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The Carbon Bubble: climate policy in a fire-sale model of deleveraging*

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Abstract

Credible implementation of climate change policy, consistent with the 2 °C limit, requires a large proportion of current fossil-fuel reserves to remain unused. This issue, named the Carbon Bubble, is usually presented as a required asset write-off, with implications for investors. We embed the Carbon Bubble in a macroeconomic model exhibiting a financial accelerator: if investors are leveraged, then the Carbon Bubble might precipitate a fire-sale of assets across the economy, and generate a large and persistent fall in output and investment, impairing the economy's ability to invest in the zero carbon assets it needs to produce output in the post-climate-transition world. We find a role for macroeconomic policy protecting investors' balance sheets in mitigating the macroeconomic effects of the Carbon Bubble, and enhancing welfare.

Keywords: Carbon Bubble; deleveraging; fire-sale; resource substitution; 2 °C target

JEL classification: *H*23; *Q*43

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1. Introduction

In 1996, European Union (EU) national governments set a global temperature target of 2 degrees Celsius (°C) above the pre-industrial level, which was made international policy in 2009, and updated in 2015 to also include the aspiration to keep within a 1.5 °C limit. However, in order to reduce the probability of exceeding 2 °C warming to 20 percent, only one-fifth of the Earth's proven fossil-fuel reserves can be burned unabated (Carbon Tracker Initiative, 2011). As this translates broadly into a near-term cessation of all coal use and only a partial exploitation of proven oil and gas reserves (McGlade and Ekins, 2015), the imposition of a climate policy consistent with these calculations would mean that the fundamental value of many fossil-fuel assets must be written off. With an inappropriate terminology for an economist familiar with the theory of bubbles (e.g., Tirole, 1985), this issue has come to be known by the wider public as the Carbon Bubble (Carbon Tracker Initiative, 2011; McKibben, 2012): the reasoning is that the current positive market value of these "stranded assets" is a "bubble", because their fundamental value is zero under the target of 2 °C. Whereas the majority of the discussions of the Carbon Bubble focus upon the risks to investors of climate policy (see e.g., Carbon Tracker Initiative, 2011; Carbon Tracker Initiative, 2013; Delis et al., 2018; Harvey, 2018a,b; McGrath, 2018; Wheaton, 2021), we consider the impact of climate policy on the macroeconomy, and consequently the appropriate macrofinancial policies that should accompany serious climate policy.

In particular, we model the consequences of the implementation of a climate policy in the spirit of a maximum degree target in a modified version of the model of Kiyotaki and Moore (1997), where entrepreneurs borrow from savers using their current asset holdings as collateral. We take as given the fact that climate science mandates a severe climate policy response, such that society has a limited "carbon budget" relative to its ability to emit carbon pollution (van der Ploeg, 2018; Dietz and Venmans, 2019; van der Ploeg et al., 2021). Because carbon-intensive assets make up a substantial proportion of asset holdings (Dietz et al., 2016; Battiston et al., 2017; Mercure et al., 2018), naïvely imposing this carbon budget damages the balance sheets of entrepreneurs, and in the presence of financial frictions, this has major macroeconomic implications. Indeed, these write-downs decrease the debt-capacity of the non-financial sector, which must then reduce the level of leveraged investment. As economic activity worsens, the asset-price drop fuels further debt capacity reductions in a downward spiral. Forward-looking markets could turn an announced carbon budget into a "sudden stop" akin to, or worse than, the 2008 global financial crisis.

We underline that a recessionary response is particularly damaging with respect to the implementation of the climate policy itself, as one of its aims is to provide the incentives for investments in alternative energy capital, in order to replace the current fossil-fuel-based energy infrastructure. A substantial stock of zero carbon productive capacity will need to be in place at the point at which the carbon budget is exhausted, but the bursting of the Carbon Bubble could throw the economy into a deep recession, thus depriving green technology of investment funds when they are most needed. Even if the fossil-fuel assets really should be written off to avoid disastrous global warming, the implementation of such a policy must pay cognisance to the impact that it will have upon investment.

Since Carney (2014), concerns around the risk of a disorderly transition and its implications for macroeconomic and financial stability have entered the policy debate, as summarized by Campiglio (2016) and Campiglio et al. (2018). In this respect, our exercise is to consider the social planner's problem in facilitating the transition from a high carbon economy to the carbon-free era, by choosing policies that maximize social welfare after the imposition of stringent climate policy. We model a scenario in which the policymaker implements credible climate policy consistent with a maximum degree limit, and we then consider policies that transfer investors' debts to the government, subsidize investment, and provide government guarantees on investors' borrowings. We show that these macroeconomic policies mitigate the impact of the Carbon Bubble upon the balance sheets of investors: their improved net asset position allows them to invest more in replacement zero carbon energy capital than in the no-policy case, driving the economy faster out of the recession. In "mitigating" the Carbon Bubble, these policies are welfare-enhancing, even if such policies are welfare-destroying under normal circumstances.

Our paper thus contributes to an emerging literature that explores the macroeconomic stability implications of climate policies using environmental macroeconomic models with credit market imperfections (Benmir and Roman, 2020; Carattini et al., 2021; Diluiso et al., 2021). Our main contribution is to begin to answer the question posed when considering the Carbon Bubble in a macroeconomic context: is there a role for policy in mitigating the impact of the abrupt implementation of ambitious climate policy? We find that policy protecting investors' balance sheets mitigates the macroeconomic downturn, and leads to higher investment in the replacement zero carbon productive capacity over the period in which we still use carbon-emitting productive capacity.

The remainder of this paper is organized as follows. In Section 2, we review the literature. In Section 3, we present the theoretical model we employ. In Section 4, we describe the calibration. In Section 5, we set out the Carbon Bubble scenario, and also examine policies that the planner can implement additionally. In Section 6, we discuss the policy relevance of our exercise in a real-world context. Finally, we conclude in Section 7.

2. Previous literature

Our paper belongs to a large body of literature that studies the potential effects of environmental regulations on the economy, combining insights from environmental economics and macroeconomics. Among these, the standard framework is the integrated-assessment model (IAM). Indeed, since the pioneering work of Nordhaus, a plethora of IAMs have been constructed to evaluate optimal paths for carbon dioxide emissions and associated prices.[1] Originally, this literature effectively assumed that all fossil fuels that could be economically extracted would be used at some point, and that the aim of climate policy was to merely manage the time-path of emissions. However, the climate science literature increasingly came to the view that over any reasonable time-scale that humans care about, it is cumulative emissions that matter, and the time-path of these emissions is only of second-order (or higher) importance: some economically extractable fossil fuels must be kept unexploited (Allen et al., 2009; Matthews et al., 2009; Zickfeld et al., 2009).

This view, that climate policy should be primarily concerned with cumulative emissions rather than their time-path, has been increasingly assimilated into the economics literature as IAMs have recently incorporated more sophisticated and/or realistic climate modules. If the optimal time-path for global temperatures features a peak, then optimal climate policy takes the form of a "carbon budget" for cumulative future emissions (van der Ploeg, 2018; Dietz and Venmans, 2019; van der Ploeg et al., 2021). This view is also reflected in policy frameworks, such as the European Union's Emission Trading Scheme (EU ETS), which, while setting carbon prices to manage the flow of emissions, claim to help implement the "net-zero by 20xx" targets that are a form of cumulative emissions policy.[2]

A carbon budget can emerge as optimal policy within an IAM when the model contains a "tipping point" between different steady states in the climate system, or features the risk of catastrophic damages associated with highly non-linear threshold effects or runaway feedback effects (e.g., Intergovernmental Panel on Climate Change, 2018). Tipping points and catastrophes have been added to IAMs many times in the literature (e.g., Lemoine and Traeger, 2014; Besley and Dixit, 2019; Nordhaus, 2019; Campiglio et al., 2020; Dietz et al., 2021), and our model also has a tipping

[1] See Nordhaus and Boyer (2000) for a description of the original modelling, Golosov et al. (2014) and Hassler et al. (2016) for the new generation of analytical IAMs, and Nikas et al. (2019) for a literature review.

[2] Note, however, that emissions flow control policies that implement a cumulative emissions constraint, such as the EU ETS, need not implement it in an intertemporally optimal manner (see Gollier, 2020).

point, which ensures that the carbon budget represents optimal policy. A carbon budget policy implies that some fossil-fuel assets, which currently have a positive value, remain unused and so are revalued to zero: such assets are referred to as "stranded" by policy. Van der Ploeg and Rezai (2020) propose a model of exploration investment, discoveries, and depletion to analyse the effects of different climate policy instruments on asset stranding. Likewise, van der Ploeg and Rezai (2021) updates Golosov et al. (2014) to analyse what climate policies imply for oil and gas asset stranding.[3]

More specifically, our paper is closely related to a recent literature using dynamic stochastic general equilibrium (DSGE) models with carbon emissions, and studying the influence of business cycles on environmental policy. For example, Fischer and Springborn (2011), Heutel (2012), Annicchiarico and Di Dio (2015, 2017), and Dissou and Karnizova (2016) have compared the macroeconomic performances of different emission policies in an economy with exogenous productivity shocks (see Fischer and Heutel, 2013, for an early literature review). This literature is well summarized in Annicchiarico et al. (2021); here, we describe three papers that are particularly close to ours, since they look at credit market imperfections in environmental macroeconomic models, in particular with reference to the climate transition to a zero carbon economy. This is because, since carbon intensive assets make up a substantial proportion of asset holdings (Dietz et al., 2016; Battiston et al., 2017; Mercure et al., 2018), there is a risk that a policy induced stranding of such assets could have macroeconomic implications via financial accelerator type mechanisms.

Diluiso et al. (2021) construct a DSGE model with financial frictions and study the financial stability implications of climate policies such as carbon taxes. They show that for orderly climate mitigation plans, the macroeconomic risks are minimal, but that policy to incentivize the decarbonization of banks' balance sheets may reduce what risks there are. Benmir and Roman (2020) and Carattini et al. (2021) also construct DSGE models with financial frictions and study the interaction of climate and macroeconomic/macroprudential policies. They find that there is a role for all types of policy, and that "green" macroprudential policy can be a useful complementary policy, alongside traditional carbon taxes, in enabling the climate transition while managing macroeconomic instability. However, they also find that a green macroprudential policy on its own is not a very effective climate policy.

[3] In other related literature, Dafermos et al. (2018) use an ecological stock-flow consistent model to gauge the consequences of severe global warming on the liquidity of firms, financial stability, and credit. Similarly to us, they argue that a global green quantitative easing programme (akin to a combination of our "transfer of investors' debt" and "subsidy" policies in Section 5) could ameliorate the financial distress caused by climate change.

These three papers all feature a banking sector, whereas in our model borrowers and lenders transact with each other directly. This is for simplicity and can be supported by the purpose of our exercise relative to the contributions of the other papers in the literature: these three papers aim to describe macroprudential policy alongside climate change policy starting from now, such that their policy prescriptions take into account the influence of lending decisions, as well as issues of moral hazard and policy interaction.

Our contribution relative to these papers is to focus on a specific policy scenario, that is, a (relatively) near-term climate policy that implies no further use of fossil-fuel assets; and to ask which, under these circumstances, are the macroeconomic policy options that will mitigate the huge impacts induced by this (necessary) environmental policy, and promote the investment needed in the alternatives to fossil fuels, which have suddenly become vital with the imposition of such stringent climate policy. Our paper differs therefore from much of the literature in not worrying about issues around moral hazard or about the *ex ante* behaviour of lenders. While others consider *ex ante* macroprudential policies that may de-risk balance sheets prior to climate risk being realized (policies that may prevent a climate-risk-induced financial crisis such as climate stress-tests, carbon disclosures, and differentiated capital requirements), we consider that with climate change we may be, or already are, *ex post*: climate risk has been realized, we currently have too many bad assets, and moral hazard concerns are in the rear-view mirror. To undertake our exercise, we use the simplest model with a financial accelerator in which the asset write-offs caused by stringent climate policy lead to fire-sale dynamics and a persistent downturn, which impedes investment in new assets.[4]

Of the other papers in the literature, Carattini et al. (2021) is closest to this, in that it does consider the abrupt implementation of ambitious climate policy, which creates macroeconomic instability that can then be alleviated by macroprudential policy; nevertheless, our climate policy scenarios, modelling frameworks, and macroeconomic/macroprudential policy options are different.[5] Furthermore, our motivating question is slightly different, and more focused on the impact of emergency climate policy and the mitigation options then available; conversely, Carattini et al. (2021) ask the more general question of whether climate policy can create macroeconomic instability and if this can be mitigated with macroprudential policy. Nevertheless, our

[4]Gerke et al. (2013) show that most models of the financial accelerator share qualitatively similar features. Therefore, if calibrated to the same shock, financial accelerator models will tend to produce similar macroeconomic dynamics irrespective of the underlying microfoundations.

[5]We use the model of Kiyotaki and Moore (1997) whereas they use Gertler and Karadi (2011); we consider debt transfers and guarantees, green subsidies, as well as progressively more ambitious climate targets (see Section 5), whereas they consider taxes or subsidies on bank assets.

conclusions are consistent and we thus believe our papers complement each other. Our paper therefore forms part of a growing literature concerned with the interaction of central bank and macroprudential policy action with climate change policy (see Campiglio, 2016; Campiglio et al., 2018).

3. The model

In this section, we extend the model of Kiyotaki and Moore (1997) by considering two types of investment good (high carbon and zero carbon energy capital) and by introducing a simple policymaker. There are two types of agent (entrepreneurs and savers) and two types of capital (fixed capital and energy capital). For example, the energy capital could include coal mines, power stations, and a balanced electricity grid, while the fixed capital includes the factory using the electricity, but not directly caring about how this electricity has been produced. Credit-constrained entrepreneurs borrow from unconstrained savers in the fixed capital market, and combine the fixed and the energy capitals to produce a final good; the final good can either be consumed or invested in energy capital. Whereas energy capital depreciates, which captures both the usual capital depreciation and exhaustible resource depletion (e.g., of coal and oil), the stock of fixed capital cannot be invested in nor does it depreciate. Indeed, our focus is on the impact of the Carbon Bubble on investment in the transition of the energy system to zero carbon, under conditions of a fixed stock (though not a fixed valuation) of all other capital.

We also add an endogenous climate sector following Golosov et al. (2014), but we impose climate policy exogenously. This is because we take a carbon budget scenario seriously, and deliberately exclude the degenerate solution of "not implementing a carbon budget": if a particular carbon budget is always the optimal policy, then the simplest, most tractable way of implementing this is to impose it exogenously.

3.1. Primitives of the model

Time is discrete and indexed by t. There are two types of infinitely lived agents: a continuum of entrepreneurs of mass one and a continuum of savers of mass m. Entrepreneurs and savers maximize the expected discounted utilities from consumption,

$$\max_{\{x_s\}} E_t\left[\sum_{s=t}^{\infty}\beta^{s-t}x_s\right] \qquad \text{and} \qquad \max_{\{x'_s\}} E_t\left[\sum_{s=t}^{\infty}(\beta')^{s-t}x'_s\right], \tag{1}$$

where x_t and x'_t represent consumption at date t of the entrepreneur and the saver, respectively, and $\beta, \beta' \in (0,1)$ indicate the discount factors. Both types of agent are risk neutral but they differ in their rates of time preference: entrepreneurs are more impatient.[6]

Assumption 1 (Impatient entrepreneurs). $\beta < \beta'$.

There are three types of goods: fixed capital K, energy capital Z, and non-durable commodity. The non-durable commodity cannot be stored but can be consumed or invested in energy capital. The energy capital has two flavours: high carbon and zero carbon, indexed by H and L, respectively. The fixed capital does not depreciate and is available in a fixed aggregate amount, given by $\bar{K}$, while both types of energy capital depreciate at rate $1 - \lambda$ per period.

At the end of each time period $t - 1$, there is a competitive asset market and a competitive one-period credit market. In the former, one unit of the fixed capital is exchanged for q_{t-1} units of the commodity; in the second, one unit of the commodity at date $t - 1$ is exchanged for R_{t-1} units of the commodity at date t. The commodity is assumed to be the numeraire, so that its price is normalized to unity; then q_t represents the price per unit of fixed capital and R_t is the gross interest rate. At the start of a new period t, markets are closed: stocks of fixed capital, energy capital, and debt holdings are state variables. Production then takes place over period t.

3.2. Entrepreneurs

An entrepreneur produces a quantity of the commodity, y, with a one-period Leontief production function: fixed capital, k, is combined with energy capital, z, in a $1:1$ proportion. The Leontief specification captures the very low elasticity of substitution between energy and other inputs to production, at least in the short run, measured by Hassler et al. (2021) and assumed by, for example, Fried (2018).

This period's decisions affect the next period's production. The entrepreneur can choose between two technologies. Choosing the first, k_{t-1} units of fixed capital are combined with z^H_{t-1} units of the high carbon energy capital, producing y_t units of the commodity. However, this choice implies that the after-tax output available to the entrepreneur will be reduced by any proportional carbon tax implemented, $\tilde{\tau}_t$:

$$y_t = \Gamma_t \times (a^H + c) \times \min\left(k_{t-1}, z^H_{t-1}\right); \quad (2a)$$

$$(1 - \tilde{\tau}_t) y_t = \Gamma_t \times (a^H + c - \tau_t) \times \min\left(k_{t-1}, z^H_{t-1}\right). \quad (2b)$$

[6] Exogenous *ex ante* heterogeneity keeps the model tractable and ensures the model simultaneously has borrowers and lenders, as in many dynamic general equilibrium models of financial friction (e.g., Iacoviello, 2005; Iacoviello and Neri, 2010; Devereux and Yetman, 2009; Pariès et al., 2011; Liu et al., 2013).

The marginal productivity of the technology is $a^H + c$, but a portion $c/(a^H + c)$ of the y_t units of output are not tradable and must be consumed by the entrepreneurs (who must therefore pay any carbon tax levied out of tradable output).[7] In the spirit of the DICE model (Nordhaus, 2018), Γ_t is a damage function capturing the effect of climate change on productivity.

Choosing the second technology, the entrepreneur combines k_{t-1} units of fixed capital with z^L_{t-1} units of the zero carbon energy capital and benefits from any proportional subsidy offered, $\tilde{\varsigma}_t$. The output available to the entrepreneur, however, will be increased by only a fraction $\delta \in [0, 1]$ of the subsidy implemented, where δ is a reduced form structural parameter representing the effectiveness of the subsidy:

$$y_t = \Gamma_t \times (a^L - (1 - \delta)\varsigma_t + c) \times \min(k_{t-1}, z^L_{t-1}); \tag{3a}$$

$$(1 + \tilde{\varsigma}_t) y_t = \Gamma_t \times (a^L + c + \delta\varsigma_t) \times \min(k_{t-1}, z^L_{t-1}). \tag{3b}$$

In the remainder of the paper, we discuss only $\tau_t = \tilde{\tau}_t(a^H + c)$ and $\varsigma_t = \tilde{\varsigma}_t(a^L - (1 - \delta)\varsigma_t + c)$, positive bijective transformations of the proportional tax rate and subsidy rate into units that can be compared with the productivities of the two alternative technologies.

In line with Acemoglu et al. (2012), we assume that zero carbon energy capital is intrinsically less productive than high carbon energy capital.

Assumption 2 (Productivity advantage of the carbon sector). $a^H > a^L$.

The commodity can be consumed or invested. For that portion of their invested output, the entrepreneur converts ϕ units of the commodity into one unit of energy capital: ϕ is the output cost of investing.[8]

We impose an upper limit on the obligations of the entrepreneurs: if the entrepreneur repudiates their contract, the lender can only repossess the

[7] The untradable portion of output can be thought of as a lower bound on the entrepreneur's savings rate or as a minimum dividend for the shareholders. This is introduced to avoid the possibility that the entrepreneur keeps postponing consumption, but Kiyotaki and Moore (1997, see their appendix) show that the same qualitative results can be obtained using an overlapping generations model with standard concave preferences and conventional saving/consumption decisions.

[8] Qualitatively, the same results are reached with a single productivity, a, and differing investment costs, $\phi^H < \phi^L$ (as in van der Zwaan et al., 2002). That $a^H > a^L$ (or $\phi^H < \phi^L$) should be an uncontroversial assumption: renewables are still more expensive than fossil fuels when the full costs are considered, and lower costs per unit output here are equivalent to a higher productivity parameter.

fixed asset. Entrepreneurs are therefore subject to the following borrowing constraint:

$$b_t \leq \frac{q_{t+1} k_t}{R_{t+1}}. \tag{4}$$

Consider an entrepreneur who holds k_{t-1} units of fixed capital, $z_{t-1} = k_{t-1}$ units of energy capital (because the Leontief production function means that any other quantity of energy capital is suboptimal), and has gross debt b_{t-1} at the end of period $t-1$. At date t, they receive net income of $\Gamma_t a^i k_{t-1}$ (depending on the technology used), they incur a new loan b_t, and acquire more fixed capital, $k_t - k_{t-1}$. Having experienced depreciation and having increased their fixed capital holdings, the entrepreneur will have to convert part of the tradable output to energy capital. In general, entrepreneurs will have to invest $\phi(k_t - \lambda k_{t-1})$ in order to have enough energy capital to cover depreciation and new fixed capital acquisition; they then repay the accumulated debt, $R_t b_{t-1}$, and choose how much to consume in excess of the amount of non-tradable output, $x_t - \Gamma_t c k_{t-1}$. In addition, they receive a per capita transfer from the government or pay the per capita tax, g_t, depending on the net position of the government. Thus, the entrepreneur's flow-of-funds constraint, as at the end of period t, is given by either

$$\begin{aligned} q_t(k_t - k_{t-1}) + \phi(k_t - \lambda k_{t-1}) + R_t b_{t-1} + (x_t - \Gamma_t c k_{t-1}) + \Gamma_t \tau_t k_{t-1} \\ = \Gamma_t a^H k_{t-1} + b_t + g_t \end{aligned} \tag{5a}$$

or

$$\begin{aligned} q_t(k_t - k_{t-1}) + \phi(k_t - \lambda k_{t-1}) + R_t b_{t-1} + (x_t - \Gamma_t c k_{t-1}) \\ = \Gamma_t a^L k_{t-1} + \Gamma_t \delta \varsigma_t k_{t-1} + b_t + g_t. \end{aligned} \tag{5b}$$

The first equation refers to an entrepreneur who uses the high carbon energy capital, while the second relates to the use of the zero carbon energy capital.

Finally, in each period, only a fraction $\pi \in (0, 1)$ of entrepreneurs have an investment opportunity. Thus, with probability $1 - \pi$, the entrepreneur cannot invest and must downsize the scale of operation, as the depreciation of their energy capital implies $z_t^i = \lambda z_{t-1}^i$. This probabilistic investment assumption, combined with Leontief production, means that with probability $1 - \pi$ the entrepreneur also faces the constraint

$$k_t \leq \lambda k_{t-1}. \tag{6}$$

3.3. Representative saver

Savers are willing to lend commodities to entrepreneurs in return for debt contracts, and they also produce commodities by means of a decreasing return to scale technology, which uses only the fixed capital as an input, k'_{t-1}, and takes one period, according to

$$y'_t = \Gamma_t \times \left[-\frac{m}{2\beta'} \left(k'_{t-1}\right)^2 + \frac{\bar{K} - \nu}{\beta'} k'_{t-1} - \frac{const}{m} \right], \tag{7}$$

where ν and $const$ are positive parameters (see Online Appendix A.1 for the derivation). Savers are never credit-constrained because they can trade all their output and no particular skill is required in their production process. Savers solve the relevant maximization problem in equation (1), subject to their budget constraint,

$$q_t \left(k'_t - k'_{t-1}\right) + R_t b'_{t-1} + x'_t = y'_t + b'_t + g_t. \tag{8}$$

A saver who produces y'_t units of the commodity, incurs (issues) new debt b'_t, and receives (pays) the per capita government expenditure (tax) g_t, can cover the cost of buying fixed capital $q_t (k'_t - k'_{t-1})$, repaying (collecting on) the previous debt (including interest) $R_t b'_{t-1}$, and consuming x'_t.

3.4. Competitive equilibrium

An equilibrium consists of a sequence of prices $\{q_t, R_t, \tau_t, \varsigma_t\}$, allocations for the entrepreneur $\{x_t, k_t, z_t, b_t\}$ and the saver $\{x'_t, k'_t, b'_t\}$ such that, taking the prices as given, each entrepreneur solves the relevant maximization problem in equation (1) subject to the appropriate constraints in equations (2)–(5); each saver maximizes the relevant part of equation (1) subject to equations (7) and (8); the government always runs a balanced budget; and the goods, asset, and credit markets clear. Note that, given Assumption 1, the impatient entrepreneurs will borrow from the patient savers in equilibrium. Moreover, given that savers are risk neutral and there is no uncertainty, the rate of interest R_t is constant and determined by the patient saver's rate of time preference (i.e., $R_t = 1/\beta' \equiv R$).

Using $\gamma_t \in [0, 1]$ to indicate the share of aggregate entrepreneurs' fixed capital holdings, which are combined with high carbon energy capital at t, let $Z^H_t, Z^L_t, I^H_t \equiv Z^H_t - \lambda Z^H_{t-1},\ I^L_t \equiv Z^L_t - \lambda Z^L_{t-1},\ B_t, mb'_t \equiv B'_t,\ K_t, mk'_t \equiv K'_t,\ X_t, mx'_t \equiv X'_t,\ Y_t, my'_t \equiv Y'_t,\ \Gamma_t \tau_t \gamma_t K_{t-1} \equiv T_t,\ \Gamma_t \varsigma_t (1 - \gamma_t) K_{t-1} \equiv P_t$, and $(1 + m) g_t \equiv G_t$ be aggregate energy capital holdings, investment flows, borrowing, fixed capital holdings, consumption, output, carbon tax, green subsidy, and aggregate lump-sum transfer (positive) or tax (negative), respectively. The government budget constraint and the market clearing conditions for assets, credit, and goods are then, respectively,

$$T_t - P_t = G_t, \tag{9a}$$

$$K_t + K'_t = \bar{K}, \tag{9b}$$

$$B_t + B'_t = 0, \tag{9c}$$

$$I_t^H + I_t^L + X_t + X'_t + G_t - T_t + P_t = Y_t + Y'_t. \tag{9d}$$

To characterize equilibrium, we start with the savers. As they are not credit-constrained, their fixed capital holdings are such that they are indifferent between buying and selling this capital. This is the case if the rate of return from buying fixed capital is equal to the rate of return of selling,

$$\frac{dy'_{t+1}}{dk'_t} = Rq_t - q_{t+1}. \tag{10}$$

This implies the following forward-looking equation of motion for the capital price,

$$q_t = \Gamma_t \left(K_t - \nu\right) + \frac{1}{R} q_{t+1}. \tag{11}$$

Entrepreneurs who can invest at date t will prefer borrowing up to the limit and investing, rather than saving or consuming, hence limiting their consumption to the current non-tradable output ($x_t = \Gamma_t c k_{t-1}$); for them, the credit constraint in equation (4) is binding. Conversely, an entrepreneur who cannot invest at t, given that they will not want to waste their remaining stock of energy capital, will adjust their levels of debt and fixed capital such that equation (6) will hold with equality (see Kiyotaki and Moore, 1997, footnote 22). At the aggregate level, these imply that entrepreneurs' aggregate fixed capital holdings and borrowing evolve according to

$$K_t = \frac{\pi}{q_t + \phi - (q_{t+1}/R)} \Bigg[\left(q_t + \phi\lambda + \Gamma_t a_t\right) K_{t-1} - RB_{t-1} + \frac{\gamma_t \tau_t - (1-\gamma_t)\varsigma_t}{1+m} \Gamma_t K_{t-1} \Bigg] + (1-\pi)\lambda K_{t-1} \tag{12}$$

and

$$B_t = q_t \left(K_t - K_{t-1}\right) + \phi \left(K_t - \lambda K_{t-1}\right) + RB_{t-1} - \Gamma_t a_t K_{t-1} - \frac{\gamma_t \tau_t - (1-\gamma_t)\varsigma_t}{1+m} \Gamma_t K_{t-1}, \tag{13}$$

where a_t represents the net productivity of the entrepreneurial technology.

Equations (11), (12), and (13) give us a three-dimensional system of dynamic equations, which characterizes the model.

4. Calibration strategy

In this section, we present briefly our calibration strategy, but an interested reader can find more details in Online Appendix A.6. Table 1 summarizes the parameter values.

4.1. Definition of welfare and time

The utilitarian social welfare function maximized by the policymaker at $t = 0$ is the discounted present value of future consumption. We assume that savers are infinitesimally more patient than the entrepreneurs and thus, for any practical calculation, their discount factors are the same. Therefore, policy is chosen by the policymaker to maximize the present discounted value of all future "net national income" flows in the model,

$$W_t = \sum_{s=t+1}^{\infty} \left[\beta^{s-t} E[x_s] + (\beta')^{s-t} m x'_s\right] \approx \sum_{s=t+1}^{\infty} R^{t-s}[E[x_s] + m x'_s]. \quad (14)$$

We interpret time periods as quarter years, and set the depreciation rate of energy capital to $\lambda = 0.975$ and the interest rate to $R = 1.01$. We calibrate $const$ in the savers' production function under the arbitrary assumption that, in the (decarbonized) steady state, consumption flow is the same for both individual savers and entrepreneurs.

Table 1. Parameter values

Description	Parameter	Value	Source/target
Interest rate	R	1.01	Kiyotaki and Moore (1997)
Depreciation rate	$1 - \lambda$	0.025	Kiyotaki and Moore (1997)
Zero carbon productivity	a^L	1.0	Normalization
Savers' marginal productivity	ν	1.5	Fall in asset values in the financial crisis run
Investment cost	ϕ	33	
Investment opportunity	π	0.02	
High carbon productivity	a^H	1.1	US Energy Information Administration (2015)
Share of high carbon	γ	0.8	US Energy Information Administration (2016), Newell et al. (2016)
Stock of fixed capital	$\bar{K}$	15	Equal consumption, energy expenditure over GDP (US Energy Information Administration, 2016), and fall in output in the financial crisis run (FRED)
Non-tradable output	c	1.14	
Relative number of savers	m	2.08	
Savers' production function	$const$	87	
Damage function parameter	μ	0.000178	Nordhaus (2017)

4.2. The energy sector

We set $\gamma_0 = 0.8$ because fossil fuels represent around 80 percent of energy generation according to Newell et al. (2016) and US Energy Information Administration (2016, table 1.2). We normalize productivity of the low carbon technology, $a^L = 1$. US Energy Information Administration (2015, table 1) provides figures on the total system levelized costs of electricity, which we apply to their energy mix figures to estimate that fossil-fuel generation costs around 10 percent less per unit of energy supplied. Thus, $a^H = 1.10$. Both fossil fuels and alternative energy-generating capacity exist in the data, and we can replicate this in the model only if their net private productivities, after taxes and subsidies, have been equalized. This means that net private productivity is $a = a^L$, and carbon tax $\tau = a^H - a^L$. A sensitivity analysis over the values of γ_0, a^H, and a^L is presented in Online Appendix A.7.

US Energy Information Administration (2016, table 1.2) suggests that energy expenditure as a percentage of total GDP is around 7.5 percent. In order to interpret this within the model, we imagine that at the start of the simulation the expenditure by the entrepreneurial final goods production sector on energy intermediate goods is equal to the flow value of the energy capital value (i.e., $(R-1)\phi K_0$) and that this represents total expenditure on energy. Therefore, we use the following object as a calibration target:

$$\frac{(R-1)\phi K_0}{\Gamma_0\left[(a+c+\gamma_0\tau)K_0 + R(\bar{K}-\nu)(\bar{K}-K_0) - 0.5R(\bar{K}-K_0)^2 - const\right]} = 7.5\%. \tag{15}$$

4.3. The financial crisis

The contemporaneous response to a shock and the persistence of its effects are influenced by π, ϕ, and ν, which we calibrate to the impact of the 2008–2009 global financial crisis on output and upon asset values. In particular, we hit our economy with a one-time initial unexpected shock to the wealth of the entrepreneurs, $\Delta K_0/(\phi K_0 + q_0\bar{K}) = 1/150$, which approximates the ratio between the total value of subprime mortgages outstanding in 2008 and the total value of global non-bank financial assets (Hellwig, 2009; Dietz et al., 2016). We then match the subsequent fall in output of around 6 percent and the fall in asset values of around 20–25 percent.

4.4. Stranded fossil-fuel assets

The Carbon Tracker Initiative (2013) estimates that 65–80 percent of listed companies' current reserves cannot be burnt unmitigated; the International

Energy Agency (2012) argues that no more than one-third of proven reserves of fossil fuels can be consumed. According to Robins et al. (2012), carbon constraints could affect the valuations of coal assets by as much as 44 percent, with average impact to the stock market valuation of mining companies between 3 and 7 percent. Moreover, "given that the mining sector comprises around 12 percent of the FSTE100 index, the risk is potentially also relevant to the broader market" (Robins et al., 2012, p. 6).

However, the financial importance of some of these write-offs can be questioned. Most of the fossil reserves that will have to stay in the ground are coal, which is quite costly to extract (relative to the price obtained for the energy that can be so generated). Further, unconventional oil and gas fracking is currently a key marginal oil and gas resource; its extraction seems to start as soon as the price is only marginally over extraction costs, which suggests that the value of the unexploited reserves is very low. Conversely, the fossil-fuel assets with significant value (e.g., conventional oil and gas with low extraction costs) are the very assets that will still be allowed to be used within a global carbon budget. Furthermore, not all the non-fossil-fuel assets that are strongly complementary with fossil fuels will be exposed to the Carbon Bubble. Assets that depreciate fairly quickly (e.g., cars) will be used almost fully even under a Carbon Bubble scenario. Some assets that depreciate slowly (e.g., the road network) may be valuable in the post-fossil-fuel era, though some proportion of its value is likely at risk (e.g., it might be in a relatively suboptimal location, or it might be utilized at a very low capacity). A Carbon Bubble scenario, compared with laissez-faire, will strongly constrain the future working life of many slowly depreciating assets, such as newly built coal power stations, whose financial value is therefore at great risk.

Estimating the financial value of the stranded fossil-fuel assets is beyond the scope of this paper. Fortunately, recent estimates are provided by Mercure et al. (2018). Relying on empirical data on socio-economic and technology diffusion trajectories, they suggest that a Carbon Bubble "could lead to a discounted global wealth loss of \$1–4 tn, a loss comparable to the 2008 financial crisis". In the rest of the paper, we thus assume that our Carbon Bubble scenario is precipitated by the need to write off a fraction of carbon-emitting energy capital equal to $1/150$ of total asset value (see Section 4.3).[9,10]

[9] Simulations with write-offs between 10 and 80 percent, reflecting different sources, are available on request. The qualitative results are unchanged: our macroeconomic policies are always associated with a welfare increase (the bigger the shock, the bigger the potential welfare increase).

[10] When considering this asset write-off, note that we are referring to new policy or to a crystallization of policy expectations. We do not claim that asset values in this sector have not already been impaired by the market attaching some probability to a Carbon Bubble scenario (e.g., Atanasova and Schwartz, 2019; Carattini and Sen, 2019), but that the realization that the

4.5. Climate damages

In the spirit of the DICE model (e.g., Nordhaus, 2018), we added a channel capturing the effect of climate change on productivity. Whereas macroeconomic models of the climate usually express damages as a function of global temperature, which in turn are a function of emissions, we follow Golosov et al. (2014) and van der Ploeg and Rezai (2021), who show that these two steps can be successfully approximated by an exponential damage function capturing the direct mapping from emissions to percent reductions in final output. We do not incorporate a carbon cycle, following insights in atmospheric science arguing that peak warming is determined by cumulative carbon emissions rather than by the stock of atmospheric carbon (Allen et al., 2009; Matthews et al., 2009; Dietz and Venmans, 2019; van der Ploeg and Rezai, 2021).

In particular, we specify the damage function as $\Gamma_t \equiv d \times \exp(-\mu S_t)$, where S_t is cumulative emissions. While entrepreneurial production using the zero carbon energy capital does not create carbon emissions, entrepreneurs using high carbon energy capital emit one unit of carbon per unit capital (i.e., the flow of carbon emissions at time t is equal to Z_t^H). We normalize cumulative emissions to zero at the beginning of the simulation, so that cumulative emissions at time t are given by

$$S_t = \sum_{s=0}^{t} Z_s^H. \tag{16}$$

The parameter μ is calibrated so as to match the new version of the DICE model (Nordhaus, 2017), where damages are 2.1 percent of global income at 3 °C warming (i.e., $\mu = 0.000178$).[11]

The damage function contains a step parameter d, denoting a threshold or tipping point. We assume d equal to one within a carbon budget $\bar{S}$, but

probability of such a scenario is 100 per cent, rather than substantially lower, causes further asset loss.

[11]This is obtained by (i) following insights in Earth system modelling showing that warming is linearly proportional to cumulative carbon emissions (this has been already applied in various economic applications; see, e.g., Dietz and Venmans, 2019; van der Ploeg and Rezai, 2021) and (ii) by assuming that each degree of warming corresponds to constant percentage damages (e.g., Golosov et al., 2014; van der Ploeg and Rezai, 2021). We suppose that a carbon budget, $\bar{S}$, implies an increase in global average temperature of 2 °C above pre-industrial level, or roughly 1 °C from today, so that $2\bar{S}$ would give an increase of roughly 2 °C from today or 3 °C above pre-industrial level. Using Nordhaus (2017), total damages (ignoring our additional tipping point threshold) would then be $\exp(-\mu 2\bar{S}) = 1$–2.1 percent. Online Appendix A.7 shows that the results are robust to the use of an exponential-quadratic damage function, following Nordhaus (2017) and Dietz and Venmans (2019), and that normalizing cumulative emissions to zero at $t = 0$ is without loss of generality.

sufficiently lower than one once cumulative emissions exceed this budget, such that it will be optimal for the social planner to keep cumulative emissions to no more than the available carbon budget.

5. Dynamic simulations

We now turn to the issue of the Carbon Bubble. In this section, we imagine a situation prior to our Carbon Bubble scenario loosely modelled upon the current state of the global economy's capital stock. Efforts have been made to provide incentives to develop and deploy zero carbon energy capital (such that the private returns from investment in both high and zero carbon energy capital are equalized via the imposition of a carbon tax). However, at the global level, the stock of high carbon energy capital is not falling, global reserves of fossil fuels are more than sufficient to exceed some carbon budget, and energy capital investments that lock the economy into high carbon patterns of use are still being made.

Our Carbon Bubble scenario then begins, at time zero, with our planner announcing a carbon tax profile consistent with a cumulative emissions constraint: no future investment in high carbon energy capital will be made and the total future use of high carbon energy capital will be limited. Effectively, the policymaker announces a carbon budget, $\bar{S}$, which satisfies

$$\bar{S} = (1 - \kappa) \times \sum_{t=0}^{\infty} \lambda^t Z_0^H = (1 - \kappa) \times \frac{\gamma_0 K_0}{1 - \lambda}, \tag{17}$$

where κ is the share of high carbon good that must be left in the ground, whereas the share $1 - \kappa$ can be used until it depreciates completely.[12] As explained in Section 4.3, this means that our Carbon Bubble scenario is precipitated by writing off a fraction κ of the current stock of carbon-emitting energy capital, such that

$$\kappa \left(\frac{\gamma_0 \phi K_0}{\phi K_0 + q_0 \bar{K}} \right) = \frac{1}{150}. \tag{18}$$

[12]The ability of the planner to announce such a policy is discussed in Online Appendix A.8. The two issues of concern are whether such a cumulative emissions constraint policy exists, and if it does, whether it is subject to the so-called Green Paradox issue (due to Sinn, 2012) under which tighter policy could lead to a paradoxically larger carbon budget. However, in the main text of this paper, it is sufficient to note that within the context of our model, such a policy exists and suffers from no paradoxical effects.

This gives $\kappa \approx 12$ percent.[13] This evaluation of κ, and hence $\bar{S}$, is equivalent to an evaluation of some time T such that

$$\bar{S} = (1 - \kappa) \times \sum_{t=0}^{\infty} \lambda^t Z_0^H = \sum_{t=0}^{T} \lambda^t Z_0^H. \tag{19}$$

To implement this carbon budget, the policymaker announces a carbon tax profile $\tau_t = a^H - a^L$ for $0 \leq t < T$, and $\tau_t \geq a^H + c$ for $t \geq T$.[14] Entrepreneurs respond optimally to this carbon tax profile, which implies that over $t \in [0, T)$ they are indifferent between using high carbon and zero carbon energy capital in production, but for $t \geq T$ they will never use high carbon energy capital as to do so would lead to post-tax losses. The fact that this period – in which they choose to abandon their high carbon energy capital – exists means that, for all $t \geq 0$, they will never choose to invest in new high carbon energy capital.[15]

Figure 1 gives an overview of the responses of the economy to announcing $\bar{S}$ at $t = 0$. It shows movement in $K_t/K^\star$, $Y_t/Y^\star$, $B_t/B^\star$, $q_t/q^\star$, and $I_t^H/I^\star$; that is, the ratios of entrepreneurs' fixed capital, total output, investors' debt, price of fixed capital, and aggregate investment flow in zero carbon energy capital, to their respective decarbonized steady-state values. Indeed, over the long run, the economy converges towards a unique steady-state equilibrium where production only involves zero carbon energy capital, characterized by

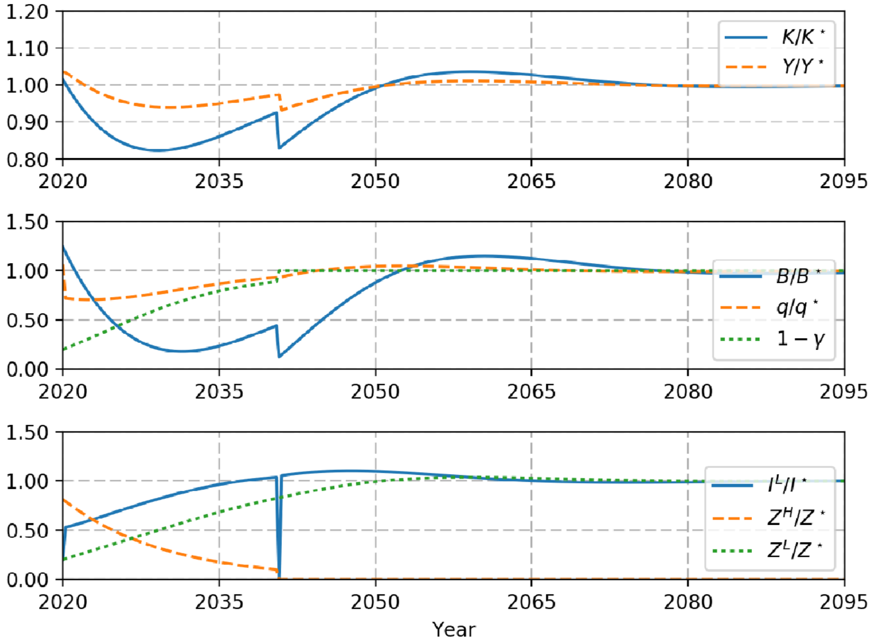
$$q^\star = \frac{R}{R-1} \left\{ \frac{\pi \Gamma a - \phi(1-\lambda)(1 - R + R\pi)}{\pi\lambda + (1-\lambda)(1 - R + R\pi)} \right\}, \tag{20a}$$

[13] Note that this is a conservative interpretation of the impact of the Carbon Bubble scenario in that only entrepreneurial net worth is affected, not their stock of assets that can be collateralized. The impact of the Carbon Bubble in this scenario comes because the reduction in entrepreneurial net worth reduces entrepreneurial demand for credit, which feeds through into reduced demand for fixed capital, lower prices for fixed capital, and hence fire-sale dynamics.

[14] This is a slight abuse of notation as there will be a final period in which this does not strictly hold for non-integer T. This is what holds in principle for arbitrarily small time periods, which we fudge here for notational convenience.

[15] In Online Appendix A.11, we check that the timing of the usage of the remaining carbon budget induced by our carbon tax profile (i.e., no investment in new high carbon assets, but full usage of existing high carbon assets until carbon budget exhausted) does indeed maximize social welfare. That is, there is no better way to use the carbon budget (e.g., abandon written-off assets at $t = 0$ but full utilization until they depreciate to nothing of the non written-off assets), which is convenient as this would imply a different carbon tax policy in order to decentralize.

Figure 1. The burst of the bubble



Notes: Each panel shows the evolution of aggregate variables to their respective decarbonized steady-state values (i.e., in which production only involves zero carbon energy capital). The middle panel also shows the share of output produced with zero carbon energy capital, $1 - \gamma_t$.

$$K^\star = \frac{R-1}{R}\frac{q^\star}{\Gamma} + \nu, \tag{20b}$$

$$B^\star = K^\star \left\{ \frac{\phi\lambda - \phi + \Gamma a}{R-1} \right\}, \tag{20c}$$

where a is the productivity of the entrepreneurial sector before climate damages and $\Gamma = \exp(-\mu\bar{S})$ is the long-run climate damage rate.[16,17] The second panel also shows the share of output produced with zero carbon

[16]Given the relationship between high carbon investments, cumulative emissions, and climate damages specified in Section 4.5, if the economy remains in the initial steady state where $\gamma_0 = 80$ percent, it would eventually cross the tipping point. Cumulative emissions would tend to infinity, and climate damages are unbounded in our specification.

[17]Online Appendices A.2 and A.12 present the assumptions used in obtaining the model's equilibrium and the stability of the system; the code files are available on the website of the authors or upon request.

energy capital, $1 - \gamma_t$, and the third panel also presents the evolution of $Z_t^H / Z^\star$ and $Z_t^L / Z^\star$, which are the ratios of each type of energy capital to the total amount of energy capital used in the decarbonized steady state (where only zero carbon energy capital is used).

As soon as the carbon budget is announced, the price of fixed capital collapses by approximately 32 percent. The price fall has damaged the entrepreneurs' balance sheets such that they choose to sell fixed capital back to the savers and repay debt. The fall in asset values precipitates forced sales to ensure borrowing and collateral requirements are aligned, but this forced sale causes prices to fall again, which causes further forced sales, and further price falls, and so on (i.e., we see fire-sale dynamics). The process stops when fixed capital becomes so unproductive in the hands of the savers that the entrepreneurs can once again afford the lowered price, and the economy recovers towards the new steady state.

In the dynamics associated with the announcement of the Carbon Bubble, the entrepreneurial sector deleverages, reducing both assets and debt, until around period 45 (11 years after the announcement). At this point, debt levels and the holdings of fixed capital in the hands of the entrepreneurs are, respectively, around 15 percent and 82 percent of starting levels. Because a large share of fixed capital is employed in the low productivity sector, output is low. Output bottoms out at almost 10 percent below the starting value, and at more than 6 percent below the new steady-state value. Investment levels fall markedly, by around 50 percent, even though the economy is in short supply of energy capital.

After 83 periods (approximately 20 years), the economy reaches its carbon budget: the remaining high carbon assets must be retired, and thus entrepreneurs return fixed capital and debt to the savers, but prices do not fall because this time the shock is expected. Given the substantial deleveraging of the entrepreneurs, investment stops for this period, before returning to the previous level. The new decarbonized economy then takes approximately 40 periods (10 years) to fully recover and start stabilizing around the new decarbonized steady state.

In the following subsections, we consider four possible additional actions for the planner that mitigate some of the welfare loss associated with writing off the high carbon energy capital.

5.1. Tax-funded transfer of investors' debt

The entrepreneurial sector is credit-constrained, and following the imposition of climate policy, it is burdened with excessive debt relative to its assets. Here, we show that the planner can achieve a better outcome if the burden of this debt is shifted to an economic actor who is not credit-constrained. We suppose that the planner first announces the carbon budget $\bar{S}$, and then takes over some share $\omega \in [0, 1]$ of the entrepreneurs' debt,[18] funding the debt repayments by raising a constant per capita tax, τ^G, over 25 years.[19]

We want to underline that any benefits from this policy are a consequence of the Carbon Bubble issue, but debt redistribution would be welfare-increasing in this model. We thus introduce a deadweight loss associated with τ^G in the production function of the entrepreneurs, $y_t = (a + c - \hat{\mu}(\tau^G)^2)k_{t-1}$, where $\hat{\mu}$ is calibrated in such way that it is optimal to use zero debt redistribution in the decarbonized steady state (see Online Appendix A.4 for more information). Given the deadweight loss, the social planner chooses the value of ω to maximize social welfare. Figure 2 shows the responses of the economy to implementing the optimal policy, $\omega = 35$ percent, at $t = 0$.

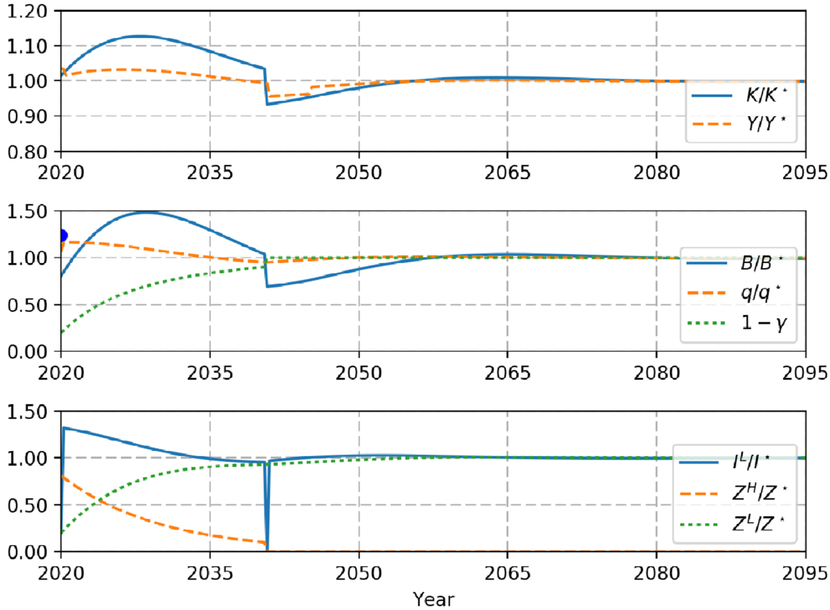
Following the policymaker's actions, the price of fixed capital increases by around 9 percent. As a consequence of the debt transfer, entrepreneurs' borrowing drops at 65 percent of the starting value, and slightly increases over the first period as the entrepreneurs use their cash flow to balance their fixed capital holdings with their energy capital stocks. This involves slightly increasing their fixed capital holdings and increasing investment levels to 1.35 times the steady-state level. The entrepreneurs start to take on debt, to operate with more of the fixed asset than in steady state, and to build up stocks of zero carbon energy capital to a level above their steady-state value. As before, at around 20 years, entrepreneurs retire the remaining high carbon asset. After that, the economy is heading towards a "steady state" with taxes, which is characterized by lower output, entrepreneur fixed asset holdings, debt, asset values, and investment levels, than in the true steady state. Once the taxes and government intervention in the debt market cease after 25 years, the economy converges to the model's true steady state. Over the course of 50 years, the cumulative investment in zero carbon energy capital is approximately 9 percent higher than in the no-policy scenario.

The percentage welfare gain, cumulated over 50 years, induced by implementing this optimal $\omega = 35$ percent policy is +3.7 percent (see Online Appendix A.10). Given the deadweight loss, implementing this debt transfer policy does not represent a Pareto improvement over the Carbon Bubble with a no-policy scenario: the welfare improvement is composed of +15.4 percent

[18]The social planner announces both policies – the carbon budget and the tax-funded transfer of investors' debt – in the same period. If the macroeconomic policy is delayed, it needs to be more aggressive and the welfare gain is lower (see Online Appendix A.9).

[19]The choice is relatively arbitrary, but 25 years is a common term for new issues of government debt. A less arbitrary choice would have been the issue of perpetuities, but this would have changed the steady state, which is problematic as we are running a numerical rather than analytical analysis.

Figure 2. Transferring entrepreneurs' debt



Notes: Each panel shows the evolution of aggregate variables to their respective decarbonized steady-state values (i.e., in which production only involves zero carbon energy capital). In the middle panel, the dot represents the ratio of the steady-state value of debt before the write-off of high carbon energy capital to the decarbonized steady-state value, while the line starts at the post-transfer value. The middle panel also shows the share of output produced with zero carbon energy capital, $1 - \gamma_t$.

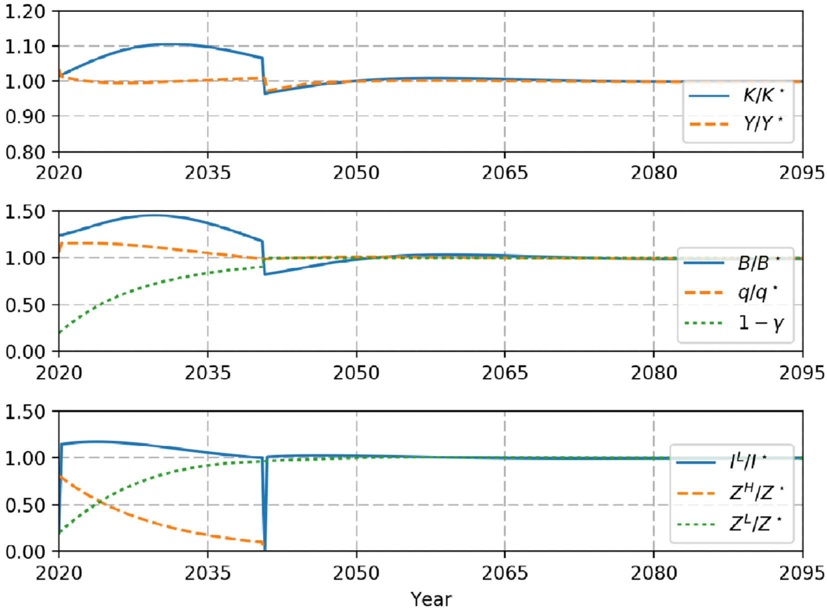
for entrepreneurs, and −6.6 percent for savers. Savers have limited upside from this policy, but they still pay taxes to fund it.

5.2. Subsidy

After banning new high carbon investment and announcing the carbon budget that constrains the use of existing high carbon energy capital, in this policy scenario the social planner also announces an increased level of subsidy paid to entrepreneurs to boost the net private productivity of their production.[20]

[20] Alternatively, the extra subsidy could be targeted to output produced with only zero carbon energy capital. Because there is no new investment in high carbon energy capital, there is no incentive problem with simply paying a general production subsidy. The only difference between these policies is that the targeted subsidy provides a lower boost to entrepreneurs' incomes.

Figure 3. Subsidizing entrepreneurs



Notes: Each panel shows the evolution of aggregate variables to their respective decarbonized steady-state values (i.e., in which production only involves zero carbon energy capital). The middle panel also shows the share of output produced with zero carbon energy capital, $1 - \gamma_t$.

This subsidy, for simplicity, will linearly decrease back to its optimal level over 25 years, as in the debt transfer policy.

We choose the subsidy-induced distortion parameter, δ, such that the optimal subsidy rate from the planner's perspective in the initial steady state is $\varsigma = 0$. We make this choice so that when we look at this subsidy policy, which mitigates the problem of the Carbon Bubble, we ensure that if there are any benefits in applying a subsidy, these must be due to the Carbon Bubble issue. We find that there is a clear optimal subsidy boosting net private productivity by, initially, around 40 percent. Figure 3 shows the dynamics following the carbon budget announcement, when the planner implements this optimal subsidy programme.

The dynamics are similar to the debt reallocation scenario. Over 50 years, the cumulative investment in zero carbon energy capital is approximately 9 percent higher, and welfare is almost 3 percent higher, than in the no-policy scenario. Again, this is not a Pareto improvement: savers are worse off (−8.2 percent) because of the increased tax they have to pay to fund the subsidy, whereas the entrepreneurs benefit from the subsidy (+15 percent).

5.3. Government guarantee

In this policy scenario, we model a government guarantee that reassures lenders and relaxes credit constraints. Specifically, we imagine a guarantee that effectively multiplies an entrepreneur's collateral: for a given quantity of collateral, the entrepreneurs can borrow more. Analytically, equation (4) is modified to $b_t \leq R^{-1} q_{t+1} k_t (1 + gtee_t)$, where $gtee_t$ is the government guarantee in t. Once again, we introduce a deadweight loss associated with $gtee$ in the production function of the entrepreneurs, $y_t = (a + c - \tilde{\mu}(gtee)^2) k_{t-1}$, where $\tilde{\mu}$ is calibrated in such a way that it is optimal to not have a government guarantee in the steady state (see Online Appendix A.5 for more information).

Immediately after the same carbon budget announcement as in the no-policy scenario, the planner announces a linearly reducing guarantee, which reaches zero after 25 years.[21] The steady state to which the economy is converging is therefore unchanged. Figure 4 shows the dynamics following the carbon budget announcement, when the planner implements a guarantee starting at $gtee_0 = 10$ percent, which is approximately optimal given our parameters.

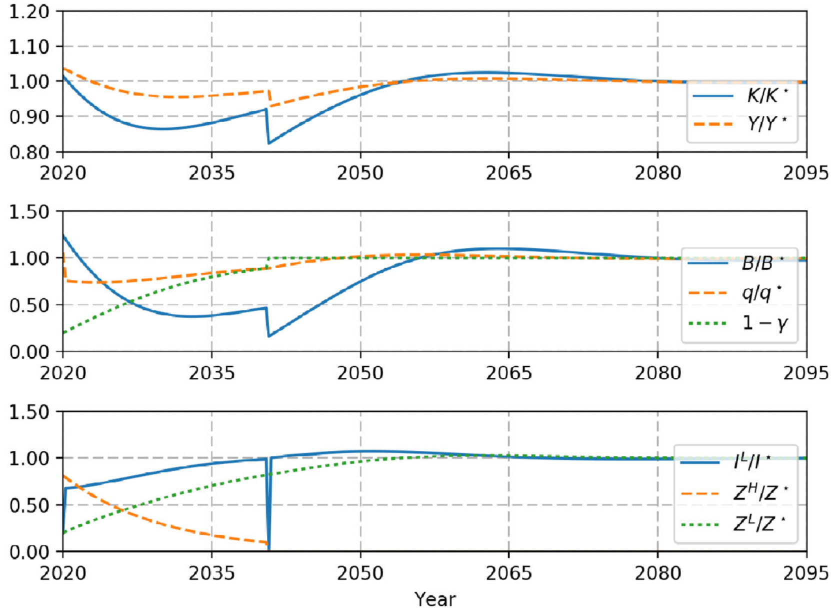
The price jump is slightly smaller than in the no-policy scenario, at approximately −28 percent. However, the guarantee allows entrepreneurs to have access to more debt, and the entrepreneurs use the proceeds of this borrowing to maintain higher fixed capital holdings and higher investment levels than in the no-policy scenario. Over the course of 50 years, the cumulative investment in zero carbon energy capital is approximately 1 percent higher, and welfare is almost 3 percent higher, than in the no-policy scenario (+7.5 percent for entrepreneurs and −1 percent for savers).

5.4. Progressively more ambitious climate targets

Here we consider a different scenario, where the social planner initially announces a more generous carbon budget, $\hat{S} \geq \bar{S}$. For $\hat{S} > \bar{S}$, the economy's actual carbon budget, $\bar{S}$, is used up at some future time. When this happens, $\bar{S}$ is revealed to all agents (and perhaps to the social planner) and the entrepreneurs are compelled to leave unused their remaining high carbon energy capital: carbon taxes are abruptly raised, such that high carbon production abruptly ceases, in a desperate attempt to avoid catastrophic climate change. This might reflect a more gradual policy approach, where the social planner aims first for a less ambitious target, to then switch gear and announce a more stringent goal

[21] Again, 25 years is chosen for consistency with the previous two policies. This implies $gtee_t = \max\{0, (100 - t)/100\} \times gtee_0$, and it ensures that the final steady state does not have a government guarantee.

Figure 4. Providing a government guarantee



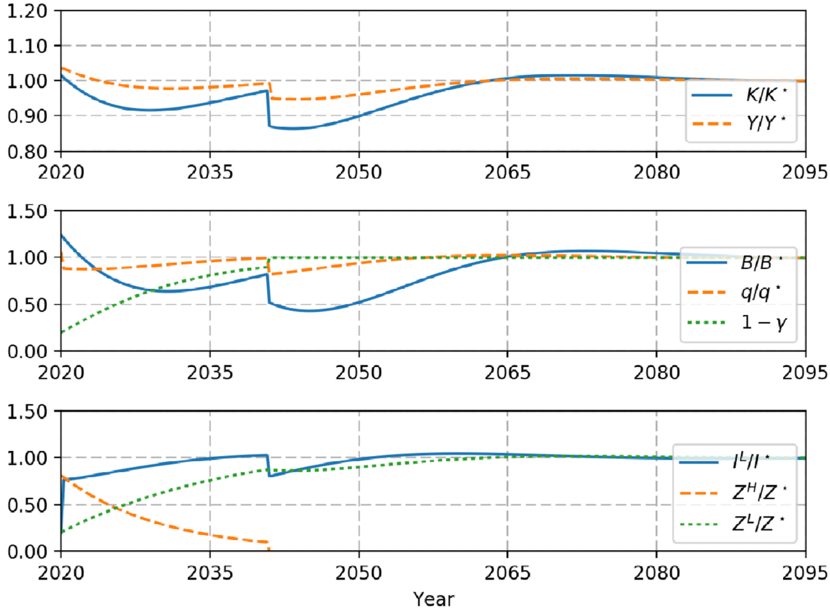
Notes: Each panel shows the evolution of aggregate variables to their respective decarbonized steady-state values (i.e., in which production only involves zero carbon energy capital). The middle panel also shows the share of output produced with zero carbon energy capital, $1-\gamma_t$.

in the future (e.g., from a 2 °C target to 1.5 °C); alternatively, it could reflect learning on the real extent of the climate warming threat, as new estimates from scientists become increasingly more worrisome.

In a canonical model, a progressively more stringent announcement would cause a welfare-destroying discontinuity in consumption across the period in which $\bar{S}$ is finally revealed. In this model, conversely, overstating the actual carbon budget limits the initial fall in the price of fixed capital and thus the decrease in the value of the collateral. This allows higher investment in zero carbon technology, and potentially generates enough productive capacity between the initial period and the period when $\bar{S}$ is revealed, to mean that the present value of consumption flows may be higher under progressively more stringent goals.

Announcing progressively more ambitious climate targets is always welfare-increasing and Figure 5 presents the simulation for the welfare-maximizing value of $\hat{S}$. This is consistent with an initially announced write-off approximately equal to 25 percent of the needed write-off. The initial shock is smaller than in the Carbon Bubble scenario, as the price of fixed capital falls immediately by approximately 16 percent (compared to

Figure 5. Progressively tighter carbon budgets



Notes: Each panel shows the evolution of aggregate variables to their respective decarbonized steady-state values (i.e., in which production only involves zero carbon energy capital). The middle panel also shows the share of output produced with zero carbon energy capital, $1 - \gamma_t$.

32 percent in the no-policy scenario). Investment does not fall as much as in the baseline scenario, and when the actual carbon budget runs out – despite a large negative shock inducing further deleveraging – investment can soon continue. When the updated, tighter, carbon budget $\bar{S}$ is announced, around 90 percent of aggregate entrepreneurs' asset holdings are already dedicated to zero carbon energy capital so that, when the remaining high carbon resources must be left unused, an alternative productive capacity already exists. This limits the magnitude of the recession that results.

Over 50 years, the cumulative investment flow in zero carbon energy capital is almost 3 percent higher than in the no-policy scenario. Welfare is around 3 percent higher with a Pareto improvement on the no-policy scenario (+8.6 percent for entrepreneurs and +0.6 percent for savers).

6. Discussion

In this section, we discuss the policy relevance of our exercise in a real-world context, and how this relates to other work in the literature. As we say in

Section 2, our objective is to study a scenario in which climate change is deemed sufficiently serious to necessitate the near-term implementation of stringent climate policy that implies the write-off of a significant portion of the world's fossil-fuel assets, and to investigate the macroeconomic policy options that will mitigate its impacts. The bulk of the literature studies instead optimal climate policy, including those levers under the control of central banks, starting from now, in which such a stringent climate policy choice may be chosen if climate uncertainty resolves in such a way as to necessitate it. In other words, the literature is typically *ex ante* with respect to climate policy risk, whereas our exercise is *ex post*: we study a scenario in which climate policy risk has already been realized.

So is the world of our exercise the real world all around us? Scientists have been sounding the alarm about climate change for three or four decades now (e.g., the Intergovernmental Panel on Climate Change was founded in 1988), and scientific advice has crystallized around the target of limiting average global temperature rise from the pre-industrial baseline to initially 2 °C, and more recently to 1.5 °C. The implementation of policy consistent with these targets is the basis of our scenario. However, despite this, we do not claim that climate policy risk has in fact been realized in the real world around us, because in the real world such policy has not been implemented. For example, the current Nationally Determined Contributions of participants to the global process of emissions reduction are well short of these targets, and market participants do not expect fossil-fuel assets in excess of the carbon budget implied by these targets to be valued at zero. Our exercise therefore imagines something that shifts global climate policy from its current trajectory, towards strictly following the scientific advice.[22] Once this has induced policymakers to implement policy consistent with strict climate targets, our exercise asks which other policies should be implemented to mitigate the macroeconomic consequences, and to maximize the investment in green capital that is suddenly needed.

We believe our exercise and results are complementary with other work within the literature (such as Benmir and Roman, 2020; Carattini et al., 2021; Diluiso et al., 2021), which consider *ex ante* macroprudential policies (such as climate stress-tests, carbon disclosures, and differentiated capital requirements) that may de-risk balance sheets prior to climate risk being realized, and thus may prevent a climate-risk-induced financial crisis;

[22] This "something" is out of the model, but could include social change – such as a real gain in political traction for a movement (e.g., Fridays For Future) or the sudden imposition of a minimum global carbon price, as recently advocated by, for example, Parry et al. (2021) – or an environmental catastrophe that increases the salience of climate change for policymakers – such as a sudden collapse in the Thwaites Glacier in West Antarctica, which could cause a sudden catastrophic rise in sea level (see, e.g., Robel et al., 2019).

acting upon them, as many central banks are doing, will limit the need for the *ex post* policy measures we discuss. Indeed, de-risking balance sheets via macroprudential policy is likely to be first-best, and surely fundamental in paving the way for subsequent stringent climate policy, as it helps by mitigating the temptation to delay climate policy implementation out of concerns about systemic risks (a point well made by Carattini et al., 2021). But, unfortunately, it might be necessary to look at the problem from both an *ex ante* and an *ex post* point of view. Indeed, we do not argue that policymakers should not be concerned about transition risk when implementing ambitious climate policy, even if they can exploit accompanying macroeconomic policies.[23] In this paper, we have provided policy advice specifically for the case in which the need for ambitious climate actions overtakes the macroprudential measures currently being investigated.

7. Conclusions

We have analysed the effects of the credible implementation of climate change targets, which imply that a substantial proportion of fossil-fuel assets become stranded in an economy characterized by collateral constraints. To do this, we extended the model of Kiyotaki and Moore (1997) to allow for two investment goods representing high carbon and zero carbon energy capital. This framework allowed us to model, for the first time in the economics of climate change, the so-called Carbon Bubble. This was introduced as a warning to investors: climate change mandates a policy response, and you, as an investor, should protect your portfolio from this policy response. By incorporating the Carbon Bubble issue within a macrofinancial model, we start the conversation around appropriate macroeconomic policies that should accompany the Carbon Bubble.

We show that policies that mitigate the impact of the Carbon Bubble upon investors' balance sheets can be beneficial. The global balance sheet will be used to fund the zero carbon infrastructure, which must be built to replace our fossil-fuel-based economy, and the bursting of the Carbon Bubble could throw the economy into a deep recession, depriving green technology of investment funds when they are most needed. Thus, even if the fossil-fuel assets really

[23] First, the macroeconomic policies we consider mitigate the downturn and incentivize green investment, but the climate-policy-induced recession remains severe. Second, we purposely abstracted from both moral hazard concerns (as explained in Section 2) and whether the climate policy is credible and implementable (see Online Appendix A.8). Third, delayed macroeconomic policies are substantially less effective (see Online Appendix A.9).

should be written off to avoid disastrous global warming, it is likely to be suboptimal to do this naïvely.

We acknowledge that there are many areas of our analysis and of the model we use that could be made more sophisticated. For example, policy interaction could be considered and it could be that a combination of policies is optimal. The supply side of the model could be made more realistic, with the depreciation of, and investment in, the non-energy capital, and a time-varying degree of substitutability between clean and dirty inputs. Endogenous growth is likely an important aspect: any under-utilization of capital (with learning-by-doing) or decrease in the demand for green inputs (in a Schumpeterian or expanding variety model) induced by the Carbon Bubble could be more damaging than in the model presented here (e.g., Ghisetti et al., 2017). The "black box" distortion associated with the macroeconomic policies could also be microfounded in an endogenous growth framework.

On the macrofinancial side, we can look to the papers of Carattini et al. (2021) and Diluiso et al. (2021), which incorporate a banking sector.[24] We note with satisfaction, however, that our conclusions are in line with these papers and thus the variety of modelling approaches provides a robustness to these conclusions. One could also properly model the bankruptcy process, incorporating a fuller description of the capital structure of investors' balance sheets with different priority creditors, and costs of financial distress. Furthermore, one could assume that green-tech projects are perceived as riskier by creditors (and thus more credit-constrained) than fossil-fuel projects. Heterogeneous agents might be an important element to add to the model, as in Punzi and Rabitsch (2015).

On the political economy side, the Pareto suboptimality of the policies suggests that a political process is important. Yet, perhaps the Pareto suboptimality problem would be reduced if savers also supplied labour, and there was the possibility of unemployment in recessions. International spillovers (e.g., Ganelli and Tervala, 2011; Annicchiarico and Diluiso, 2019), and some measure of the costs of acting through the planner, might also be important (in our model, an obvious optimal policy would be to nationalize investment in energy so that the unconstrained government maintains investment in the face of the Carbon Bubble).

There remains much to do in fully specifying a model that will allow a macroeconomic forecast of the impact of the Carbon Bubble, and will allow

[24] The key mechanism in this paper is the fall in the collateral value of the entrepreneurs following a tighter climate policy. But, in reality, it is not only entrepreneurs who own fossil-fuel capital or fossil-fuel reserves. In a model with a financial intermediation sector, we would observe costlier bank credit and bank runs if the tighter climate policy influences, directly or indirectly, the balance sheets of the intermediaries (see, e.g., Gertler and Kiyotaki, 2015).

the design of an optimal policy response. This paper contributes to this, and has shown that there is a role for policy in mitigating its impact. Policy that protects investors' balance sheets mitigates the macroeconomic downturn, and leads to a higher investment in the replacement zero carbon productive capacity over the period in which we still use carbon-emitting productive capacity.

Supporting information

Additional supporting information can be found online in the supporting information section at the end of the article.

Online appendix

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