economy (see Methods). **ii.** A disaggregation of the International Labour Organisation (ILO) global workforce participation rate data 1990-2020 (solid line) into recruitment, retirement, working life and remaining working life probability densities (see Methods). 95 percentile uncertainties shown on the ILO data and the spline model fitted to these.

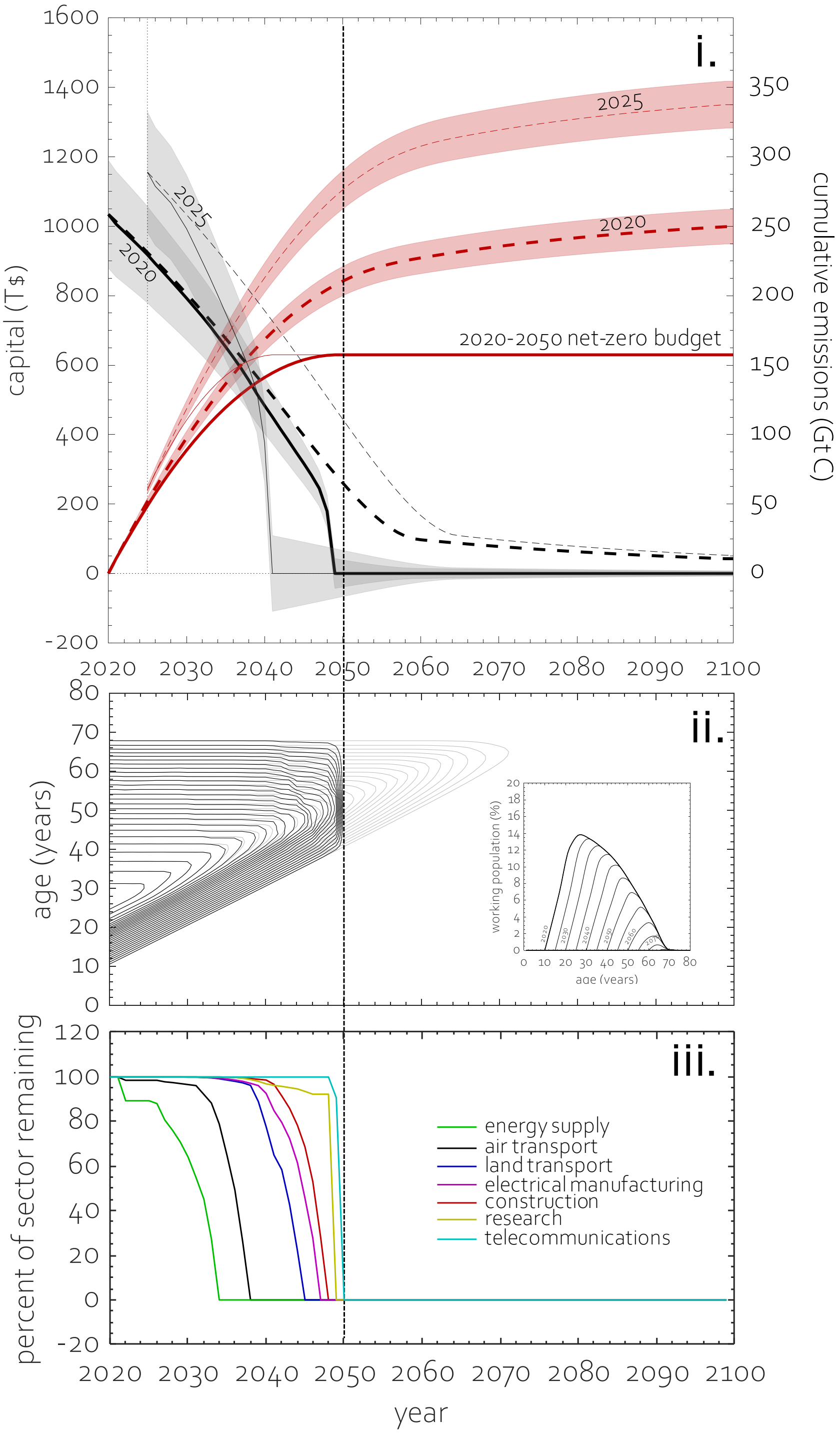

Figure 2. i. The evolution of capital (black) and cumulative emissions (red) for the 2020 – 2050 and 2025 – 2050 net-zero scenarios (solid) and their associated business-as-usual conditions (dashed). Uncertainties are 95 percentiles. **ii.** The age distribution of human capital for in the 2020 – 2050 net-zero (black) and business-as-usual (grey) scenarios. Contours represent 0.1 % increments of the overall working population. The inset also shows the business-as-usual scenario for the age distribution of human capital. **iii.** Relative decreases in the size of sectors by value for the 2020 – 2050 net-zero scenario. See Methods for details.

Table 1. The cumulative end of century budgets for both carbon, the value of early retired capital and capital Value at Risk (VaR) of early retirement for the four scenarios shown in Figure 2i.

start year	carbon added post 2020		total	human	produced
	GtC		T$ (% of start value)		
2020	238 – 263		0	0	0
	160	Value	312–476	203–309	109–167
			(27 - 42)	(28 - 42)	(36-55)
		VaR	37-55	25-38	11-17
			(3-5)	(2-3)	(1-1)
2025	321-355		0	0	0
	160	Value	687–991	509–734	178–257
			(52 - 75)	(60 - 86)	(51 - 73)
		VaR	154-232	118-177	36-55
			(12-18)	(9-14)	(3-4)

Suppl. Table 1. Sectoral disaggregation of the global economy for 2020 and subsequent estimates of capital associated with the 2020 net-zero simulation in Figure 2i.

			2020			2030			2040			2050		
Sector	Productivity	Emissions intensity	**Total capital**	Produced capital	Human capital	**Total capital**	Produced capital	Human capital	**Total capital**	Produced capital	Human capital	**Total capital**	Produced capital	Human capital
	/yr	GtC/T$	T$	T$	T$	T$	T$	T$	T$	T$	T$	T$	T$	T$
Accommodation and food service activities	10.74%	0.07	**30.61**	3.40	27.21	**22.30**	2.66	19.64	**14.52**	2.07	12.44	**0.00**	0.00	0.00
Activities auxiliary to financial services and insurance activities	2.54%	0.07	**10.60**	0.36	10.24	**7.67**	0.28	7.39	**4.90**	0.21	4.68	**0.00**	0.00	0.00
Activities of extraterritorial organizations and bodies	26.97%	0.00	**0.00**	0.00	0.00	**0.00**	0.00	0.00	**0.00**	0.00	0.00	**0.00**	0.00	0.00
Activities of households as employers; undifferentiated goods- and services-producing activities of households for own use	5.00%	0.21	**3.80**	0.53	3.27	**2.75**	0.39	2.36	**1.78**	0.28	1.50	**0.00**	0.00	0.00
Administrative and support service activities	2.51%	0.11	**35.74**	4.34	31.39	**25.92**	3.26	22.66	**16.81**	2.45	14.36	**0.00**	0.00	0.00
Advertising and market research	2.41%	0.41	**5.04**	0.22	4.82	**3.65**	0.17	3.48	**2.31**	0.10	2.20	**0.00**	0.00	0.00
Air transport	9.08%	3.20	**4.14**	1.01	3.13	**2.78**	0.52	2.26	**0.00**	0.00	0.00	**0.00**	0.00	0.00
Architectural and engineering activities; technical testing and analysis	3.52%	0.11	**12.14**	0.57	11.58	**8.80**	0.44	8.36	**5.64**	0.35	5.30	**0.00**	0.00	0.00
Computer programming, consultancy and related activities; information service activities	5.31%	0.10	**21.07**	1.26	19.81	**15.22**	0.91	14.30	**9.73**	0.66	9.06	**0.00**	0.00	0.00
Construction	17.16%	0.75	**64.81**	4.57	60.25	**46.90**	3.41	43.49	**28.05**	1.09	26.96	**0.00**	0.00	0.00
Crop and animal production, hunting and related service activities	4.34%	0.73	**36.23**	6.23	30.00	**26.16**	4.50	21.66	**14.98**	1.36	13.62	**0.00**	0.00	0.00
Education	7.75%	0.16	**51.43**	5.09	46.34	**37.44**	3.99	33.45	**24.32**	3.12	21.20	**0.00**	0.00	0.00
Electricity, gas, steam and air conditioning supply	6.00%	7.01	**18.47**	10.82	7.65	**4.91**	2.76	2.15	**0.00**	0.00	0.00	**0.00**	0.00	0.00
Financial service activities, except insurance and pension funding	4.91%	0.07	**29.10**	2.82	26.27	**21.06**	2.10	18.97	**13.58**	1.56	12.02	**0.00**	0.00	0.00
Fishing and aquaculture	5.09%	0.32	**3.40**	0.37	3.03	**2.45**	0.26	2.19	**1.55**	0.17	1.39	**0.00**	0.00	0.00
Forestry and logging	2.39%	0.36	**2.63**	0.45	2.18	**1.89**	0.31	1.57	**1.18**	0.18	1.00	**0.00**	0.00	0.00
Human health and social work activities	9.49%	0.23	**85.20**	5.80	79.40	**61.87**	4.56	57.32	**39.90**	3.58	36.32	**0.00**	0.00	0.00
Insurance, reinsurance and pension funding, except compulsory social security	10.80%	0.08	**13.69**	1.03	12.65	**9.91**	0.78	9.13	**6.37**	0.58	5.79	**0.00**	0.00	0.00
Land transport and transport via pipelines	5.16%	1.11	**29.71**	7.36	22.34	**21.79**	5.66	16.13	**4.83**	0.98	3.85	**0.00**	0.00	0.00
Legal and accounting activities; activities of head offices; management consultancy activities	1.49%	0.11	**35.81**	1.76	34.06	**25.94**	1.36	24.58	**16.62**	1.05	15.58	**0.00**	0.00	0.00
Manufacture of basic metals	1.52%	1.02	**9.65**	2.88	6.77	**6.95**	2.07	4.89	**1.85**	0.23	1.62	**0.00**	0.00	0.00
Manufacture of basic pharmaceutical products and pharmaceutical preparations	10.00%	0.74	**4.67**	1.31	3.36	**3.28**	0.85	2.43	**1.64**	0.13	1.52	**0.00**	0.00	0.00
Manufacture of chemicals and chemical products	6.39%	0.74	**10.88**	3.34	7.54	**7.91**	2.47	5.44	**4.17**	0.76	3.40	**0.00**	0.00	0.00
Manufacture of coke and refined petroleum products	29.83%	2.00	**3.56**	1.49	2.07	**2.47**	0.98	1.50	**0.00**	0.00	0.00	**0.00**	0.00	0.00
Manufacture of computer, electronic and optical products	8.25%	0.51	**16.17**	3.19	12.99	**11.44**	2.06	9.37	**6.66**	0.73	5.94	**0.00**	0.00	0.00
Manufacture of electrical equipment	10.56%	0.83	**7.16**	1.30	5.87	**5.09**	0.86	4.24	**2.47**	0.11	2.37	**0.00**	0.00	0.00
Manufacture of fabricated metal products, except machinery and equipment	3.58%	0.57	**12.85**	1.83	11.03	**9.28**	1.32	7.96	**5.61**	0.56	5.04	**0.00**	0.00	0.00
Manufacture of food products, beverages and tobacco products	23.56%	0.45	**18.44**	3.86	14.58	**13.43**	2.90	10.52	**8.35**	1.68	6.67	**0.00**	0.00	0.00
Manufacture of furniture; other manufacturing	10.40%	0.58	**7.22**	1.30	5.92	**5.25**	0.97	4.28	**3.15**	0.44	2.71	**0.00**	0.00	0.00
Manufacture of machinery and equipment n.e.c.	12.25%	0.66	**15.37**	2.36	13.01	**11.11**	1.72	9.39	**6.56**	0.61	5.95	**0.00**	0.00	0.00
Manufacture of motor vehicles, trailers and semi-trailers	21.04%	0.52	**12.99**	2.39	10.60	**9.28**	1.63	7.65	**5.49**	0.64	4.85	**0.00**	0.00	0.00
Manufacture of other non-metallic mineral products	1.67%	2.27	**6.80**	1.45	5.35	**4.83**	0.97	3.86	**0.00**	0.00	0.00	**0.00**	0.00	0.00
Manufacture of other transport equipment	11.75%	0.58	**6.96**	0.98	5.98	**5.03**	0.72	4.32	**3.04**	0.30	2.74	**0.00**	0.00	0.00
Manufacture of paper and paper products	3.12%	0.46	**4.09**	0.99	3.10	**2.98**	0.74	2.24	**1.84**	0.42	1.42	**0.00**	0.00	0.00
Manufacture of rubber and plastic products	3.16%	0.55	**6.83**	1.21	5.61	**4.96**	0.91	4.05	**3.01**	0.44	2.57	**0.00**	0.00	0.00
Manufacture of textiles, wearing apparel and leather products	13.06%	0.59	**8.77**	1.96	6.81	**6.42**	1.50	4.92	**3.84**	0.72	3.12	**0.00**	0.00	0.00
Manufacture of wood and of products of wood and cork, except furniture; manufacture of articles of straw and plaiting materials	2.31%	0.49	**3.48**	0.65	2.83	**2.54**	0.49	2.04	**1.57**	0.28	1.29	**0.00**	0.00	0.00
Mining and quarrying	1.87%	0.90	**21.53**	8.98	12.55	**15.96**	6.90	9.06	**6.13**	1.85	4.28	**0.00**	0.00	0.00
Motion picture, video and television programme production, sound recording and music publishing activities; programming and broadcasting	5.99%	0.21	**7.61**	3.48	4.13	**5.46**	2.49	2.98	**3.66**	1.77	1.89	**0.00**	0.00	0.00
Other professional, scientific and technical activities; veterinary activities	2.52%	0.11	**9.92**	0.47	9.45	**7.17**	0.35	6.82	**4.59**	0.27	4.32	**0.00**	0.00	0.00
Other service activities	7.47%	0.15	**38.21**	7.91	30.30	**27.81**	5.94	21.87	**18.32**	4.46	13.86	**0.00**	0.00	0.00
Postal and courier activities	1.08%	0.07	**4.12**	0.44	3.68	**2.98**	0.32	2.65	**1.92**	0.24	1.68	**0.00**	0.00	0.00
Printing and reproduction of recorded media	1.93%	0.21	**3.34**	0.56	2.78	**2.43**	0.43	2.00	**1.59**	0.32	1.27	**0.00**	0.00	0.00
Public administration and defence; compulsory social security	7.50%	0.20	**136.81**	31.64	105.17	**99.37**	23.46	75.92	**65.49**	17.39	48.11	**0.00**	0.00	0.00
Publishing activities	6.53%	0.21	**6.27**	0.58	5.70	**4.55**	0.44	4.11	**2.94**	0.33	2.61	**0.00**	0.00	0.00
Real estate activities	7.96%	0.07	**106.09**	93.93	12.16	**89.47**	80.70	8.77	**74.89**	69.33	5.56	**0.00**	0.00	0.00
Repair and installation of machinery and equipment	5.76%	0.04	**2.75**	0.22	2.53	**2.00**	0.17	1.83	**1.29**	0.13	1.16	**0.00**	0.00	0.00
Retail trade, except of motor vehicles and motorcycles	9.74%	0.04	**46.18**	4.22	41.96	**33.61**	3.32	30.29	**21.81**	2.61	19.19	**0.00**	0.00	0.00
Scientific research and development	6.82%	0.41	**8.10**	0.81	7.28	**5.83**	0.58	5.26	**3.65**	0.31	3.33	**0.00**	0.00	0.00
Sewerage; waste collection, treatment and disposal activities; materials recovery; remediation activities and other waste management services	2.52%	0.70	**4.59**	1.41	3.18	**3.34**	1.05	2.30	**1.82**	0.36	1.45	**0.00**	0.00	0.00
Telecommunications	10.51%	0.07	**12.42**	4.63	7.79	**8.96**	3.34	5.62	**5.97**	2.41	3.56	**0.00**	0.00	0.00
Warehousing and support activities for transportation	2.58%	0.14	**11.94**	3.33	8.61	**8.83**	2.61	6.22	**5.99**	2.05	3.94	**0.00**	0.00	0.00
Water collection, treatment and supply	5.46%	1.05	**2.76**	1.64	1.11	**2.07**	1.26	0.80	**0.49**	0.24	0.25	**0.00**	0.00	0.00
Water transport	3.69%	2.01	**3.15**	1.31	1.84	**2.24**	0.91	1.33	**0.00**	0.00	0.00	**0.00**	0.00	0.00
Wholesale and retail trade and repair of motor vehicles and motorcycles	8.34%	0.04	**12.64**	0.74	11.89	**9.17**	0.58	8.59	**5.89**	0.45	5.44	**0.00**	0.00	0.00
Wholesale trade, except of motor vehicles and motorcycles	6.48%	0.04	**52.09**	3.73	48.37	**37.79**	2.88	34.91	**24.34**	2.22	22.12	**0.00**	0.00	0.00

Methods

Overview

The aim is to estimate how much carbon derives from present-day global capital stocks if they were allowed to depreciate along their planned trajectory, and to contrast this with carbon budgets believed to be consistent with the Paris Agreement. Unlike previous such simulations,[23] we do not partition the economy into a limited number of activities that necessarily produce carbon and the rest that does not. Instead, we take the view that all current capital is reliant on fossil fuel use to varying degrees as reflected in the carbon intensity of the output of different sectors.

We disaggregate the global economy into 56 sectors, with the capital in each sector being comprised of a 'human' and 'produced' component. For each sector and component we specify a 'service life' (for produced capital), or a 'working life' (for human capital). These determine the aggregate turnover timescale for that component if it were to operate as planned. These timescales range from years (machines and equipment) to decades (structures, houses and careers).

As capital depreciates over time it continues to produce output according to the productivity and capital value of a sector. Using the carbon intensity of the sector we translate this output into annual carbon emissions. As a result, we attempt to estimate the temporal dynamic and total emissions derived from current produced and human capital stocks as if they were to live out their planned lifetimes. We then compare the cumulative carbon budget that arises from this with those thought to be compatible with the Paris Agreement and the associated policy responses, in particular the emerging net-zero framework.

Finally, if we exceed a required carbon budget, we impose early retirement on portions of the global capital portfolio using both carbon intensity and age relative to service life as our selection criteria. This approach prioritises removing elements of the economy that contribute most to climate change and yet are closest to satisfying their planned payback. We estimate the capital Value at Risk (VaR) from these early retirements as the sum value of all such retirements, weighted by their age relative service life, reflecting the likelihood that capital at or beyond the service life will invariably have fully redeemed the investor's expectations, whereas capital younger than this would not.

Intuition for capital inventory turnover, service lives and inertia

The conservation equation for capital used in all national account procedures[42] necessarily defines the turnover and hence the inertial dynamics of any given stock. If K_i is the value size of the i'th capital stock (T$) and u_i the yearly investment in each of these categories (T$/yr), the conservation of capital follows the dynamics

$$\dot{K}_i = u_i - \frac{K_i}{T_i} \quad (1)$$

where T_i (yrs) is the turnover timescale of the stock, which is equivalent to the inverse of its effective depreciation rate. There are various equivalent ways of understanding the turnover timescale T_i. For example, in a hypothetical steady state where investments balance net retirements, T_i can be viewed as the average length of time an individual asset is expected to survive within a sectoral cohort and hence directly parallels the projected service life of an asset in any given class, even if observed service lives vary significantly about this value. It is because of this we are able to exploit service life information to specify the turnover timescale of specific sectors of the economy (see below). In this context T_i mirrors the residence time of an idealised well-mixed physical system, but also the average queuing time of non-idealised social systems as reflected in Little's law (in queueing theory),[43] where u_i is analogous to the arrival rate and K_i the queue size.

In the context of economic inertia, T_i is the time constant, or e-folding time, for the temporal evolution of any first order system specified along the lines of equation (1). As a result, it provides a universal measure of the speed at which such a system approaches any steady state. As such, T_i is an appropriate measure of the inertia of an asset cohort or sector, while the capital inertia of the entire economy is represented by how these cohort effects aggregate into the distribution of turnover timescales comprising the entire economy. In particular, this aggregation critically depends on how much capital is associated with each timescale. Just as service lifetimes of individual assets aggregate through the cohort-level survival function to determine the representative cohort level service life, so with the entire economy the turnover timescales of each sector weighted by the aggregate value of that sector themselves aggregate to determine the turnover timescale, or service life, of the economy and hence its inertia.

Estimating capital stocks and turnover times

To conduct our analysis we construct a dataset of the portfolio of global capital stocks in 2020 and their associated turnover times. To capture the heterogeneity in capital stocks with respect to carbon intensity, we estimate the value of capital assets disaggregated across 56 economic sectors within each of 43 major national economies. The two main forms of capital stock we consider are produced and human capital. Produced capital is the value embodied in assets such as buildings, machinery, and other longer-lived types of durable equipment. Human capital is the value of the productive output of the labour force.

Our primary starting point is the World Input-Output Database (WIOD).[44] This dataset contains a range of detailed national accounts data for 43 countries accounting for ~85% of world GDP. As well as a comprehensive accounting of annual economic flows between producing sectors and to final consumers, the database also includes information on a number of key inputs like employment, wages and capital assets. The latest 2016 version of this dataset includes data spanning the years 2000-2014. Because the input-output table is particularly concerned with sectoral interactions, the data is also consistently disaggregated according to the 56 sectors in line with the NACE rev.2 / ISIC rev.4 industry classification system. Using the WIOD as a basis, we undertake a range of further calculations to estimate capital stocks more fully for a range of detailed asset types, whilst maintaining this same level of country and sectoral detail.

1. Produced capital

The value of produced capital assets can be thought of as the present discounted value of all future returns from various buildings, machines, and other longer-lived durable equipment that are used in the economy. The WIOD includes estimates of the nominal capital stock for each sector in each country.

To estimate the effective turnover timescale of each sector we divide the national sector totals into eight representative asset classifications for which we know approximate service lives and sectoral shares. We then re-aggregate based on the capital share of each asset type to estimate the sectoral turnover timescale. The eight generic asset types we use are based on the ESA2010 asset classification system and are as follows: two types of buildings (dwellings and other non-residential); four types of machinery and equipment (transport, other machines, computer hardware, and telecoms); two types of intellectual property assets (computer software, and research & development); and lastly cultivated assets associated with food supply.

To disaggregate sector produced capital totals between the eight representative asset types we use the EUKLEMS Growth and Productivity Accounts, supplemented with national accounts statistics from the OECD where appropriate. In both cases, these datasets include data on capital stocks at the country by sector by asset class level. For instance, the capital used in the mining sector in Australia is mostly comprised of commercial buildings (62%) and machinery (29%). Conversely, the capital in the computer programming sector in Germany is less dominated by commercial buildings (27%) and machinery (28%), with a greater proportion being concentrated in computer hardware (16%) and software (11%). Where these asset shares were not available for some countries or sectors we interpolated based on those we did have data for. We then apply these asset shares to the total sectoral produced capital stocks in the WIOD dataset to get estimates of the produced capital stock for each country by sector by asset type combination in our sample.

To characterize the inertia embodied in the eight produced capital assets we use the asset service lives for each as used in the original construction of the national accounts data. Whilst the values used for different asset types and sectors can vary across different national statistics offices, in general this variance is relatively small. With that in mind, we source sector specific asset service life values from the OECD, UK Office of National Statistics (ONS),[45] Statistics Netherlands, the US Bureau of Economic Analysis, and Statistics Canada (pers comm).

Lastly, to account for the residual 15% of world GDP not included in the WIOD dataset we rescale the WIOD total produced capital with the World Bank equivalent values. Our sectoral values for produced capital and final demand, totalling 203 T$ and 63 T$ respectively, were scaled to the 2014 World Bank equivalents estimates of 231 T$ and 74 T$ respectively. We then extrapolated estimates for 2020 and 2025 using a constant 2.25% growth rate, based on the average rate of growth in global current US$ GDP between 2011-2019. The 2020 sectoral produced capital values are given in Suppl. Table 1.

2. Human capital

The economic value embodied in the labour force is the largest component of the capital stock in most countries.[46] However, most national accounts do not yet include estimates of the stock of human capital, and this is also the case for the WIOD dataset that forms the basis of our analysis. We therefore estimate human capital stocks for each sector within each country based on the approach set out by Jorgenson & Fraumeni'[47] and implemented recently by the World Bank.[46] Essentially this involves using a similar approach as for produced capital; namely calculating the present discounted value of future returns, where returns are represented through average wages.

Annual average wage compensation is available for each country and sector in the WIOD dataset. In line with the World Bank,[46] we assume these annual returns persist for the remaining working lifetime of the representative person in the labour force of each sector. To estimate remaining working lifetimes we use labor force participation rates and unemployment rates by age group from the International Labour Organisation (ILO). We rely on the modelled estimates as these are more complete and consistent across countries, providing values for all the 43 countries in our sample from 1990 to 2023. For each age cohort in the ILO data we calculate expected remaining working lifetime for a representative person by summing their participation rates in the economy over all future years.

We now calculate human capital stocks by country and sector by taking the annual average wage compensation values from the WIOD dataset, projecting this forward according to average expected remaining working lifetimes of each age cohort in a given year, and then summing to present discounted value terms using a 1.5% discount rate.[46] Human capital stocks can then be aggregated across age cohorts using the age distribution of the total labour force. Here differences in human capital across sectors and countries are driven by differences in average wages, the number of workers in each sector and country, and the working lifetime distributions of these workers. The age structure and working lifetimes of the labor force are assumed to be the same across sectors, although these factors do vary marginally across countries.

Lastly, as with produced capital, we rescale for consistency with the World Bank global human capital values to again account for the residual 15% of world GDP not included in the WIOD dataset. Our sectoral values for human capital totalling 626 T$ were scaled to total the 2014 World Bank estimates of 737 T$. We then extrapolated estimates for 2020 and 2025 using a constant 2.25% growth rate, again based on the average rate of growth in global current US$ GDP between 2011-2019. The 2020 sectoral human capital values are given in Suppl. Table 1.

Sector carbon emissions intensity

During rapid decarbonisation, some parts of the economy will be more exposed to stranded assets than others. We choose to measure this exposure with the carbon intensity of each sector, similarly to [2], as well as using this intensity to project future sectoral emissions. Unfortunately, the WIOD database does not include sectoral emissions estimates, and so we assign each of our 56 sectors a carbon emissions rate by sector through matching with the EXIOBASE database estimates, which shares a very similar sectoral disaggregation to that of WIOD but also includes sectoral emssions estimates.

We use the production-based emission estimates to reflect how capital is directly tied fossil fuel reserves and to avoid double counting between sectors. We calculate emissions intensities for each sector by dividing the total sector production emissions by WIOD sector demand. Lastly, we rescale our sectoral emissions to ensure the 2014 sum (8.32 GtC) aligns with the Global Carbon Project's observed emissions from fossil fuels and industry (9.60 GtC), again compensating for the fact that WIOD represents 85% of the global economy. These emissions are extrapolated to the 2020 and 2025 start dates assuming the 2014 carbon intensities hold, and these intensities are also assumed to hold for the entire lifetime of the carbon-dependent captial therafter. This is because we are attempting to represent the lock-in of capital to particular parterns of energy use. This is not to be confused to the economy-wide sectoral carbon intensities, which will fall dramatically post-2020 (2025) in our forward simulations due to the implied effects of net-zero capital investments (see below). The 2020 sectoral carbon intensities are given in Suppl. Table 1.

Forward simulations

We consider two classes of forward simulations. The first simply explores the amount of carbon associated with the 2020 (or 2025) global stock of produced and human capital. The second explores any additional removals of capital required to reduce annual emissions to a level consistent with the recent net-zero interpretations of the Paris Agreement, where annual emissions decline linearly to net-zero in 2050, starting in 2020. This equates to a total net release of an additional ~160 GtC given an assumed 2020 emissions rate of 10.6 GtC based on the GDP and carbon intensity extrapolations discussed above. In both sets of scenarios, future investments are not considered explicitly given the aim is to evaluate the size of the *current* capital at risk in a rapid transition. As a result, there is an implicit idealisation, for simplicity of interpretation, that all future investment is, by definition, net-zero compliant.

When no early retirements are considered, starting in 2020 (or 2025), produced capital is depreciated according to the inverse of its estimated sectoral timescale as shown in Figure 1i. In contrast, and because of the importance of human capital both economically and in our study, we handle the working population retirements more explicitly, attempting to represent the full range of working lifetimes in populations (Figure 1ii). We assume that in 2020 (or 2025) the workforce is distributed with age according to the ILO global participation rate data (Figure 1ii) and simply increment retirements by annually incrementing this population and removing participants to maintain the ILO profile (Figure 2ii inset).

The i'th sectoral output (GDP), y_i, is then calculated annually according to each sector's productivity, A_i, and total (human + produced) capital, K_i,

$$y_i = A_i K_i \qquad (2)$$

where A_i is estimated for each sector from the 2020 values of K_i and y_i. These 2020 sectoral productivities are given in Suppl. Table 1 and are assumed constant post-2020 again because they relate to legacy capital. Note labor is being represented explicitly through capital and not as a separate factor of production.

Emissions from each sector are estimated by multiplying the GDP values by the estimated sectoral emissions intensities described above, and summed across all sectors to give total industrial emissions. We evaluate carbon accumulation to 2100 both because this is a common end point, and because the longest lived elements of capital have largely disappeared in the intervening 80 years. The capacity of any future negative emissions technology is highly uncertain,[7] likewise emissions from land-use change. As a result, we focus exclusively on the accumulation of industrial emissions.

To quantify the active removal from the global capital portfolio required to restrict emissions to the net-zero pathway, the predicted total emissions in any year were compared to the desired pathway leading to net-zero in 2050 and then an amount of capital, human or produced, was removed in year to reduce emissions to the desired level. Here capital was prioritised for retirement according to its emissions intensity and age relative to service life or expected working lifetime. The rationale for these selection criteria was that it is likely that capital with higher carbon intensity would be retired first, as would capital closest to end of working life. These two criteria were applied simultaneously following the multicriteria selection method of Ehrgott.[48] The effect of retiring the highest carbon intensity and closest to end of life capital first is that this also will tend to retire the smallest possible amount of capital, hence implicitly minimising the capital at risk value. All additional retirements are incremented on top of the planned retirements detailed above, tracking sectoral capital values and ages accordingly.

The value of the capital retired reported in Table 1 is simply the sum of all early retirements, and these are also tracked in Suppl. Table 1. Again, Value at Risk (VaR) is calculated from these early retirements as the sum value of all such retirements, weighted by their age relative service life, reflecting the likelihood that capital at or beyond the service life will invariably have fully redeemed the investor's expectations, whereas capital younger than this would not. Beyond this we do not discount value in any way.

We estimate uncertainty in our simulations by incorporating the effects of uncertainties in our initial starting values of capital, GDP, emissions, and how these transfer into our estimates of carbon intensities and productivities. Uncertainty in our starting values for global capital are derived from the standard deviation of the three available 2014 global produced estimates; WIOD, World Bank, and Penn World Tables (± 36 T$). Uncertainty in global GDP are taken from the standard deviation of the eight available global estimates presented in Jarvis and King (± 15 T$/yr).).[49] For industrial emissions we replicate the 1σ confidence level reported in Global Carbon Project (± 0.5 GtC). The relative uncertainties in the sectoral emissions intensities and productivies are assumed to be the same as their global counterparts, which are estimated using method of moments and presented in Suppl. Table 1.

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