

Climate constraints on the carbon intensity of economic growth

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LETTER

Climate constraints on the carbon intensity of economic growth

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8 September 2015Julie Rozenberg¹, Steven J Davis², Ulf Narloch¹ and Stephane Hallegatte¹¹ World Bank Group, Climate Change Vice Presidency, Chief Economist Office, Washington, DC 20433, USA² University of California, Irvine, Department of Earth System Science, Irvine, CA 92697, USAE-mail: jrozenberg@worldbank.org**Keywords:** kaya, carbon budget, climate change mitigation, carbon intensity, committed emissions, stranded assetsSupplementary material for this article is available [online](#)

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**Abstract**

Development and climate goals together constrain the carbon intensity of production. Using a simple and transparent model that represents committed CO₂ emissions (future emissions expected to come from existing capital), we explore the carbon intensity of production related to new capital required for different temperature targets across several thousand scenarios. Future pathways consistent with the 2 °C target which allow for continued gross domestic product growth require early action to reduce carbon intensity of new production, and either (i) a short lifetime of energy and industry capital (e.g. early retrofit of coal power plants), or (ii) large negative emissions after 2050 (i.e. rapid development and dissemination of carbon capture and sequestration). To achieve the 2 °C target, half of the scenarios indicate a carbon intensity of new production between 33 and 73 g CO₂/\$—much lower than the global average today, at 360 g CO₂/\$. The average lifespan of energy capital (especially power plants), and industry capital, are critical because they commit emissions far into the future and reduce the budget for new capital emissions. Each year of lifetime added to existing, carbon intensive capital, decreases the carbon intensity of new production required to meet a 2 °C carbon budget by 1.0–1.5 g CO₂/\$, and each year of delaying the start of mitigation decreases the required CO₂ intensity of new production by 20–50 g CO₂/\$. Constraints on the carbon intensity of new production under a 3 °C target are considerably relaxed relative to the 2 °C target, but remain daunting in comparison to the carbon intensity of the global economy today.

1. Introduction

Despite the complexity of the climate system, climate models project a nearly direct relationship between cumulative CO₂ emissions and mean global temperatures over the remainder of this century [1, 2]. Thus, limiting total human-induced warming to a given level implies a budget of cumulative CO₂ emissions [3] and that CO₂ emissions eventually decrease to zero [4]. For example, limiting the temperature increase to less than 2 °C relative to the period 1861–1880 with a 66% probability would require cumulative CO₂ emissions after 1870 to remain below ~2900 (2550–3150) Gt CO₂, with the range depending on non-CO₂ forcing and the temporal pathway of emissions. Of this 2900 Gt CO₂ budget, roughly two-thirds, or ~1900 Gt CO₂ has already been emitted, leaving a remaining budget of ~1000 Gt CO₂. The remaining budget increases

under less ambitious climate targets: ~1900 Gt CO₂ to limit the temperature increase to 2.5 °C and ~2800 Gt CO₂ to limit the increase to 3 °C [5].

Economic growth will tend to increase energy demand over this century [5]. In 2013, 92% of CO₂ emissions were from burning fossil fuels [6] that in turn produced 85% of the energy used worldwide [7]. Avoiding high levels of climate warming while meeting growing world energy demands thus depends upon rapidly transforming our energy system so that it relies on technologies that do not emit CO₂ to the atmosphere [8–10]. However, existing and long-lived capital infrastructure such as fossil fuel-burning power plants may constrain how quickly such a transformation can occur [8, 11, 12].

Future CO₂ emissions ‘committed’ by now-existing infrastructure can only be avoided by retiring or retrofitting the capital prior to the end of its expect lifetime and replacing it with lower-emitting

technologies. But early retirement would in many cases undermine short-term economic growth, and raise issues of political economy: stranded assets translate into a loss of wealth concentrated in a few vested interests, whose owners may oppose climate mitigation policies [13–16]. In addition, the scaling-up of new, cleaner capital is constrained by capital and labor availability, learning processes, and institutions [17–20]; and the retrofitting of existing capital, buildings in particular, is impeded by lack of skilled labor, lack of funding, and bad economic incentives [21, 22]. This is especially true in the developing world given the current infrastructure finance deficit [23–25]. Hence the challenge for the carbon intensity of production by new capital may be even bigger than widely believed.

Here, we assess the carbon intensity of production generated by new capital required to meet climate targets and satisfy needs from population and economic growth by 2050. Using a simple and transparent model, we explore several thousand scenarios to analyze the uncertainty space that arises from demographic, socio-economic, and technical evolutions.

2. Materials and methods

Our analytic approach and results are based on a modified version of the Kaya identity [26, 27], which decomposes global CO₂ emissions, F , into three factors:

$$F = P \times \left[\frac{G}{P} \right] \times \left[\frac{F}{G} \right] = P \times g \times h, \quad (1)$$

where P is population, G is gross domestic product (GDP), $g = G/P$ is GDP per capita, and $h = F/G$ is carbon intensity of production. For the purposes of this study, the production factor is further disaggregated by the share that is related to existing capital in 2013 and the share related to new capital after 2013 (distinguished by the subscripts *exist* and *new*, respectively). We assume that if investment stopped tomorrow, total production would decrease in proportion to the stock of existing ‘energy-related’ capital (i.e. energy capital and capital that indirectly creates demand for energy, like transport, buildings, industry) (see supplementary material available at stacks.iop.org/ERL/10/095006/mmedia). New production in our model comes from either new capital investment or retrofitting of existing capital. In this paper we refer to production generated by existing capital in 2013 as ‘committed production’ and production generated by new—or retrofitted—capital after 2013 as ‘new production’. A separate Kaya identity can thus be written for existing and new production, which sum to global CO₂ emissions F :

$$\begin{aligned} F &= P \times \left[\frac{G}{P} \right] \times \left[\frac{F}{G} \right] \\ &= P \times \left[\frac{G}{P} \right] \times \left[\frac{F_{\text{exist}}}{G_{\text{exist}}} \times \frac{G_{\text{exist}}}{G_{\text{exist}} + G_{\text{new}}} \right. \\ &\quad \left. + \frac{F_{\text{new}}}{G_{\text{new}}} \times \frac{G_{\text{new}}}{G_{\text{exist}} + G_{\text{new}}} \right] \\ &= P \times g \times \left[h_{\text{exist}} \cdot sh_{\text{exist}} + h_{\text{new}} \cdot sh_{\text{new}} \right], \quad (2) \end{aligned}$$

where sh_{exist} and sh_{new} are the shares of existing and new production respectively.

Our focus is the carbon intensity of new production, h_{new} , and in particular what value of h_{new} is required on average between 2014 and 2050 to meet different cumulative budgets of emissions. We focus on the carbon intensity of production and not of capital for two reasons. First, capital stocks are difficult to measure [28, 29]. Second, CO₂ emissions are directly linked to production and not to the capital stock (for a power plant for instance, a useful measure is the CO₂ emitted by kilowatt-hour of produced electricity), therefore the binding constraint for emissions is on production and not on capital. Of course, a constraint on the CO₂ intensity of production will be translated into a constraint on capital: a lower CO₂ intensity of production requires cleaner capital and/or more efficient capital. This can be done through investment in new capital and technologies or through retrofitting of existing capital [30–32]. The less productive the new capital stock, the bigger the stock and the tighter the constraint on what it can emit per dollar invested. In the supplementary material we present some results on the constraint on the carbon intensity of new capital for different productivities of capital. We find that the main conclusions of the paper hold, and that a constant or higher productivity of capital can mitigate the constraints on capital to a small extent.

In our scenarios, P grows according to a demographic trend. We assume existing production G_{exist} will decrease over time because of capital depreciation, in proportion to committed emissions, F_{exist} (supplementary data, section 2). To calculate committed emissions, we differentiate between four sectors: energy (power plants and refineries), industrial (e.g., cement factories), buildings (e.g., residential buildings), and transport (e.g. cars, planes). New emissions F_{new} will be derived from production related to new capital investments G_{new} , which depends on the GDP growth rate and the lifetime of existing capital.

Given these assumptions, the required carbon intensity of new production depends on seven parameters: (1) the budget of cumulative CO₂ emissions, (2) population growth (growing P), (3) the lifetime of energy capital, (4) the lifetime of industrial capital, (5) the lifetime of buildings, and (6) the lifetime of transport capital, and (7) growth of GDP per capita (determining g).

We model the carbon intensity of new production, h_{new} , by varying these parameters across a large range

of possible values to build a database of 3000 scenarios of different parameter combinations, in each case calculating committed emissions, deducting the remaining budget F_{new} from the available carbon budget and solving for h_{new} given the constraints of P , and g . We use a latin hypercube sample algorithm to generate these scenarios, sampling the parameters uniformly across a range of plausible values to ensure that we represent the broadest set of possible futures (see 'Robust Decision Making' described by [33]). The simplicity of this approach allows for a transparent exploration of the uncertainty space and assessment of the relative importance of the different parameters. Further details of our methods are available in the supplementary data.

2.1. Carbon budgets

The budget of cumulative CO₂ emissions that is consistent with any temperature target is uncertain, depending on the strength of natural carbon sinks and climate sensitivity (i.e. the change in temperature in response to changes of radiative forcing). Climate model results can provide an estimate of future cumulative CO₂ emissions consistent with a given temperature target. The representative concentration pathway (RCP) 2.6, which corresponds to radiative forcing of 2.6 W m⁻² in 2100, represents a low-emissions scenario with a 66% chance of maintaining global temperature increase below 2 °C by the end of the century [34, 35]. Here we explore budgets up to those which have 50% chance of staying below a 3 °C temperature increase by the end of the century according to the emissions pathways used by the Intergovernmental Panel on Climate Change [5].

Since the focus of this paper is the role of committed emissions in the efforts needed in the short to medium run to stay on track of a 2 or 3 degrees temperature increase by the end of the century, we focus on the 2013–2050 period. We use RCP trajectories by 2050, but the total budget is higher, as emissions reach zero in the second half of the century.

With a 2 °C target, the short- to medium-term budget 2013–2050 is highly dependent on the availability of large negative emissions after 2050 [36, 37]. In the RCP2.6, net global emissions are negative after 2075, at a rate of about 2.3 Gt CO₂ per year. In other scenarios this rate increases up to 20 Gt CO₂ of net negative emissions per year after 2075 [5]. To assess the impact of these uncertainties on the required carbon intensity, we run the same analyses as above with different short-term budgets consistent with 0 to 20 Gt CO₂ of net negative emissions after 2075.

2.2. Committed emissions and the expected lifetime of capital

Committed emissions are the product of the annual emissions of production from existing capital and the remaining lifetime of capital [11]. We calculate the

committed emissions related to power plants, other energy capital (e.g., refineries), transportation infrastructure (road and air), industrial capital (e.g., cement- and steel-making) and buildings using estimated annual emissions from each type of capital [38, 39] combined with data or estimates of the vintage of existing capital [8, 40]. In each case, we assume emissions are from capital that depreciates linearly, at a rate of 1/L where L is the lifetime of this capital, such that committed emissions vary according to the assumed lifetime of the different infrastructures. We model lifetimes ranging from 20 to 60 years for energy capital (power plants and refineries), from 10 to 50 years for industrial capital, from 20 to 100 years for buildings, and from 5 to 30 years for transportation capital. Because accurate numbers for the average lifetime of these aggregated categories of capital are not available, these ranges are wide but in each case represent plausible assumptions (see supplementary data for further details on how the ranges were chosen). Note that this lifetime depends on economic decisions, and the lower range can result from early decommissioning or retrofitting of the capital. Since our numbers are averages over the global stock, 20 years lifetime means that some power plants or buildings can last much longer in developing countries while in developed countries others are immediately decommissioned or retrofitted.

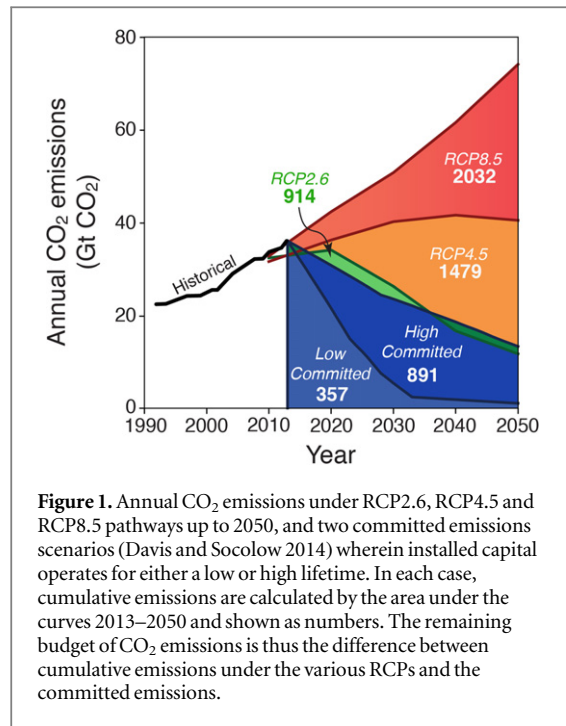
2.3. Economic and population growth

Assumptions about future population and economic growth are as or even more uncertain as assumptions on the lifetime of carbon-intensive capital. For population projections, we use the low and high range of UN Population Statistics scenarios of between 8.3 and 10.9 billion in 2050 [41].

For GDP per capita growth, the potential futures lie between 0 growth on average worldwide (for instance if developed countries have a negative per capita growth while developing countries keep growing) and up to 4% GDP per capita growth globally until 2050. Combined with population growth, this gives a range of 0.5%–6.5% per year for global GDP growth by 2050. Here and throughout this paper, we report GDP and carbon intensities of GDP in 2011 USD relative to purchasing power parity in 2011.

3. Results

Figure 1 shows the large range of committed emissions that result from varying expected capital lifetimes, which may be as small as 357 Gt CO₂ or as large as 891 Gt CO₂ (table S1 shows the corresponding lifetimes). These commitments leave little room for future emissions under the 2013–2050 carbon budget in RCP2.6, which is 914 Gt CO₂. There is greater flexibility under the remaining budget of 1480 Gt CO₂ in RCP4.5. As a comparison, figure 1



also shows the RCP8.5 budget, consistent with a 5 °C temperature increase, for which the budget by 2050 is 2030 Gt CO₂.

Despite our wide-ranging assumptions of carbon budgets, commitments, population and economic growth, the carbon intensity of new production, h_{new} , is consistently much lower than the current carbon intensity of global GDP, which is around 360 g CO₂/\$ (figure 2(A)). In order to follow a low-emissions pathway such as RCP2.6, the carbon intensity of new production ranges between 14 and 110 g CO₂/\$, but with 50% of scenarios falling between 33 and 73 g CO₂/\$ (figure 2(A)).

The range of possible carbon intensities of new production increases with less ambitious climate targets. For a budget consistent with the RCP4.5 by 2050, the carbon intensity range stretches between 97 and 299 g CO₂/\$. This range contains the carbon intensities of the least intensive countries today (between 200 and 300 g CO₂/\$; figure 2(A)) but is still lower than the global average (380 g CO₂/\$).

If global emissions continue to grow before countries begin to decarbonize, for a 2 °C budget we find that each year of delay decreases the required carbon intensity of new production by roughly 20 g CO₂/\$ in the scenarios with the highest required carbon intensity and by 50 g CO₂/\$ in the scenarios with the lowest intensity (assuming that between 2013 and the year when mitigation starts, carbon intensity of global GDP stays constant) (figure 2(B)). In other words, if the required carbon intensity between 2013 and 2050 is very low, it decreases even faster each year that mitigation is delayed. This is because those scenarios with low carbon intensity of new production are characterized by high economic growth and high lifetime of

energy and industry capital. If the start of mitigation is delayed until 2018, in the majority of scenarios the required carbon intensity of new production under a 2 °C budget would be negative (figure 2(B)). For a 3 °C budget, the target can be reached with positive carbon intensities of production even if additional mitigation (compared to today) starts around 2020. However each year of delay decreases the required carbon intensity of new production by 10 g CO₂/\$ in scenarios with high growth rates.

The carbon intensity of new production is also sensitive to the availability of negative emissions. In scenarios where negative emissions technologies (NETs) deployed later this century, for instance after 2075, deliver large (up to 20 Gt CO₂ per year) net removal of CO₂ from the atmosphere, the 2 °C carbon budget between 2013 and 2050 could increase from 914 to 1970 Gt CO₂ (see supplementary material for details). Such large-scale deployment of NETs is uncertain [42]. But taking into account this uncertainty, one third of the scenarios achieve a 2 °C target with carbon intensities of new production by 2050 that are similar to the least carbon intensive economies today (between 200 and 300 g CO₂/\$; figure 2(C)).

Thus, if large quantities of negative emissions are available, it is possible to meet a 2 °C target if all countries invest in new patterns of economic development that produce an output as clean as the French or Brazilian GDP today. Those scenarios, however, have GDP per capita that grows no more than 2.8% per year through 2050 and negative emissions of more than 12 Gt CO₂ per year after 2075 (table 1). Such scenarios would lead to rather unrealistic emission trajectories (i.e. initial increase in emissions followed by a very sharp decrease after 2050) and may not be feasible given the inertia of current economic systems (or would require the stranding of carbon-intensive capital after 2050). Moreover, these scenarios could result in substantial temperature overshoot before 2050 and concomitant risks to vulnerable human and natural systems.

All the scenarios that stay within the 2 °C carbon budget without negative emissions after 2075 imply lower carbon intensities of new production than even the least carbon-intensive countries today (below 150 g CO₂/\$; figure 2(C)). Of these, the scenarios with the highest carbon intensities (over 70 g CO₂/\$) are also characterized by low GDP growth (lower than 1.2% per year) and average lifetimes of energy and industry capital shorter than 36 years (i.e. early decommissioning of power plants and factories; table 1 and figure 3).

Figure 3 shows the relationship between GDP per capita growth, energy and industry capital lifetime and the required carbon intensity of new production over 2013–2050 for a 2 °C budget with low availability of negative emissions. It shows a correlation between GDP growth and the carbon intensity of new production: the higher GDP growth, the lower the required

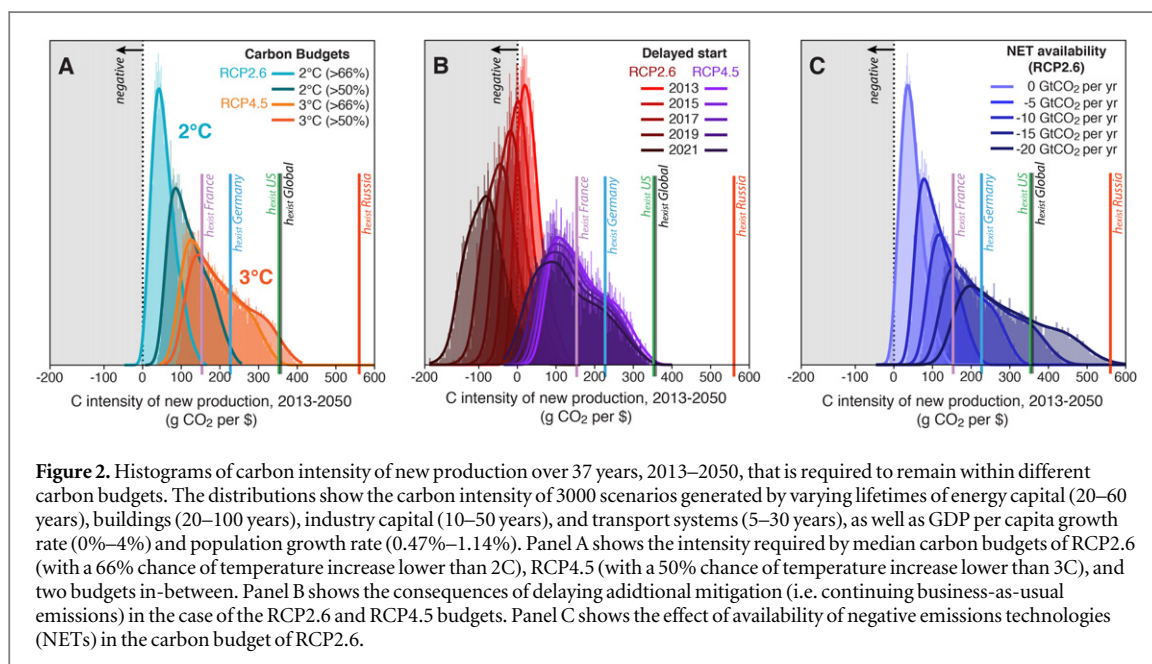


Table 1. Main conditions for selected carbon intensity of new capital investments thresholds required for achieving a 2 °C target. Carbon intensity is measured in g CO₂ per 2011 PPP \$. Calculations based on a patient rule induction method (PRIM).

	Negative emissions technologies available	No negative emissions technologies available
Carbon intensity of new GDP	>200 g CO ₂ /\$	>70 g CO ₂ /\$
% of scenarios	33%	10%
Main conditions		
Energy capital lifetime		<36 years
Industry capital lifetime		<37 years
Transport systems lifetime		
Buildings lifetime		
GDP p.c. growth	<2.8% p.a	<1.3% p.a.
Population growth		
Net negative emissions	>12.5 GtCO ₂ p.a.	
Coverage ^a	76%	69%
Density ^b	90%	74%

^a Coverage measures the share of scenarios as described by the main conditions relative to all scenarios above the threshold.

^b Density measures the share of the scenarios that are above the threshold relative to all scenarios that meet the main conditions.

carbon intensity of new production. It also shows that the lifetime of energy and industry capital drive the required carbon intensity of new production for a given GDP per capita growth rate. Since electricity generation accounts for half of current CO₂ emissions and industry accounts for one third, the lifetime of existing power plants and factories have a big impact on committed emissions and thus on the remaining budget available for production related to new capital (figures 3, 4 and table S1). For each year of lifetime added to existing, carbon intensive energy capital, the carbon intensity of new production required to meet a 2 °C carbon budget (i.e. RCP2.6) decreases by 1.0–1.5 g CO₂/\$.

Figure 4 shows the relative importance of the various parameters on the required carbon intensity of new production 2013–2050 for different targets (assuming the availability of NETs as in RCP2.6). For

strict budgets, the lifetime of energy and industry capital, and thus committed emissions, dominate. As the carbon budget increases, per capita GDP growth becomes the main determinant of the required carbon intensity of new production, explaining 90% variance in required carbon intensity for a 3 °C target. In scenarios with per capita GDP growth greater than 2.5% per year, even a 3 °C target can only be reached with carbon intensities of new production lower than 72 g CO₂/\$. Meanwhile, the uncertainty in UN population scenarios has very little influence on the required carbon intensity of new production that will be built before 2050 (figure 4).

4. Discussion and conclusions

Our results regarding the carbon intensity of new production are broadly consistent with previous

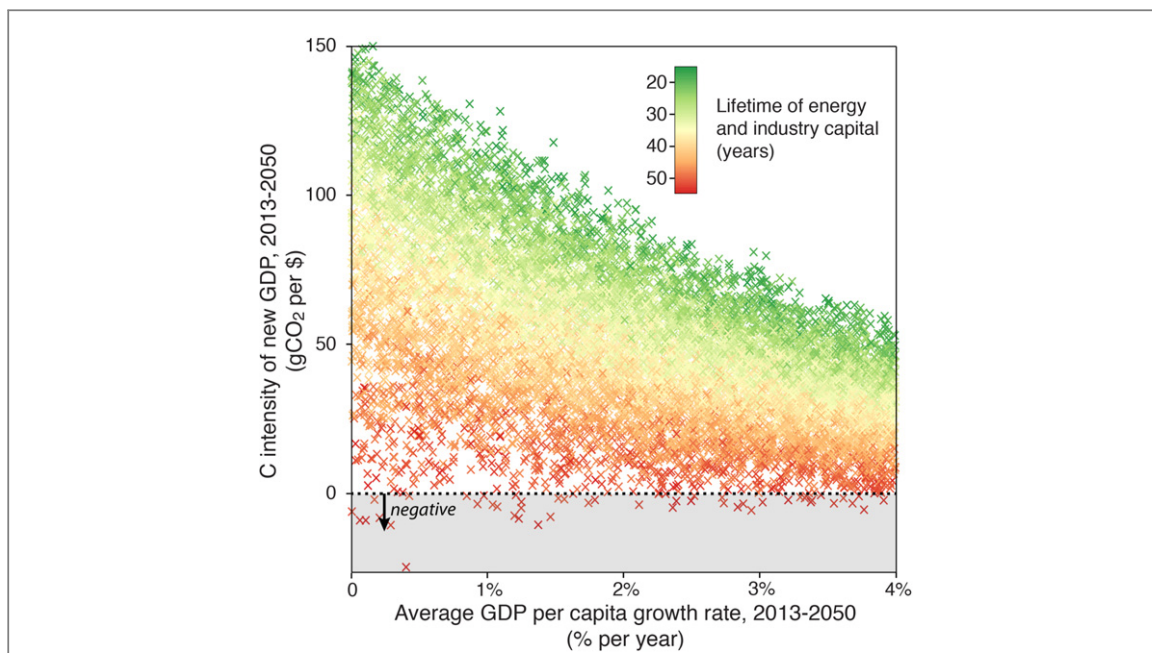


Figure 3. The relationship between GDP per capita growth, lifetime of energy and industry capital and the required carbon intensity of new production 2013–2050 under a 2 °C target.

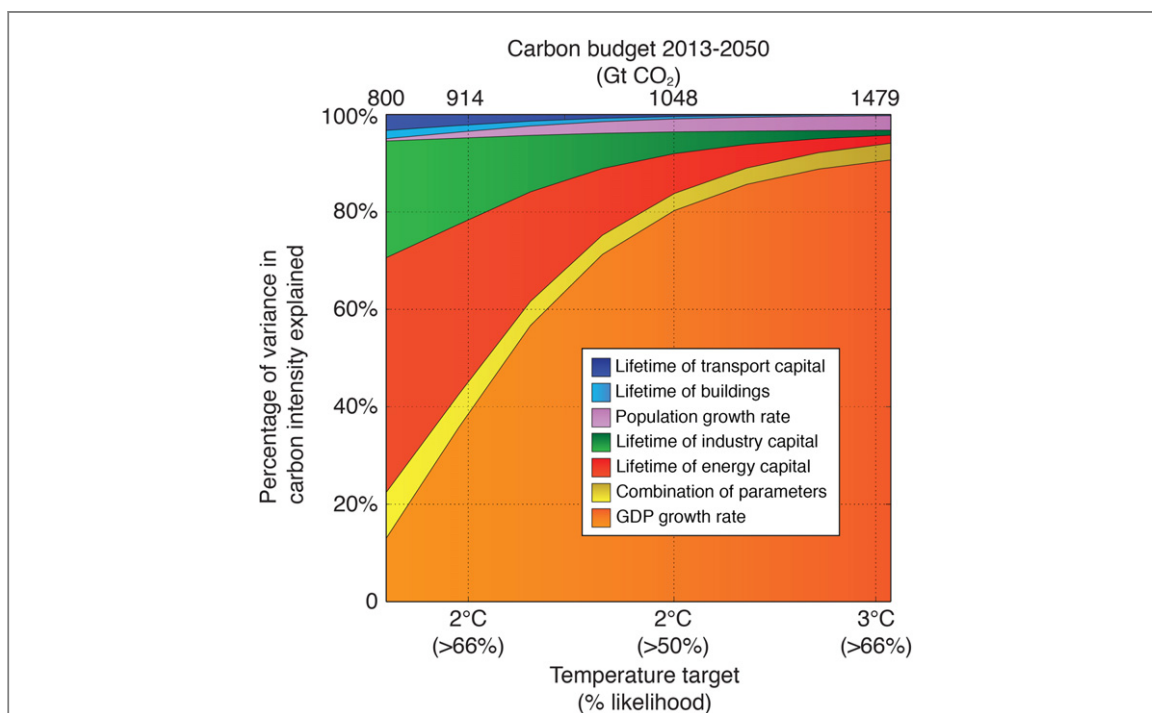
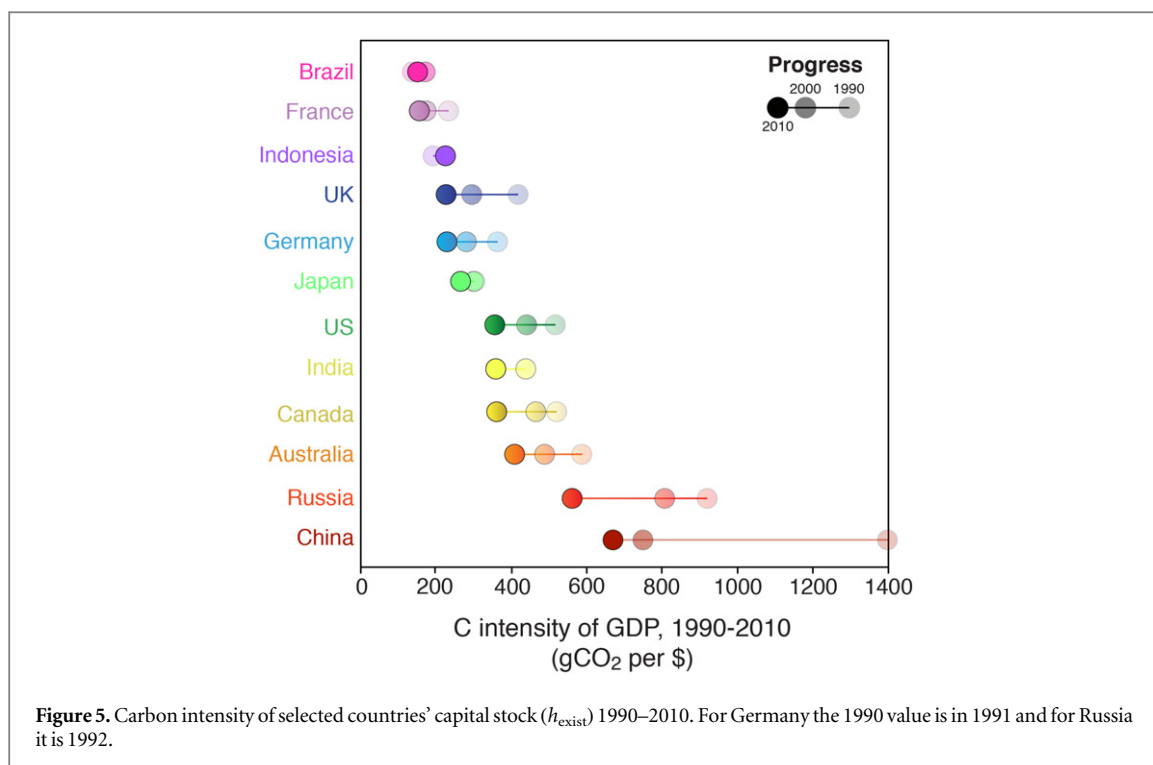


Figure 4. The relative importance of different parameters on the carbon intensity of new production 2013–2050 under different climate targets.

studies using large integrated assessment models [43–49]. However, the simplicity of our model allows for a systematic exploration of the uncertainties and a level of transparency that the complex, integrated models do not. For instance, [49] explore stranded assets using a large integrated assessment model, providing useful estimates on how many assets are likely to be stranded. But they only explore three possible lifetimes of energy infrastructure. In comparison, we continuously vary

all the key parameters across large ranges of possible values and then assess the relative importance of these parameters.

In doing so, we confirm the limited role played by population change [50], suggesting that at the global level, demographic policies are not an effective mitigation tool. We also confirm the critical role of energy investments in the next decades [43, 45, 48, 51, 52], and the importance of the ability to remove large



amounts of CO₂ from the atmosphere after 2050 [37, 47].

Reducing the carbon intensity of new production to the extent and at the speed required to avoid warming in excess of 2 °C or even 3 °C will be extremely challenging. The carbon intensity of global production decreased from 480 to 400 g CO₂/\$ between 1990 and 2000, then experienced a slight rise over the period 2000 to 2005 before falling to 380 in 2010. If total intensities continue to decrease at this rate (between 2.5 and 5.3 g CO₂/\$ per year based on 2000–2010 and 1990–2010, respectively), the carbon intensity of global production would be between 280 and 170 g CO₂/\$ in 2050, which would correspond to an average intensity of 260–320 g CO₂/\$ over the period 2014–2050³. In stark contrast, the average carbon intensity of global production implied by a 2 °C budget is between 110 and 200 g CO₂/\$ if (1) mitigation efforts start immediately, (2) the lifetime of existing energy infrastructure is shorter than expected, (3) economic growth is modest, or (4) large quantities of negative emissions are available after 2050. A pathway compatible with the 2 °C target thus demands a *radical* deviation from the current, business-as-usual trend: indeed, failing to realize any of these optimistic assumptions will mean that new production prior to 2050 need to be essentially carbon neutral unless climate sensitivity is much less than most climate models predict [53]. Although somewhat relaxed, the constraints on carbon intensity implied by a 3 °C target remain challenging: for a budget consistent with the

³ In this section we discuss the carbon intensity of total production because we compare it to past data.

RCP4.5 by 2050, the carbon intensity of global production is between 180 and 270 g CO₂/\$ for GDP per capita growth rates between 1 and 3% per year, and below 100 g CO₂/\$ for GDP per capita growth rates higher than 3% per year.

As further context for the carbon intensity implied by climate targets of 2 °C and 3 °C, there is no country—except those which outsource emissions such as Singapore or Hong-Kong—whose carbon intensity of GDP today approaches 100 g CO₂/\$, including countries that produce most of their electricity from non-fossil energy sources such as France and Brazil (figure 5). The largest emitters, China and the US, have carbon intensities of 671 and 356 g CO₂/\$, respectively (figure 5), and the carbon intensities of these economies have decreased by ~4 g CO₂/\$ per year between 1990–2013 (figure 5). The sort of drastic reductions in the carbon intensity of new production that are required by climate targets like 2 °C may necessitate new economic goals as well as extensive energy innovation [51].

Due to the long lifetime and relatively high capital cost of energy infrastructure, delaying action increasingly locks the global economy into a carbon-intensive pathway, where it becomes increasingly more difficult and expensive to reduce CO₂ emissions sufficiently to stay within a low budget of cumulative emissions. Each year that additional mitigation efforts are delayed (i.e. we continue along the business-as-usual path), the required carbon intensity of new production decreases by 20–50 g CO₂/\$ for a 2 °C budget. If action were delayed until 2019, half of the 2 °C scenarios we evaluate would entail a negative carbon intensity of new production.

Our results show that carbon budgets are highly sensitive to the availability of negative emissions after 2050, as well as the climate sensitivity of the climate system. Almost all energy-economic models have negative emissions after 2050 in order to reach a 2 °C target [37, 47]. However, the quantity and cost of negative emissions that will be available is highly uncertain due to biophysical and resource limits as well as environmental risks [54]. For instance, large-scale implementation of bioenergy with carbon capture and storage would require large areas of land per unit of negative CO₂ emissions, in conflict with land use for agriculture and ecological conservation, and the transport and storage of large volumes of compressed CO₂ subject to technical challenges and public opposition.

Future pathways consistent with low-warming climate targets, which allow for continued economic growth involve prompt and drastic reductions in the carbon intensity of new production and either a short lifetime of energy capital (e.g., early retirement or retrofit of coal power plants), or negative emissions in the next decades (i.e. rapid development and dissemination of carbon capture and storage). We cannot depend upon the necessary combination of these conditions to arise spontaneously. An integrated and bold set of policies and programs is urgently needed to speed the transition to carbon-free economy.

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