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Inge van den Bijgaart, Mauricio Rodriguez

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Abstract

Despite ambitious climate goals and already substantial stocks of developed fossil energy reserves, development of new fossil energy reserves continues to be high. This raises concerns, as it reinforces the fossil industry's opportunities and incentives to continue extraction, and may necessitate abandonment of developed fossil reserves to meet climate targets. In this paper, we analyze the energy transition, considering fossil exploration and development activities. We provide conditions for when the fossil industry will abandon reserves, and establish that continued exploration of fossil resources is not incompatible with abandoning developed reserves. The first-best implementation of a carbon budget always involves reserve abandonment, and thus exploration that pushes developed reserves in excess of the remaining budget. A quantitative assessment reveals that a volume equal to 9-19% of current oil and gas reserves are optimally abandoned, and that, even under a 1.5°C warming target, positive exploration of new reserves is justified for another decade.

JEL-Codes: Q210, Q310, Q350, Q540, Q580.

Keywords: carbon budget, energy transition, fossil exploration, non-renewable resources, renewable energy, stranded assets.

Inge van den Bijgaart
Department of Economics
University of Gothenburg
Sweden – 41101 Gothenburg
inge.van.den.bijgaart@economics.gu.se

*Mauricio Rodriguez**
Department of Economics
University of Rosario
Colombia – 111711 Bogotá
mauricio.rodriguez@urosario.edu.co

*corresponding author

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1 Introduction

In recent years, concerns about climate change have put the composition of the global energy mix under increased scrutiny. Meeting global climate targets will require a rapid transition away from fossil fuels, and towards renewable sources of energy. To promote this transition, many countries have introduced mitigation policies, including carbon taxes and emission trading schemes, as well as feed-in tariffs for renewable energy. In response to these policies, renewable energy capacity investment has rapidly expanded, from \$40 billion in 2004, to \$300 billion by 2017 (Frankfurt School-UNEP Centre/BNEF, 2019).

Still investment in fossil energy continues to be substantial. In 2017 alone, investment in exploration and development of new oil and gas reserves amounted to \$450 billion, and for every single year to date, investment in new fossil energy supply has exceeded investment in renewable energy generation (IEA, 2018a). These investments raise concerns. Meeting climate targets requires forfeiting extraction of known oil and gas reserves (McGlade and Ekins, 2015). These reserves can be classified as either undeveloped or developed reserves; the carbon emissions embedded in developed reserves alone are currently close to the cumulative emission budget associated to the $1.5°C$ warming target (Muttitt, 2016; Rogelj et al., 2018). Unless fossil exploration and development is rapidly reduced, either large amounts of developed fossil reserves will remain unextracted, or climate goals will not be met.

In this paper, we analyze the energy transition in a framework that explicitly considers fossil exploration and development and the distinction between developed and undeveloped reserves. This setup allows us to rationalize new fossil exploration and development in the presence of an anticipated abandonment of developed reserves. We evaluate the optimal implementation of a carbon budget and find that it always involves abandonment of developed fossil reserves. Thereby, the optimal energy transition always features exploration that pushes developed reserves in excess of the allowable budget. As revealed by our simulation exercises, optimal abandonment is nonnegligble; for our central estimates, the equivalent of 9% and 19% of current developed reserves are optimally abandoned under a $2°C$ and $1.5°C$ target, respectively.

Our framework of the energy transition includes the exploration of new fossil reserves and subsequent extraction of developed reserves, alongside gradual investment in renewable energy capacity. In this model, the energy needs of the economy can be satisfied by fossil or renewable energy. Fossil energy generation requires extraction of fossil resources, which need to be explored and developed before they are available for extraction. Realistic limits on the rate at which resources can be extracted provide a rationale for keeping positive levels of developed reserves. Similarly, renewable energy supply is subject to capacity constraints, where convex investment costs prevent rapid expansions of renewable energy capacity.

Our analysis consists of three parts. First, we take climate policy as given and establish conditions under which the transition features developed reserve abandonment and determine whether anticipated abandonment rules out exploration and development of additional fossil energy reserves. Second, we consider the optimal implementation of a carbon budget, characterize the optimal policy trajectory and assess whether abandonment is part of an optimal energy transition. Third, we quantitatively evaluate the energy transition under alternative carbon budgets, consistent with $2°C$ and $1.5°C$ warming targets. We simulate the optimal transition, and the transition when climate policy implementation is delayed by a decade.

We establish that the energy transition features strictly positive abandonment of developed fossil reserves when fossil energy taxes are sufficiently high in the long run, relative to the cost of renewable energy. Still, despite anticipated abandonment, a fossil energy firm may face positive incentives for fossil resource exploration and development as, by expanding extraction capacity, this allows for higher energy supply levels in the short run. The optimal implementation of a binding carbon budget requires a positive fossil energy tax, which is increasing at the rate of interest. Consequently, optimally implementing a budget necessarily leads to the abandonment of developed reserves, and thus development of fossil energy reserves in excess of the allowable budget.

Our quantitative evaluation reveals that optimal abandonment is substantial: under the $2°C$ target, 68 to 97 billion barrels of oil-equivalent energy (BBOE) are abandoned, for the $1.5°C$ target this value increases to 120 to 146 BBOE. Reserve abandonment coincides with the full phase-out of fossil fuels, which occurs in 2081 and 2049 under the $2°C$ and $1.5°C$ target, respectively. Exploration and development of new reserves comes to an end 20 to 25 years prior to the fossil phase-out. Implementing the optimal phase-out trajectory requires 2017 fossil energy taxes equal to \$28 and \$104 per tCO_2 under the $2°C$ and $1.5°C$ target, respectively. Delaying the introduction of this tax by a decade has little effect on reserve abandonment and future tax levels under the $2°C$ target. Instead, under the $1.5°C$ target, delaying the introduction of the tax by a decade causes reserve abandonment to nearly triple. Taxes, once introduced, are increased by a third.

Our paper builds on recent contributions on fossil resource exploration, development and extraction, in particular Venables (2014) and Anderson et al. (2018). A primary contribution of Venables (2014) and Anderson et al. (2018) is to consider the role of geology in limiting the capacity to adjust the rate of fossil resource extraction. This departure from the conventional framework where extraction is unconstrained and prices are governed by the Hotelling rule, generates an equilibrium where production from existing wells is relatively unresponsive to price shocks. Instead, exploration and field development activities are strongly price sensitive, which as highlighted by Anderson et al. (2018), is in line with empirical regularities. A similar regularity is captured by Bornstein et al. (2017), who develop a stochastic model of the oil industry, featuring a lag between developed stock additions and investment in exploration capital.[1] While Venables (2014), Anderson et al. (2018) and Bornstein et al. (2017) present detailed models of the fossil energy sector, they do not evaluate the energy transition towards a greater share of renewable energy supply, nor consider climate policy in their analyses.

Vice versa, the body of literature considering the energy transition towards renewables generally abstracts from fossil resource exploration and development, and thereby does not distinguish between developed and undeveloped reserves.[2] In a recent contribution, van der Ploeg and Rezai (2020) analyze the implementation of greenhouse gas emissions budgets in a framework that considers investment in fossil exploration. The focus of their analysis is on the effect of alternative policy scenarios and policy uncertainty on phase-out trajectories and the value of fossil firm assets. van der Ploeg and Rezai (2020) do not distinguish between developed and undeveloped reserves, nor consider the role of extraction constraints. Rather, exploration reduces extraction costs by increasing total oil and gas reserves, and firms are unconstrained to extract from reserves, causing prices to follow a Hotelling rule.[3]

Like van der Ploeg and Rezai (2020), Gollier (2018) and Dietz and Venmans (2019) consider the energy transition and emission mitigation policies in the presence of a carbon budget. They characterize the optimal carbon price to ensure cumulative CO_2 emissions remain within this budget. Gollier (2018) focuses on the role of economic uncertainties on optimal carbon prices, while Dietz and Venmans (2019) consider several policy strategies in line with the $2°C$ warming target. We abstract from uncertainty, and determine the policy strategy that minimizes the cost of meeting a warming target.

Abandoned developed reserves can be considered a type of stranded asset. The notion of stranded assets encompasses multiple phenomena, including ‘unburnable carbon’, underutilization of fossil energy infrastructure due to anticipated climate policy, as well as the loss of value in (fossil) firms and other energy infrastructure due to an unanticipated introduction or tightening of emission mitigation policy (Carbon Tracker and Grantham Institute, 2017; Caldecott, 2017). Contributions to this literature

[1] An early contribution on fossil resource management that explicitly consider both extraction and exploration decisions is Pindyck (1978). More recent contributions are Bai and Okullo (2018), Boyce and Nøstbakken (2011), Cairns (2014) and Okullo et al. (2015). There also exists an earlier literature that considers exploration, taking the extraction decision as exogenous. See for instance Nystad (1985) and Thompson (2001).

[2] See for instance, van der Ploeg and Withagen (2015), Rezai and van der Ploeg (2017), van der Meijden and Smulders (2017) and Heal and Schlenker (2019).

[3] Additionally, by considering a backstop technology that delivers renewable energy at infinitely elastic supply, van der Ploeg and Rezai (2020) cannot capture the important distinction between the present day, with insufficient renewable capacity to satisfy energy demand, and the long run, when sufficient renewable energy capacity has been built.

include Rozenberg et al. (2018) and Baldwin et al. (2019), who analyze the underutilization of fossil energy infrastructure due to the inability to relocate capital from the fossil to the renewable energy generation sector.

The remainder of the paper is structured as follows. The model setup and firm optimization problems are presented in Section 2. Section 3 discusses the long run equilibrium, and conditions under which developed reserves are abandoned. The implementation of the carbon budget is discussed in Section 4. The quantitative analysis is presented in Section 5. Section 6 concludes. Derivations, proofs and additional calibration details can be found in the Appendix.

2 Model

Energy is produced from fossil resources and renewable energy capital. The extraction of fossil resources depletes developed reserves. To replenish these reserves and expand extraction capacity, a fossil energy firm can invest in fossil exploration and development. Renewable energy is generated using a renewable capital stock, which depreciates over time and can be expanded through investment. We abstract from strategic behavior and assumethat markets are competitive. This allows us to characterize the fossil and renewable energy sector as each represented by a single firm. The fossil energy firm chooses the levels of extraction and exploration and development activities that maximize firm value. The firm maximization problem in the renewable energy sector is similar, with the renewable energy firm instead choosing the levels of renewable energy supply and investment in new renewable energy capacity.

2.1 Setup

Energy supply We denote time t energy from fossil sources by $E_F(t)$, and renewable energy by $E_R(t)$, such that we obtain the following accounting equation for total energy supply:

$$E(t) = E_F(t) + E_R(t). \tag{1}$$

Fossil energy The production of each unit of fossil energy requires one unit of fossil resources, which is extracted from a stock of developed reserves, $S(t)$. To convert $E_F(t)$ units of fossil resources in to fossil energy, the firm incurs cost $C_F(E_F(t))$. This cost includes all cost associated with extracting the fossil resource, transforming it into energy, and any net taxes imposed on the extraction or use of the resource. Common examples of such taxes are environmental taxes, and royalty payments to local governments. We take $C_F(t)$ as directly proportional to total use of fossil energy $E_F(t)$, and separate the extraction and use cost, c_F, and net taxes $\tau(t)$ as follows:

$$C_F(E_F(t)) = (c_F + \tau(t))\, E_F(t), \tag{2}$$

where we assume c_F is constant, allow taxes $\tau(t)$ to change over time, and require $E_F \geq 0$.

Fossil resource extraction is limited by the available extraction capacity. In line with Anderson et al. (2018), we assume this extraction capacity is endogenously determined by the level of developed fossil reserves. This gives[4]

$$E_F(t) \leq \kappa S(t), \tag{3}$$

with $\kappa > 0$. The parameter κ represents the maximum rate at which the developed stock can be extracted. Conversely, κ determines the minimum amount of stock holdings required to extract a unit of fossil resources per unit of time, which is equal to $1/\kappa$. Our consideration of a maximum extraction capacity that is a function of remaining developed stock is motivated by the so-called field or well decline curves in oil production (Höök et al., 2014). These curves relate well or field production rates to time since opening, assuming continued production at capacity.[5] Equation (3) mimics this approach.

The level of developed reserves can be increased through exploration and development. This includes the search for fossil deposits using e.g., seismic surveys and the drilling of exploration wells, the drilling of production wells, and the installation of injection wells which allow for increased extraction from previously-developed depositis. We denote the cost of exploring and developing $X(t)$ units of additional stock by $C_X(X(t), U(t))$, where $U(t)$ is the level of *undeveloped* resource stock at time t. The cost of stock exploration and development is convex and increasing in the level of exploration: $\partial C_X(X(t), U(t))/\partial X(t) = c_X(X(t), U(t)) \geq 0$ and $\partial c_X(X(t), U(t))/\partial X(t) > 0$, where in the remainder we refer to $c_X(\cdot)$ as the marginal exploration cost. This convexity of the cost function is consistent with evidence presented by Anderson et al. (2018) and Mason and Roberts (2018), who show that there exists a positive relationship between the number of oil wells drilled in a given year and the marginal cost of drilling. We take the exploration cost as equal to zero when exploration is zero, $C_X(0, U(t)) = 0$, and require $X(t) \geq 0$. To capture the notion that the most accessible resources

[4]See also Cairns (2014), Cairns and Davis (2001), and Thompson (2001).

[5]For individual oil wells, maximum per-period extraction is a function of a number of reservoir characteristics, such as stock, pressure, porosity, and the viscosity of the resource. As extraction ensues, a reservoir's remaining stock, pressure, and consequently maximum production, falls. Several techniques, such as water or steam injection, can be used to increase the amount of oil recoverable from a well. We implicitly assume that κ captures such techniques (Höök, 2009).

are exploited first, we assume that the (marginal) cost of exploration increases as more reserves have been developed: $\partial C_X(\cdot)/\partial U(t) \leq 0$, and $\partial c_X(\cdot)/\partial U(t) \leq 0$.[6]

Given exploration $X(t)$ and fossil resource use $E_F(t)$, the developed resource stock $S(t)$ evolves according to

$$\dot{S}(t) = -E_F(t) + X(t), \tag{4}$$

where the dot denotes the time derivative; we assume $S(0) = S_0 > 0$. We take the stock of ultimately discoverable resources in the earth's crust as finite. This immediately imposes the following limit on cumulative exploration:

$$\int_t^{\infty} X(\nu)d\nu \leq U(t), \tag{5}$$

with $U(0) = U_0 > 0$.

Renewable energy Renewable energy, $E_R(t)$, is produced using renewable energy capital, $K(t)$. This capital includes wind turbines, solar panels, bioenergy plants, hydroelectric facilities and nuclear power plants. Each unit of capital generates one unit of renewable energy capacity such that

$$E_R(t) \leq K(t). \tag{6}$$

Producing energy from renewable capital has a constant marginal cost $c_R \geq 0$. This cost captures all costs associated to the use of renewable energy capacity, like the fuel cost of biomass used as an input to bioenergy, and any operational or maintenance cost, such as the cost of staffing a nuclear power plant. Compared to the use cost of fossil energy, which includes the cost of extracting the fossil resource, c_R is likely small.[7] In line with this we assume that $c_R < c_F + \tau(t)\ \forall t$ in the remainder, which implies that the available renewable energy capacity is always utilized prior to energy from fossil resources.

A renewable energy firm can invest to expand renewable energy capacity. The cost of investment $I(t)$ is denoted by $C_I(I(t))$ and increasing and convex in the investment level: $\partial C_I(I(t))/\partial I(t) = c_I(I(t)) \geq 0$, $\partial c_I(I(t))/\partial I(t) > 0$, where the $c_I(\cdot)$ denotes the marginal investment cost. Due to the convexity of the investment cost function, it is costly to rapidly expand renewable energy capacity.

[6] Though technological progress has dramatically reduced the cost of fossil exploration and development over time, and made previously inaccessible deposits accessible (Boyce and Nøstbakken, 2011), we abstract from explicitly modeling such progress. Insofar part of this progress can be attributed to learning by doing, it would reduce the extent to which lower levels of $U(t)$ are associated with higher marginal cost of exploration and development $c_X(\cdot)$.

[7] An exception might be biomass, which has a fuel cost comparable to fossil. The fuel cost of other renewables is (near) zero (EIA, 2019).

This can be due to capital adjustment cost. Also a rapid expansion of renewable energy capacity may limit the extent to which the firm can take advantage of technical progress in renewable energy technologies.[8]

We assume that investment costs are independent of the level of installed capital, $K(t)$. This specification does not consider that marginal investment costs may be decreasing in the current level of $K(t)$, due to e.g., learning, as is commonly assumed in the macroeconomics literature. Simultaneously however, the investment cost function abstracts from the notion that the lowest cost locations for e.g., building wind farms and solar parks will be developed first. Also it does not capture that as a greater share of energy comes from renewables, challenges such as intermittency will likely require larger investments in renewable capital to substitute away a given amount of fossil energy. Both of these effects suggest marginal investment costs increasing in the level of $K(t)$. To date, it remains uncertain whether the positive or negative effects dominate, in particular in the long run.

Renewable energy capital depreciates at rate $\delta > 0$, which gives

$$\dot{K}(t) = I(t) - \delta K(t), \tag{7}$$

with $K(0) = K_0 \geq 0$.

Energy demand Finally, energy is used in output production. We refrain from a detailed modeling of output markets, and rather assume that there exists a continuous inverse energy demand function $P(E^D(t))$, which is decreasing and convex in energy demand $E^D(t)$: $P'(E^D(t)) < 0$ and $P''(E^D(t)) > 0$ with $\lim_{E^D \to 0} P(E^D) = \infty$.

2.2 Firm optimization

Both fossil and renewable energy firms maximize the present value of profits. As they both supply energy, they face the same energy price, denoted by $p_E(t)$, which they take as given. We assume firms discount future profits at the, exogenously given, rate of interest $r > 0$.

Fossil firm The fossil firm chooses the path of fossil extraction and fossil exploration, $[E_F(\nu), X(\nu)]_{\nu=t}^{\infty}$, that maximizes $\Pi_F(t) = \int_t^{\infty} \pi_F(\nu) e^{-r(\nu - t)} d\nu$, with instantaneous profits $\pi_F(t) = (p_E(t) - c_F - \tau(t)) E_F(t) - C_X(X(t), U(t))$, subject to the extraction constraint (3), the constraint on cumulative exploration (5), developed reserves evolution (4), and the non-negativity constraints on

[8] Akin to exploration and development, we do not explicitly incorporate technological progress in renewable energy technology.

exploration and extraction, $X(t), E_F(t) \geq 0$. We present and discuss the relevant first order conditions below. The Hamiltonian, and the full set of first order, complementary slackness and transversality conditions can be found in Appendix A.1.

The fossil firm's tradeoff in extraction is characterized by the first order condition with respect to $E_F(t)$:

$$p_E(t) - c_F - \tau(t) = \mu_S(t) + \left[\phi_{F,cap}(t) - \phi_{F,0}(t)\right], \tag{8}$$

where $\mu_S(t)$ denotes the shadow value of $S(t)$, and $\phi_{F,cap}(t)$ and $\phi_{F,0}(t)$ are the shadow values of the extraction capacity and nonnegativity constraint, respectively. At time t, extracting fossil reserves has an immediate net benefit of $p_E(t) - c_F - \tau(t)$, while keeping developed reserves in the ground and extracting in the future has value $\mu_S(t)$. Then whenever the net benefit of extraction exceeds the value of keeping developed reserves in the ground, the firm would like to choose a higher extraction level. From here, it immediately follows that the extraction level chosen will equal extraction capacity; the extraction constraint will be binding, as implied by a positive shadow value of of the extraction capacity constraint, $\phi_{F,cap}(t) > 0$. Conversely, if $p_E(t) - c_F - \tau(t)$ falls short of $\mu_S(t)$, the firm is better off choosing a lower level of extraction. Extraction will be zero, and the shadow value of the nonnegativity constraint on extraction will be positive, $\phi_{F,0}(t) > 0$.

The exploration and development decision is described by the first order condition with respect to X, which shows that adding a unit of developed reserves through exploration has value $\mu_S(t)$, and cost equal to c_X plus the shadow value of undeveloped reserves $\mu_U(t)$:

$$\mu_S(t) = c_X\left(X(t), U(t)\right) + \mu_U(t) - \phi_{X,0}(t), \tag{9}$$

where $\phi_{X,0}(t)$ denotes the shadow value of the nonnegativity constraint on $X(t)$. Then, similar to (8), whenever the value of developed reserves $\mu_S(t)$ falls short of the cost of the first unit of exploration, $c_X(0, U(t)) + \mu_U(t)$, the firm will not find it optimal to explore, and the non-negativity constraint on $X(t)$ will be binding ($\phi_{X,0}(t) > 0$). If instead $\mu_S(t)$ exceeds $c_X(0, U(t)) + \mu_U(t)$, the firm will choose positive exploration.

The first order condition with respect to $S(t)$ is a no-arbitrage condition that equalizes the net return to owning developed fossil reserves, which is the rate of change in the reserve value, plus immediate profit increase associated to relieving the extraction constraint, to the market rate of return r:

$$\frac{\dot{\mu}_S(t)}{\mu_S(t)} + \kappa \frac{\phi_{F,cap}(t)}{\mu_S(t)} = r. \tag{10}$$

Similarly, the first order condition with respect to $U(t)$ dictates that along the optimal path, the net return to leaving stock undeveloped must equal r. This return is equal to the rate of change of the stock value, plus any exploration cost savings due to the higher level of $U(t)$:

$$\frac{\dot{\mu}_U(t)}{\mu_U(t)} - \frac{\partial C_X\left(X(t), U(t)\right)/\partial U(t)}{\mu_U(t)} = r. \tag{11}$$

From (10) and the transversality condition (A.6) we arrive at the following solution for the value of developed stock

$$\mu_S(t) = \kappa \int_t^\infty \phi_{F,cap}(\nu) e^{-r(\nu - t)} d\nu. \tag{12}$$

This solution indicates that a unit of developed reserves is valuable only insofar the extraction constraint is eventually binding. From here it follows that if the firm has an extraction plan that never hits the maximum fossil extraction capacity, then it has no incentive to engage in exploration activities. The latter can be observed through (9): as we obtain $\mu_S(t) = 0$ for all t, we must either have $\phi_{X,0} > 0$ or $c_X(X(t), U(t)) = 0$. In either case, $X(t) = 0$.

Renewable firm Likewise, the renewable firm chooses the path of renewable energy production and investment in capacity, $\left[E_R(\nu), I(\nu)\right]_{\nu=t}^\infty$, that maximizes $\Pi_R(t) = \int_t^\infty \pi_R(\nu) e^{-r(\nu-t)} d\nu$, with instantaneous profits $\pi_R(t) = \left(p_E(t) - c_R\right) E_R(t) - C_I(I(t))$, subject to the renewable capacity constraint (6), evolution of renewable energy capacity (7) and non-negativity constraints on investment and renewable energy use $I(t), E_R(t) \geq 0$. We again present the Hamiltonian, full set of first order, complementary slackness and transversality conditions in the Appendix, and focus on the relevant first order conditions below. The decision to supply renewable energy is characterized by the first order condition with respect to $E_F(t)$:

$$p_E(t) - c_R = \left[\phi_{R,cap}(t) - \phi_{R,0}(t)\right], \tag{13}$$

where $\phi_{R,cap}(t)$ and $\phi_{R,0}(t)$ are the shadow values of the renewable energy capacity and nonnegativity constraint, respectively. Whenever the net benefit of generating renewable energy from capacity, $p_E(t) - c_R$, is strictly positive, the renewable energy firm will decide to produce at full capacity ($\phi_{R,cap}(t) > 0$). Conversely, if the energy price falls short of c_R, the non-negativity constraint on renewable energy production will be binding, $\phi_{R,0}(t) > 0$, and renewable energy production will be zero. Investment can relieve the capacity constraint on renewable energy generation. The FOC with respect to I establishes that any positive level of investment is chosen such that the marginal cost of investment

$c_I(I(t))$ is equal to the value of additional renewable capacity $\mu_K(t)$:

$$\mu_K(t) = c_I(I(t)) - \phi_{I,0}(t), \tag{14}$$

where $\phi_{I,0}(t)$ is the shadow value of the nonnegativity constraint on investment. Finally, the no-arbitrage condition (15) describes that the rate of change in the capacity's value, net of depreciation, plus the immediate value of allowing for higher renewable energy supply, must equal the rate of return r:

$$\frac{\dot{\mu}_K(t)}{\mu_K(t)} - \delta + \frac{\phi_{R,cap}(t)}{\mu_K(t)} = r. \tag{15}$$

Equations (15) and the transversality condition (A.12) allow us to solve for the value of adding renewable capacity:

$$\mu_K(t) = \int_t^\infty \phi_{R,cap}(\nu) e^{-(r+\delta)(\nu-t)} d\nu. \tag{16}$$

Akin to (12) we find that an additional unit of renewable capacity has positive value only if, at some point in time, renewables are used at full capacity. As the use cost of renewable capacity lies below the use cost of fossil, $c_R < c_F + \tau(t)$, renewable capacity is always used first. From here it follows that whenever a positive amount of fossil energy is used, renewables must be used at full capacity: $E_R(t) = K(t)$. In fact, as we show in Appendix B.2.1, whenever a strictly positive amount of fossil energy is used at $t = 0$, $E_R(t) = K(t)\ \forall t$. In the remainder of the paper we assume that this is the case, which allows us to use (13) and (16) to write

$$\mu_K(t) = \int_t^\infty [p_E(\nu) - c_R] e^{-(r+\delta)(\nu-t)} d\nu. \tag{17}$$

Equation (17) is straightforwardly interpreted. Each unit of renewable capacity generates one unit of renewable energy, and depreciates at rate δ. In turn, one unit of renewable energy earns an immediate net return of $p_E(t) - c_R$. Hence, $\mu_K(t)$ captures the present value of adding a unit of renewable capacity.

3 Equilibrium: exploration and resource abandonment

Section 2.2 characterizes the fossil and renewable firm extraction, exploration and investment decisions for given prices $p_E(t)$. Yet, energy prices are endogenous; they depend on total energy supply and thereby the decisions of the fossil and renewable firms. In this section we briefly discuss the equilibrium in the energy market, focusing on the incentives of the fossil firm to engage in exploration and the conditions under which the firm will abandon developed reserves.

Throughout this section, we define an equilibrium as paths $[E_F(t), X(t), E_R(t), I(t), S(t), U(t), K(t), p_E(t), \tau(t)]_{t=0}^{\infty}$ such that the fossil and renewable firms are maximizing the net present value of profits taking the path of prices and taxes as given, and the energy market clears, $E(t) = E^D(t)$. In turn, we define the long-run equilibrium as the equilibrium that will prevail as $t \to \infty$. We consider only equilibria with weakly increasing fossil fuel taxes $\tau(t)$; i.e., we assume that $\dot{\tau}(t) \geq 0$ for all t. As we establish in Section 4, the tax path that optimally implements a carbon budget satisfies this assumption.

Due to the finiteness of total reserves, $U_0 + S_0$, a long run equilibrium with positive fossil use is not feasible; in the long run, energy use must be fully renewable. From (13)-(15) this gives the following implicit solution for long-run equilibrium energy use and the corresponding energy price:[9]

$$P(E^{ss}) = c_R + (r + \delta)\, c_I(\delta E^{ss}), \tag{18}$$

where the *ss* superscript indicates we are in the long run equilibrium (steady state) and $p_E^{ss} = P(E^{ss})$. In the long run, the energy price equals the total marginal cost of producing energy from renewables. This total marginal cost comprises the marginal use cost c_R, plus a marginal cost of maintaining a renewable energy capacity of $E^{ss} = K^{ss}$. The latter is equal to the rental rate $r + \delta$, multiplied by the marginal cost of capital. The marginal cost of capital in turn is equal to the marginal investment cost evaluated at the level of investment that ensures K is stable at its long run level: $I^{ss} = \delta E^{ss}$. As $\partial c_I(t)/\partial I(t) > 0$, (18) establishes a positive relationship between the level of steady-state renewable energy use and the long-run equilibrium price of energy; as the long-run marginal costs of renewable energy is increasing in the level of renewable energy use, higher levels of E^{ss} require higher prices to support them.

The finiteness of fossil resources imposes a physical constraint on cumulative fossil use, thereby making a long run equilibrium with fossil energy use infeasible. This need not imply however that this constraint is binding; the fossil firm may decide not to develop all available reserves, or refrain from the extraction of remaining developed reserves. We refer to the latter situation as the abandonment of developed reserves. Below, we establish that abandonment of developed reserves will prevail whenever at the long run energy price, the extraction of fossil reserves is no longer economically viable:

Proposition 1. *If $P(E^{ss}) - \tau(t) < c_F$ for some t, then developed fossil reserves will be abandoned in the long run ($S^{ss} > 0$). If $P(E^{ss}) - \tau(t) > c_F$ for all t, then all developed fossil reserves will be*

[9] Appendix B.2.2 establishes that the long run equilibrium is globally stable.

extracted in the long run ($S^{ss} = 0$).

Proof. See Appendix B.1.1. $\square$

Proposition 1 establishes that if fossil *use* costs or taxes are relatively high, such that for some t, $P(E^{ss}) - \tau(t) < c_F$, then a strictly positive amount of developed reserves will remain unextracted in the long run. If instead $P(E^{ss}) - \tau(t) > c_F$ for all t, the long run equilibrium is consistent only with full extraction of developed reserves: $S^{ss} = 0$.[10] This result is intuitive: the fossil firm is willing to extract any remaining stock as long as the price of energy net of taxes is sufficiently high to compensate for the cost associated with extracting and using the fuel c_F. Yet, the extraction constraint prevents the firm to fully extract its stock in finite time, which implies that some developed reserves must remain in the ground whenever extraction is uneconomical in the long run. As we assume $\tau(t)$ weakly increasing over time, this is the case whenever $P(E^{ss}) - \tau(t) < c_F$ for some t.

An intuitively similar condition can be established regarding the abandonment of *undeveloped* reserves. Here, $U^{ss} > 0$ only if for all t, the energy price net of taxes in the long run lies below the cost associated to developing and extracting the final unit of undeveloped reserves: $P(E^{ss}) - \tau(t) \leq c_F + (r+\kappa)\frac{c_X(0,0)}{\kappa}$.[11] Akin to total renewable costs, this cost can be separated into the cost associated to extracting and using a unit of fossil energy, c_F, and the capacity cost of fossil extraction, $(r+\kappa)\frac{c_X(0,0)}{\kappa}$.[12]

Whenever the condition in Proposition 1 holds, the fossil firm anticipates that it will abandon developed reserves, either immediately or at some future point in time. Developing additional reserves through exploration in the short run would then increase the amount of stock that is abandoned, suggesting it is never optimal for the firm to do so.

This however need not be the case. Firms have an incentive to explore whenever the shadow value of developed fossil reserves, $\mu_S(t)$, is positive. From (9), this in turn leads to positive exploration whenever the value of fossil reserves exceeds the marginal cost of exploring the first unit: $\mu_S(t) > c_X(0, U(t))$. As explained in Section 2.2, $\mu_S(t)$ is positive only if exploration is constrained at some future point, i.e., if $\phi_{F,cap}(t) > 0$ for some t. From (8), it then follows that, at time t, exploration incentives are absent only if energy prices net of taxes are below the use cost along the *entire* transition: $P(E(v)) - \tau(v) \leq c_F$ for all $v \geq t$.[13]

[10] In the remaining case, with $P(E^{ss}) - \tau(t) \geq c_F$ $\forall t$ and $P(E^{ss}) - \tau(t) = c_F$ for some t, additional conditions are required to determine whether developed reserves will be abandoned in the long run.

[11] See Appendix B.2.3 for a proof.

[12] $c_X(0,0)$ is the minimum cost of exploring the last unit of undeveloped reserves. Each unit of $S(t)$ allows for κ units of fossil extraction. With extraction at capacity, this gives a net rental rate of fossil capacity of $r+\kappa$.

[13] Whenever $\mu_S(t) = 0$, (8), $E_F(t) > 0$ requires $P(E(t)) - \tau(t) = c_F$, otherwise $E_F(t) < 0$ and $p_E(t) = P(K(t))$. Hence,

As developed reserve abandonment requires this condition to only be fulfilled in the long run (note that $\tau(t)$ is weakly increasing over time), the condition for 'no exploration' is more demanding than the condition for 'developed reserve abandonment'. Hence, an anticipated abandonment of developed reserves does not automatically rule out positive exploration.

A combination of elements of the framework explain exploration in the short run despite future developed reserve abandonment. First, low fossil energy taxes in the immediate future vis-à-vis the long run imply a relatively high return to fossil energy extraction is maintained in the short run. This is exacerbated by the convex renewable investment cost, which delays the build-up of competing renewable energy generation capacity. Simultaneously, extraction constraints limit the fossil firm's ability to satisfy demand for fossil energy. Exploration then acts as a lever to increase extraction; it relieves the extraction constraint by adding extraction capacity, and hence allows the fossil firm to increase fossil energy supply.

4 Fossil phase-out under a carbon budget

Fossil fuel taxes reduce the incentive to use fossil energy, and when set sufficiently high, can even lead to the abandonment of developed fossil reserves. Fossil fuel taxes are often motivated by the substantial environmental externalities associated to fossil energy use, such as local pollution and the climate externality. Limiting climate change in particular requires a transition away from fossil energy use, and towards a greater share of renewables in energy production. It is not immediate however that abandoning developed reserves should be part of such a strategy, as it implies foregoing extraction of reserves for which a large part of the cost, i.e., the exploration and development cost, is already sunk.

Below, we establish that developed reserves abandonment is part of the optimal phase-out strategy under a binding carbon budget. This result is independent of the level of the budget and of initial developed reserves. Carbon budgets are commonly employed to frame temperature stabilization policies; the IPCC 5th assessment report and IPCC special report on $1.5°C$ warming present cumulative CO_2 emission budgets for several peak temperature targets (Stocker et al., 2014; Rogelj et al., 2016). The use of carbon budgets as a policy tool exploits the insight that the maximum global mean temperature increase is approximately linear in cumulative CO_2 emissions, and independent of the exact timing of those emissions (Stocker et al., 2014; Allen, 2016; Rogelj et al., 2016; Dietz and Venmans, 2019).[14]

$\mu_S(t) = 0$ implies that we are in a scenario where developed reserves are effectively abundant, and markets are competitive: the fossil energy firm supplies the market at the marginal cost of use plus taxes, $c_F + \tau(t)$, and if $P(K(t))$ lies below this marginal cost, no fossil energy will be sold.

[14] Analytically, an advantage of a carbon budget approach is that it allows the modeler to refrain from explicitly characterizing the carbon cycle and atmospheric temperature adjustment process.

To determine the optimal transition path under a carbon budget, we define the socially optimal allocation as the allocation that maximizes the present value sum of consumer and producer surplus

$$\int_t^\infty [CS(v) + PS(v)] \, e^{-r(v-t)} dv, \tag{19}$$

subject to (1)-(7) and cumulative emissions remaining below a carbon budget B:

$$\int_t^\infty E_F(v) dv \leq B(t), \tag{20}$$

where we express $B(t)$ in units of fossil energy use and take $B(0) = B_0$ as strictly positive and finite.

Consumer and producer surplus, follow the conventional definitions $CS(t) \equiv \int_0^{E(t)} (P(e) - p_E(t)) \, de$ and $PS(t) \equiv \pi_F(t) + \pi_R(t) + \Omega(t)$, where $\Omega(t)$ captures lump sum recycling of taxes. The first order conditions corresponding to the socially optimal allocation are presented in Appendix A.3. From these first order conditions, we establish the following result regarding the implementation of the socially optimal allocation:

Lemma 1. *The socially optimal allocation can be decentralized by a fossil fuel tax $\tau(t)$ that is positive and rising at the rate of interest if the carbon budget is binding, and zero otherwise.*

Proof. See Appendix B.1.2. □

The carbon budget puts a constraint on cumulative extraction. If, in the absence of additional taxation, this constraint is not binding, then there is no need to introduce a fossil fuel tax to ensure cumulative extraction remains within the budget. If however the constraint is binding under $\tau(t) = 0$ $\forall t$, a positive fossil fuel tax will be required to ensure that (20) is met. In the optimum, this tax is equal to the shadow value of the carbon budget. This shadow value in turn captures the increase in total surplus that can be obtained by relaxing the binding carbon budget.

Along the optimal tax trajectory, taxes rise at the rate of interest. The intuition behind this is as follows. The carbon budget imposes an additional opportunity cost to extraction, as extracting one unit of fossil today implies that the budget is depleted, and at some point in the future, one fewer unit must be extracted. To ensure that the firm is indifferent between depleting the budget today or at some point in the future, the present value cost of doing so, must be constant. From here, it follows that the nominal tax rate $\tau(t)$, must rise at the rate of interest.[15]

[15] As noted by Gollier (2018), "determining the optimal timing to consume this carbon budget is a problem equivalent to the Hotelling's problem of extracting a non-renewable resource" (Gollier, 2018, p2). Hence, in the absence of uncertainty, optimally implementing a carbon budget requires a carbon price following the Hotelling rule (Hotelling, 1931). This result is also established in Dietz and Venmans (2019) and van der Ploeg and Rezai (2020).

This rising tax implies that, unless energy prices rise accordingly, there exists a finite time as of which the fossil firm no longer finds it profitable to extract stock. The presence of the renewable substitute prevents energy prices from permanently increasing in the long run; high energy prices encourage the expansion of renewable energy capacity, which in turn dampens the energy price increase. As the extraction constraint (3) prevents all fossil energy to be extracted in finite time, the optimal transition under a binding carbon budget always features abandonment of developed fossil reserves:

Proposition 2. *The socially optimal allocation features abandonment of developed reserves ($S^{ss} > 0$) if the carbon budget is binding.*

Proof. Follows from Proposition 1 and Lemma 1. □

Proposition 2 states that the socially optimal allocation under a binding carbon budget always features abandonment of developed reserves. Hence observing levels of developed stock in excess of the carbon budget is not at odds with satisfying the budget. To the contrary, an optimal transition requires that developed fossil stocks $S(t)$, at some point in time, strictly exceed the remaining budget $B(t)$.[16] It then follows that whenever developed reserves are equal to or below the remaining budget, exploration must be strictly positive at some future point in time:

Corollary 1. *Whenever $S(t) \leq B(t)$, $\int_t^\infty X(\nu)d\nu > 0$.*

Proof. Directly follows from (4), (20), and Proposition 2. □

More generally, positive exploration may be observed even if $S(t) > B(t)$. The intuition behind this is akin to discussed in the previous section: exploration allows the fossil energy to increase extraction in the short run, which may generate sufficient return to justify exploration, even if part of the developed reserves are eventually abandoned. Whether positive exploration is indeed optimal for the relevant values of the carbon budget requires a quantitative assessment. In the next section, we calibrate the model, and quantitatively evaluate time paths of fossil exploration and extraction, and renewable energy investment under the budgets corresponding to the $2°C$ and $1.5°C$ warming targets.

5 Quantitative analysis

To provide a more comprehensive picture of the optimal energy transition under a carbon budget, we parameterize the model and simulate the equilibrium path. We consider budgets consistent with

[16] As fossil fuels are phased-out and abandoned in finite time, and the budget is binding, we must observe $\gamma S(T) > B(T) = 0$, where we define T as the time of phase-out, i.e., the time such that for all $t \geq T$, $E_F(t) = 0$.

global warming targets of $2°C$ and $1.5°C$. We assess equilibrium trajectories when policy is optimal and immediately introduced, or postponed by 10 years. We compare trajectories to a laissez-faire counterfactual, under which no policy is implemented to ensure cumulative emissions remain within the budget.

We parameterize the framework considering the markets for oil and gas, abstracting from coal. While coal is also an important source of fossil energy, cost compositions and extraction patterns are quite distinct, and less accurately characterized by our framework. Still, coal plays a significant role in meeting the carbon budgets, and reductions in coal use, alongside oil and gas, are accounted for in the carbon budget scenarios that we analyze. We provide further details regarding our approach below.

The model specification and parameterization are discussed in Section 5.1, and the results from the simulations are presented in Section 5.2. Additional details regarding the parameterization and numerical strategy can be found in Appendix C. Throughout this section energy is measured in billion barrels of oil equivalent (BBOE), with energy prices proxied by the oil price.[17] All prices and taxes are expressed in 2017 USD, and emissions in $GtCO_2$.

5.1 Specifications and parameterization

Energy demand We adopt the following specification for the inverse energy demand:[18]

$$P(E(t)) = \chi E(t)^{-\frac{1}{\varepsilon}}. \tag{21}$$

The empirical literature on energy demand arrives at an (absolute) elasticity of energy demand ε of around 0.2 in the short run, and 0.6 in the long run (Labandeira et al., 2017; Hassler et al., 2019). As our analysis concerns long run energy transitions we adopt $\varepsilon = 0.6$. The demand parameter χ is set to match the 2017 average Brent crude oil price of \$54.4 per BOE (IMF, 2020), setting $E(t)$ equal to the 2017 supply for primary energy of all fuels excluding coal.[19] Here, and in the remainder of the section, we rely on IEA data for supply estimates (IEA, 2019).

Fossil energy The costs associated to the production of a barrel of oil or gas equivalent varies substantially across fields; average per barrel costs associated to extraction is about \$5.5 in Saudi Arabia, and \$21.7 in the UK, with a weighted average of about \$8.1 (WSJ, 2016; IEA, 2018b).[20] Based on

[17]To convert all units into BBOE we use conversion factors from British Petroleum (2018).

[18]As we abstract from coal, (21) respresents demand for residual, non-coal, energy.

[19]This price is close to the 2015-2019 average Brent crude oil price of \$57.2.

[20]We assign administrative costs and production costs to use costs. Any capital costs will be assigned to exploration and development costs as explained below.

this, and the fact that a shift to higher-cost reserves is anticipated (IEA, 2018b), we set $c_F = 10$.

In the model, the parameter κ captures the maximum extraction rate from a developed fossil reserves S. To parameterize κ we rely on Höök et al. (2014), who estimate extraction (depletion) rates for 880 'post-peak' fields. They find a production-weighted average of 7.3%. Based on this we set $\kappa = 0.073$. We then choose S_0 such that extraction capacity of energy from oil and gas is equal to actual use of 55.4 BBOE. This gives $S_0 = 759$.[21]

To parameterize our exploration cost function we use McGlade and Ekins (2015) and Anderson et al. (2018). McGlade and Ekins (2015) provide estimates of the quantity of ultimately recoverable oil and gas resources across the globe and corresponding cost of exploration, development and extraction of these resources. To reproduce their distribution of global resources, we adopt the following specification for exploration costs:

$$C_X(X(t),U(t)) = \left[\frac{\theta}{1-e^{-\omega U(t)}} + \rho\left(U_0 - U(t)\right)\right]\left[X(t) + \left[e^{\psi X(t)} - 1\right]\right]. \tag{22}$$

McGlade and Ekins (2015) set remaining recoverable oil and gas resources equal to about 9 trillion barrels of oil equivalent in 2010. Correcting for extraction up to 2017, and our estimate for initial capacity, this gives $U_0 = 7903$. We then calibrate the parameters θ, ω, ρ and ψ to the McGlade and Ekins (2015) cost distribution, where we constrain the elasticity of marginal exploration cost to be in line with results from Anderson et al. (2018). Further details on this calibration procedure and the resulting fit vis-à-vis the McGlade and Ekins (2015) can be found in Appendix C.

Renewable energy We set initial renewable energy capacity K_0 equal to 19.2, to match the 2017 primary energy demand of nuclear, renewables, and solid biomass (IEA, 2019). In this year, the main sources of renewable energy were biofuel and waste (50% of total renewable), nuclear (26%), hydro (13%) and wind and solar (10%). Wind turbines and solar panels have an expected lifetime of about 20 to 25 years, which is similar to the lifetime of a biogas plant, one of the technologies used for biofuel production. Nuclear energy installations and hydropower are more durable, with decomissioning or major retrofitting only required after 40-50 years. Based on this, we choose the renewable capital depreciation rate, δ, to match a renewable capital half-life of 15 years. This gives $\delta = 0.045$.

For the majority of renewable energy sources, the use cost is very low. To reflect this we set $c_R = 0$. Hence, all costs associated to renewable energy are due to investment, where we adopt a

[21] Hence, at the level of 2017 extraction, developed reserves amount to $759/55.4 \approx 14$ years of extraction.

quadratic investment cost function:

$$C_I(I(t)) = \frac{\xi}{2} I(t)^2. \tag{23}$$

The investment cost parameter ξ is set to match the long-run cost of renewables. We formulate three scenario's for this cost: an upper and lower-bound, and a baseline at the mean of these bounds. For the upper bound with relatively expensive renewables in the long run, we use the current levelized cost of energy (LCOE) associated to solar photovoltaic, a technology in a relatively early stage of development, while for the lower bound we adopt the current LCOE for hydroelectric and nuclear power, which both are technologies at a mature stage of development. Using data from IRENA (2018) this gives a long-run cost of renewables of \$75 and \$150, respectively. The baseline ξ is set such that the long-run cost of renewables sits at the midpoint of this interval, \$112.5. In Appendix C we present a sensitivity analysis, where we set the long-run cost of renewables equal to \$75 and \$150. Finally, we set $r = 0.04$. A complete overview of parameter values and initial conditions can be found in Table C.1 in Appendix C.

Carbon budgets We evaluate transition paths consistent with the $2°C$ and $1.5°C$ warming targets, adopting budget estimates from the IPCC special report on global warming of $1.5°C$ (Rogelj et al., 2018). As noted in this report, there exists substantial uncertainty regarding the exact value of the budgets, due to uncertainties in historical temperature increases, equilibrium sensitivity of the climate to CO_2 emissions, impacts of non-CO_2 greenhouse gas emissions and earth system feedbacks.[22] For this reason, instead of considering a single value for the budget, we adopt a central value $\pm 25\%$.[23] The central values are consistent with a 2/3 probability of staying below the temperature target, and are equal to 1170 and 420 $GtCO_2$ for $2°C$ and $1.5°C$, respectively (Rogelj et al., 2018). These budgets apply to all CO_2 emissions from 2018, which requires us to make two further adjustments. First, we add 2017 emissions to obtain budgets from our base year 2017 (Global Carbon Project, 2019). Second, our framework captures only energy from oil and gas; as described above it abstracts from other sources of CO_2 emissions, most importantly coal. Yet, coal is a major contributor of CO_2 emissions, and ignoring this would cause a substantialoverestimation of allowable emissions from oil and gas. To account for this, we assign 1/3 of allowable emissions to coal, leaving the remainder for oil and gas. This coal share is consistent with cumulative coal, oil and gas use in the IPCC AR5 WGIII mitigation scenarios (Stocker et al., 2014, Figure 6.15). This gives a central budget for oil and gas of

[22]Such feedbacks include greenhouse gas emissions from wetlands and permafrost thawing.

[23]This range is more conservative than the uncertainty reported by Rogelj et al. (2018), who report a variation of at least $\pm 50\%$ for the remaining carbon budget for $1.5°C$.

804 $GtCO_2$ for the $2°C$ target, and a budget of 304 $GtCO_2$ for the $1.5°C$ target, which amount to 2298 and 869 BBOE, respectively.[24,25]

5.2 Results

In this section we present the results of two sets of quantitative exercises. First, we determine the optimal implementation of a carbon budget, where the tax on fossil use is immediately introduced in 2017, and it follows a path in accordance with the conditions of Lemma 1, such that (20) is met. Then, we consider a sub-optimal implementation due to a delayed, yet anticipated, introduction of the tax. Specifically we consider the situation in which the introduction of the tax on fossil use is delayed by 10 years, until 2027. After its introduction, the tax follows the path that optimally implements the, remaining, budget. Both for the immediate and delayed introduction of the tax, we consider the implementation budgets consistent with the $2°C$ and $1.5°C$ targets as described above. To put these policy scenarios into perspective, we additionally present the results under a laissez-faire (zero tax) scenario.

5.2.1 Optimal implementation of a carbon budget

Figure 1 presents the results of the simulations under the immediate introduction of the tax on fossil use. The results for the central budget values are depicted by the solid curves, dashed curves represent the $\pm 25\%$ bounds. As shown in panel a, fossil fuels are fully phased out between 2068 and 2093 for the $2°C$ target (in 2081 for the central budget value). A stricter budget leads to a faster transition: for the $1.5°C$ target, fossil energy is fully phased out between 2044 and 2055 (in 2049 for the central value). Across scenarios, it takes about 25 more years for renewable capacity to approach its long run level (panel b), and the energy price to reach its long run value of \$112.5 (panel c). These transitions are in stark contrast to the laissez-faire scenario, where by year 2200, still 40% of total energy is fossil, and renewable capacity is 25% below its long-run level. The implementation of the carbon budget requires a tax with an initial value of \$28 and \$104 per tCO_2 for the central estimates of the

[24] To determine the emissions per BBOE we divide 2017 emissions by 2017 oil and gas extraction (Global Carbon Project, 2019; IEA, 2019). This gives 0.35 $GtCO_2$/BBOE. Conversely, $S_0 = 759$ gives 266 $GtCO_2$ embodied in initially developed oil and gas reserves.

[25] Our approach does not explicitly account for carbon dioxide removal (CDR) technologies. Yet, mass-deployment of such technologies would allow for greater use of fossil fuels, in which case trajectories are closer to the upper budget bounds. Many CDR technologies however, are still at early stages of development, making it highly uncertain whether such mass-deployment is feasible. Similarly, greater use of coal would reduce the budget available for oil and gas. As such, one can alternatively consider the results for lower budget bounds as an estimate under greater coal use, and likewise the upper bounds as the trajectory under a low-coal counterfactual.

$2°C$ and $1.5°C$ targets, respectively. These taxes subsequently grow at 4% per year (see Lemma 1).

As established in Proposition 2, the optimal implementation of a binding carbon budget implies that the fossil phase-out occurs before developed fossil reserves are fully depleted. Figure 1 (panel e) shows that the lower the budget, the higher the abandonment of developed reserves. In the long run between 68 and 97 BBOE of developed fossil reserves will remain unused under the $2°C$ target, and between 120 and 146 BBOE under the $1.5°C$ target. To put these values into perspective: with initially developed reserves calibrated at 759 BBOE, this is equivalent to between 9% and 19% of the initially developed reserves.

Despite the substantial level of abandonment, all scenarios feature positive exploration and development of new fossil reserves (panel d). Initial exploration and development is close to laissez-faire for the $2°C$ target, albeit falling rapidly, reaching zero by 2058 for the central budget estimate. For the $1.5°C$ target, exploration and development is notably lower, and fully terminated between 2024 and 2034.[26] For this target, initial exploration is rather sensitive to the value of the budget, ranging between 0% and 62% of laissez-faire exploration levels.

As explained in Section 3, the fossil firm's incentive to engage in exploration and development activities stems from the possibility to expand extraction whenever extraction is constrained. This incentive is particularly strong when fossil energy commands a high price net of taxes, in particular in the short to medium run. With the relatively low taxes under the $2°C$ target, incentives for exploration in the short run are sizable. Yet, over time, the expanding renewable capacity (panel b) reduces the 'residual' demand for fossil energy, while a rising tax reduces the return to extraction; jointly, this reduces the incentive for further exploration.[27,28]

The optimal implementation of a budget entails the abandonment of developed reserves, which implies that exploration and development activities necessarily induce reserve development in excess of what can ultimately be extracted under the budget. At first glace, if one would not take into account that abandonment is part of the fossil firm's profit-maximizing strategy, some of this exploration would be deemed 'excessive'. We compute this 'excessive exploration' as a fraction of the budget net of the

[26]A comparison of these dates to the time of fossil phase-out reveals that fossil exploration and development activities come to a halt about 20-25 years prior to the termination of fossil extraction.

[27]Additionally, marginal exploration costs rise as undeveloped reserves fall. While this mechanism contributes to the fall in fossil exploration and development, and subsequent use under laissez-faire (panels b and c), it has little additional effect on the trajectories in the budget scenarios.

[28]The same intuition applies to the inverted-U shaped trajectory of exploration and development under the lower bound of the $1.5°C$ target. Here, high energy taxes cause extraction to be unconstrained initially, which diminishes exploration incentives. The absence of exploration implies rapidly falling fossil energy capacity, which in this particular case, causes extraction to become constrained in the short run, creating incentives for fossil exploration and development. This effect is however only temporary; over time, rising taxes and renewable energy supply will reduce incentives for fossil exploration and development, and cause a fossil phase-out.

266 $GtCO_2$ embedded in initially developed reserves.[29] We find that 'excessive exploration' is rather sensitive to, and decreasing in, the value of the budget. For the $2°C$ target, it amounts to between 3% and 9% of cumulative exploration, with a central value of 5%. For the $1.5°C$ target, 27% and 55% of exploration is 'excessive' for the upper budget bound and the central estimate, respectively. For the lower bound, emissions embedded in initially developed reserves are already in excess of the corresponding budget, hence, all exploration can be deemed 'excessive'.

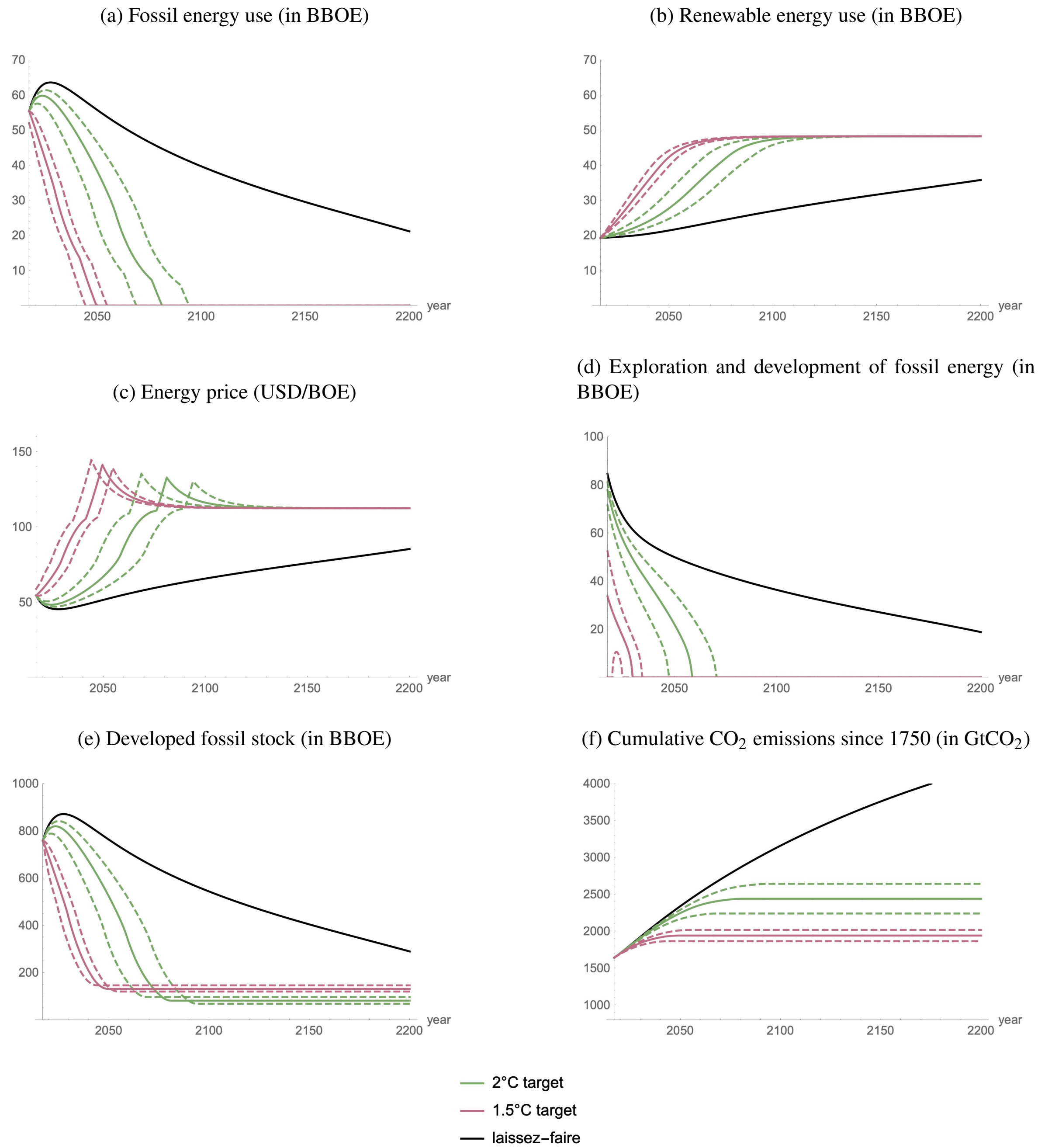
While the trajectories for fossil exploration and development, fossil energy use and renewable energy use are generally smooth, energy prices peak during the transition (panel c). This overshooting of the energy price occurs because renewable capacity gradually builds up to its long-run value, while rising taxes cause fossil energy to be phased-out in finite time. Hence, at the time of phase-out, energy supply is below its long run value. From the figure, we observe that implementing a stricter budget results in an earlier and higher energy price peak. An earlier peak is naturally the result of an earlier phase-out; the higher peak is the result of the lower renewable capacity at the time of the phase-out, despite the faster expansion in renewable capacity under rapid phase-outs. Energy prices peak at \$130 and \$140 for the central estimates of the $2°C$ and $1.5°C$ target, respectively, overshooting the long-run price level by 16% and 25%.

The peak in the price trajectory signals the onset of the final stage, fossil phase-out, in the energy transition. More generally, we can characterize the energy transition under a carbon budget as a sequence of stages. Initially, the fossil firm engages in both exploration and development and extraction of fossil resources (stage I). Next, exploration and development comes to a halt, but extraction is still positive (stage II). Finally, fossil energy is phased-out (stage III). At some point during stage II, fossil extraction shifts from being constrained to unconstrained. Unconstrained extraction and anticipated abandonment implies that fossil energy is effectively abundant, and extraction capacity has zero value ($\mu_S(t) = 0$). Prices are then equal to extraction costs plus taxes: $p_E(t) = c_F + \tau(t)$. As the optimal $\tau(t)$ rises at the rate of interest, prices follow a policy-induced Hotelling rule until fossil energy is fully phased-out. The timing of this shift to unconstrained extraction can be identified by the kink in the price trajectory, about 5-10 years prior to the peak.

Carbon budget implementation with a delayed introduction of the carbon tax Figure 2 presents the results when the introduction of the tax on fossil use is delayed by 10 years, to 2027. The long-run energy price and renewable capacity are unaffected by the timing of the introduction of the tax, as they are pinned down by (18).

[29] Put differently, we compute the share of newly-explored reserves that would remain unextracted under the budget, if all previously-developed reserves would be extracted.

Figure 1: Results, carbon budget and laissez-faire



Dashed curves indicate paths for alternative estimates for the oil and gas budget. 2017 emission taxes equal $28 for the central budget of the $2°C$ target ($16 and $46 for the upper and lower budget bound, resp.) and $104 for the central budget of the $1.5°C$ target ($83 and $131 for the upper and lower budget bound, resp.). Taxes subsequently increase at an annual rate of 4%.

The results from the simulations show the tax delay has little effect on the energy transition for the $2°C$ target. A comparison of Figures 1 and 2 reveals that price paths are nearly identical under an immediate or delayed introduction of the tax (panel a). In both cases, for the central budget estimate, the capacity constraint is still binding beyond 2050, while prices peak and fossil energy is phased out in 2081 (panels a and c). Even though the delayed, but anticipated, introduction of the tax leads to higher exploration levels in the first decade, lower subsequent exploration levels cause cumulative exploration and developed stock abandonment to be virtually the same as under the immediate introduction of the carbon tax (panels d and e). Delaying the tax introduction by 10 years also adds little premium to the tax level; the 2027 tax level under delayed introduction is \$42 per tCO_2, as compared to a 2027 tax of \$41 per tCO_2 when tax is first introduced in 2017.

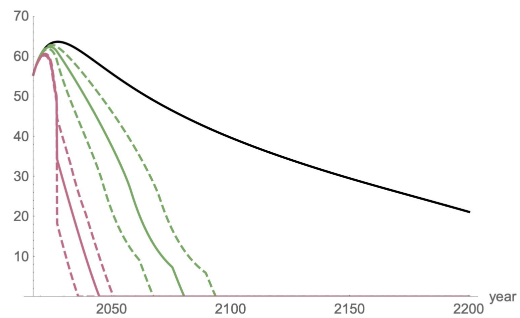
In contrast, the energy transition under the $1.5°C$ target is substantially affected by the delay in the introduction of the tax. The absence of carbon taxation significantly increases exploration, development and extraction of fossil reserves during the first decade of the transition. To ensure the $1.5°C$ target is still met, policy needs to be particularly aggressive once introduced: for the central budget estimate, we obtain a tax of \$193 per tCO_2 in 2027. As a reference: this is 25% higher than the 2027 tax level under immediate tax implementation. While postponing the tax introduction puts initial exploration and development on par with the laissez-faire level, as the tax introduction draws nearer, exploration rapidly declines, and reaches zero two years before the tax is introduced (panel d). The 2027 tax introduction induces a large discrete jump in prices (panel c) and a corresponding drop in fossil energy use (panel a), where the latter causes extraction capacity to suddenly exceed demand for fossil energy.

While meeting the $1.5°C$ target remains feasible despite the delayed introduction, the higher initial exploration and development levels translate into substantially higher levels of abandoned developed reserves (panel e). For the central estimate abandoned reserves amount to 370 BBOE, nearly 3 times the amount abandoned under immediate implementation. For the lower budget bound, the simulation reveals a particularly striking effect of delaying climate policy; here abandonment almost quadruples, to 575 BBOE. All in all, these results indicate that the effect of delaying the introduction of the tax on the abandonment of developed reserves is highly sensitive to the remaining budget: while under the $2°C$ target, the delay has virtually no effect abandonment, it causes significantly higher levels of abandonment for $1.5°C$ target.

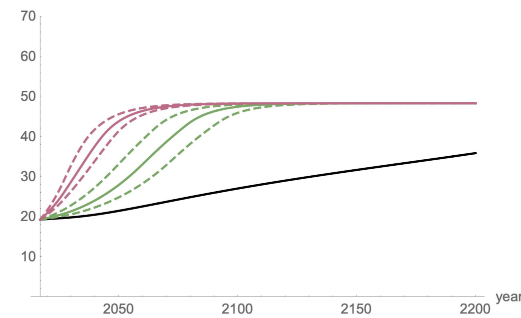
Sensitivity to renewable cost estimates There exists a significant degree of uncertainty around the long run cost of renewable energy. To assess the sensitivity of our results to alternative estimates for renewable costs we simulate the energy transition under a long run renewable cost of \$75 and \$150

Figure 2: Results, carbon budget and laissez-faire - delayed tax

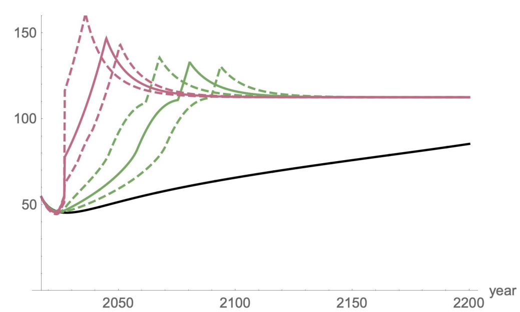
(a) Fossil energy use (in BBOE)



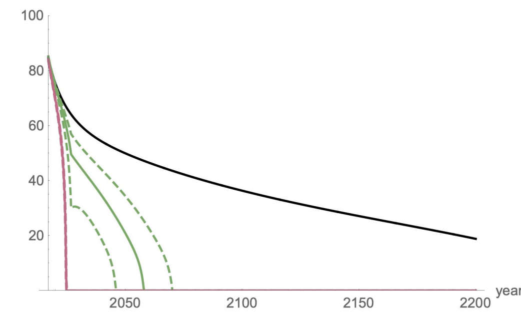
(b) Renewable energy use (in BBOE)



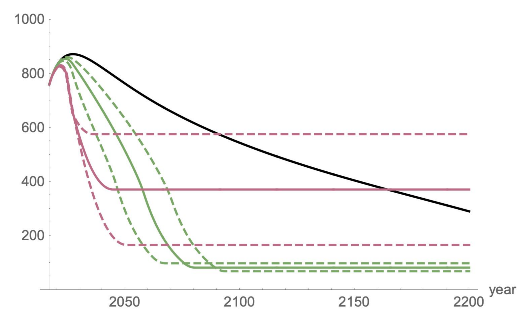
(c) Energy price (USD/BOE)



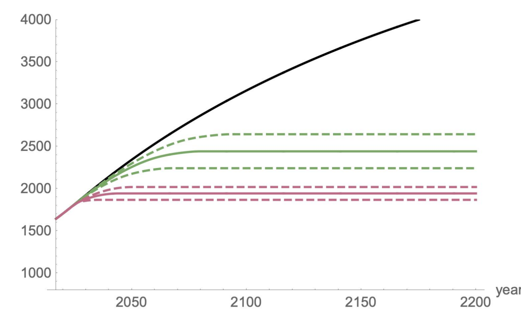
(d) Exploration and development of fossil energy (in BBOE)



(e) Developed fossil stock (in BBOE)



(f) Cumulative CO_2 emissions since 1750 (in $GtCO_2$)



Dashed curves indicate paths for alternative estimates for the oil and gas budget. Emission taxes are zero from 2017-2026. 2027 emission taxes equal \$42 for the central budget of the 2°C target (\$24 and \$72 for the upper and lower budget bound, resp.) and \$193 for the central budget of the 1.5°C target (\$149 and \$304 for the upper and lower budget bound, resp.). Taxes subsequently increase at an annual rate of 4%.

per BBOE. The results are presented in Figures C.2 and C.3 in Appendix C, alongside the results for our baseline calibration of \$112.5 per BBOE. Across all simulations we present only the results for the central budget estimates. A lower long run cost of renewables implies lower long run energy prices (panel c), and higher levels of renewable energy use (panel b). Because renewable energy is more competitive, lower taxes are needed to implement the budget: optimally meeting the $2°C$ target requires initial taxes on fossil use equal to \$16, \$28 and \$37 per tCO_2 when long run renewable costs are \$75, \$112.5 and \$150, respectively. Similarly, for the $1.5°C$ target, we obtain taxes of \$75 to \$125 per tCO_2 for the lowest and highest long run renewable cost estimates, with a baseline value of \$104 per tCO_2.[30]

While more competitive renewable energy discourages fossil extraction, and hence exploration and development, lower carbon taxes have the opposite effect. Taken together, effects approximately cancel out, and the paths of fossil exploration and development (panel d) and extraction (panel a), and the level of developed stock abandonment (panel e) are similar across renewable cost levels. This applies for both temperature targets, and for both immediate and postponed tax implementation. An exception is fossil exploration and development under the optimal implementation of the $1.5°C$ target (Figure C.2, panel b). Here, higher renewable costs are associated with a shift of exploration and development toward the future.

6 Concluding comments

In this paper, we build a dynamic model of the energy transition that explicitly considers the exploration and development of new fossil reserves and subsequent extraction of those reserves, alongside gradual investment in renewable energy capacity. This model enables us to examine the characteristics of the energy transition, focusing on the exploration and development of new fossil reserves, and the potential for abandonment of previously-developed reserves. We characterize the implementation of a carbon budget in this setting, establishing that the optimal implementation of a binding carbon budget always involves developed reserve abandonment and thereby development of new fossil energy reserves in excess of the allowable budget.

We use the model to investigate the transition path under the $2°C$ and $1.5°C$ warming targets. The optimal implementation leads to significant abandonment of developed reserves, equivalent to between 9% and 19% of current developed reserves. Initial exploration and development is close to the laissez-

[30] An alternative sensitivity analysis in which we abstract from renewable capacity buildup reveals that under the assumption that the renewable functions as a backstop technology (with infinitely elastic supply at a given marginal cost), initial taxes increase by 20-30%.

faire under the $2°C$ target, yet declines rapidly, until it reaches zero in 2058. The more stringent $1.5°C$ target yields lower exploration levels, which remain positive until 2030. A delayed introduction of the tax brings forward exploration and development activities, yet does not affect abandonment under the $2°C$ target. In contrast, abandonment nearly triples under the $1.5°C$ target.

The significant volume of abandoned reserves warrants concern about the political viability of ambitious climate targets. Forced abandonment of developed reserves implies the fossil extraction industry foregoes revenue for which a significant part of the associated costs have already been incurred; a back-of-the-envelope calculation assuming a $40 per BOE price net of extraction cost produces a total lost revenue of $2.7 to $5.8 trillion. As such, higher levels of abandonment reinforce the industry's vested interests and incentives to lobby against ambituous climate policy. Our results signal a large increase in reserve abandonment due to a delay in climate policy, which poses a warning: by further reinforcing vested interests, a delay may end up curtailing the scope for viable policies.

In this paper we take the climate target as given, abstract from market power in the fossil energy sector as well as any political economy considerations surrounding the implementation of a climate target. Following the above, we consider an analysis of the political economy implications of fossil exploration, development and reserve abandonment as an important avenue for future research. The setup put forward in this paper can serve as the starting point for an analysis that considers the impact of exploration and development activities on the implementation of climate policy, and the incentives of the fossil industry to strategically engage in fossil exploration to stall the introduction of stringent climate policies.

Our setup can also be used to contribute to the discussion on the merits and drawbacks of different climate policy instruments. By explicitly considering the fossil exploration and development, the framework is particularly suited to analyze the scope for supply-side policies such as restrictions on exploration and development activities. Such policies have received increasing attention in recent years, both in the academic literature (Harstad, 2012; Asheim et al., 2019), and the policy debate (Lazarus and van Asselt, 2018).

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References

Allen, M. R. (2016). Drivers of peak warming in a consumption-maximizing world. *Nature Climate Change 6*(7), 684–686.

Anderson, S. T., R. Kellogg, and S. W. Salant (2018). Hotelling under pressure. *Journal of Political Economy 126*(3), 984–1026.

Asheim, G. B., T. Fæhn, K. Nyborg, M. Greaker, C. Hagem, B. Harstad, M. O. Hoel, D. Lund, and K. E. Rosendahl (2019). The case for a supply-side climate treaty. *Science 365*(6451), 325–327.

Bai, Y. and S. J. Okullo (2018). Understanding oil scarcity through drilling activity. *Energy Economics 69*, 261–269.

Baldwin, E., Y. Cai, and K. Kuralbayeva (2019). To build or not to build? capital stocks and climate policy. *Journal of Environmental Economics and Management*.

Bornstein, G., P. Krusell, and S. Rebelo (2017). Lags, costs, and shocks: An equilibrium model of the oil industry. NBER working paper 23423.

Boyce, J. R. and L. Nøstbakken (2011). Exploration and development of us oil and gas fields, 1955–2002. *Journal of Economic Dynamics and Control 35*(6), 891–908.

British Petroleum (2018). BP Statistical Review of World Energy. London.

Cairns, R. D. (2014). The green paradox of the economics of exhaustible resources. *Energy Policy 65*, 78–85.

Cairns, R. D. and G. A. Davis (2001). Adelman's rule and the petroleum firm. *The Energy Journal*, 31–54.

Caldecott, B. (2017). Introduction to special issue: stranded assets and the environment. *Journal of Sustainable Finance & Investment 7*(1), 1–13.

Carbon Tracker and Grantham Institute (2017). Unburnable carbon 2013: Wasted capital and stranded assets.

Dietz, S. and F. Venmans (2019). Cumulative carbon emissions and economic policy: in search of general principles. *Journal of Environmental Economics and Management 96*, 108–129.

Frankfurt School-UNEP Centre/BNEF (2019). Global trends in renewable energy investment 2019. Frankfurt School of Finance & Management GmbH.

Global Carbon Project (2019). Supplemental data of global carbon budget 2019. https://doi.org/10.18160/gcp-2019.

Gollier, C. (2018). On the efficient growth rate of carbon price under a carbon budget. mimeo, Toulouse School of Economics (TSE).

Harstad, B. (2012). Buy coal! a case for supply-side environmental policy. *Journal of Political Economy 120*(1), 77–115.

Hassler, J., P. Krusell, and C. Olovsson (2019). Directed technical change as a response to natural-resource scarcity. Sveriges Riksbank Working Paper Series 375.

Heal, G. and W. Schlenker (2019). Coase, Hotelling and Pigou: the incidence of a carbon tax and CO2 emissions. NBER working paper 26086.

Höök, M. (2009). *Depletion and decline curve analysis in crude oil production*. Ph. D. thesis, Global Energy Systems, Department for Physics and Astronomy, Uppsala University.

Höök, M., S. Davidsson, S. Johansson, and X. Tang (2014). Decline and depletion rates of oil production: a comprehensive investigation. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences 372*(2006), 20120448.

Hotelling, H. (1931). The economics of exhaustible resources. *Journal of Political Economy 39*(2), 137–175.

IEA (2018a). World Energy Investment 2018. Iea, Paris.

IEA (2018b). *World Energy Outlook 2018*, Chapter Executive Summary, pp. 23–28. Paris: OECD Publishing.

IEA (2019). World energy balances.

IMF (2020). Primary commodity price system.

IRENA (2018). Renewable Power Generation Costs in 2017. Irena, Abu Dhabi.

Judd, K. L. (1998). *Numerical methods in economics*. Cambridge, Massachusestts: The MIT press.

Labandeira, X., J. M. Labeaga, and X. López-Otero (2017). A meta-analysis on the price elasticity of energy demand. *Energy Policy 102*, 549–568.

Lazarus, M. and H. van Asselt (2018). Fossil fuel supply and climate policy: exploring the road less taken. *Climatic Change 180*(1), 1573–1480.

Mason, C. F. and G. Roberts (2018). Price elasticity of supply and productivity: an analysis of natural gas wells in Wyoming. *The Energy Journal 9*(1).

McGlade, C. and P. Ekins (2015). The geographical distribution of fossil fuels unused when limiting global warming to 2°C. *Nature 517*(7533), 187–190.

Muttitt, G. (2016). *The sky's limit: why the Paris Climate Goals require a managed decline of fossil fuel production*. Oil Change International.

Nystad, A. N. (1985). Petroleum taxes and optimal resource recovery. *Energy Policy 13*(4), 381–401.

Okullo, S. J., F. Reynès, and M. W. Hofkes (2015). Modeling peak oil and the geological constraints on oil production. *Resource and Energy Economics 40*, 36–56.

Pindyck, R. S. (1978). The optimal exploration and production of nonrenewable resources. *Journal of Political Economy 86*(5), 841–861.

Rezai, A. and F. van der Ploeg (2017). Abandoning fossil fuel: how fast and how much. *The Manchester School 85*, e16–e44.

Rogelj, J., M. Schaeffer, P. Friedlingstein, N. P. Gillett, D. P. Van Vuuren, K. Riahi, M. Allen, and R. Knutti (2016). Differences between carbon budget estimates unravelled. *Nature Climate Change 6*(3), 245–252.

Rogelj, J., D. Shindell, K. Jiang, S. Fifita, P. Forster, V. Ginzburg, C. Handa, H. Kheshgi, S. Kobayashi, E. Kriegler, J. Mundaca, R. Seferian, and M. V. Vilariño (2018). Mitigation pathways compatible with 1.5°C in the context of sustainable development. In V. Masson-Delmotte, P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P. R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J. B. R. Matthews, Y. Chen, X. Zhou, M. I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, and T. Waterfield (Eds.), *Global Warming of* 1.5°*C. An IPCC Special Report on the impacts of global warming of* 1.5°*C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty*.

Rozenberg, J., A. Vogt-Schilb, and S. Hallegatte (2018). Instrument choice and stranded assets in the transition to clean capital. *Journal of Environmental Economics and Management 100*, 102183.

Stocker, T., D. Qin, G.-K. Plattner, L. Alexander, S. Allen, N. Bindoff, F.-M. Bréon, J. Church, U. Cubasch, S. Emori, P. Forster, P. Friedlingstein, N. Gillett, J. Gregory, D. Hartmann, E. Jansen, B. Kirtman, R. Knutti, K. K. Kumar, P. Lemke, J. Marotzke, V. Masson-Delmotte, G. Meehl, I. Mokhov, S. Piao, V. Ramaswamy, D. Randall, M. Rhein, M. Rojas, C. Sabine, D. Shindell, L. Talley, D. Vaughan, and S.-P. Xie (2014). Technical summary. In T. Stocker, D. Qin, G.-K. Plattner, M. Tignor, S. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P. Midgley (Eds.), *Climate Change 2013: the physical science basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge, United Kingdom and New York, NY, USA, pp. 33–115. Cambridge University Press.

Thompson, A. C. (2001). The Hotelling Principle, backwardation of futures prices and the values of developed petroleum reserves-the production constraint hypothesis. *Resource and Energy Economics 23*(2), 133–156.

U.S. Energy Information Administration (2019). Levelized cost and levelized avoided cost of new generation resources. In *Annual Energy Outlook 2019*. EIA.

van der Meijden, G. and S. Smulders (2017). Carbon lock-in: the role of expectations. *International Economic Review 58*(4), 1371–1415.

van der Ploeg, F. and A. Rezai (2020). The risk of policy tipping and stranded carbon assets. *Journal of Environmental Economics and Management*, 102258.

van der Ploeg, F. and C. Withagen (2015). Global warming and the green paradox: a review of adverse effects of climate policies. *Review of Environmental Economics and Policy 9*(2), 285–303.

Venables, A. J. (2014). Depletion and development: natural resource supply with endogenous field opening. *Journal of the Association of Environmental and Resource Economists 1*(3), 313–336.

WSJ (2016). Barrel breakdown. http://graphics.wsj.com/oil-barrel-breakdown/. accessed July 3, 2020.

A Optimization problems

A.1 Fossil firm optimization

The fossil firm chooses the path of fossil extraction and fossil exploration, $[E_F(\nu), X(\nu)]_{\nu=t}^{\infty}$, that maximizes $\Pi_F(t) = \int_t^{\infty} \pi_F(\nu) e^{-r(\nu-t)} d\nu$, with instantaneous profits $\pi_F(t) = (p_E(t) - c_F - \tau(t)) E_F(t) - C_X(X(t), U(t))$, subject to (3)-(5), and $X(t), E_F(t) \geq 0$. This gives the following Hamiltonian with first order, complementary slackness and transversality conditions:

$$\begin{aligned} \mathscr{H}_F &= (p_E(t) - c_F - \tau(t)) E_F(t) - C_X(X(t), U(t)) + \mu_S(t)[-E_F(t) + X(t)] \\ &\quad + \mu_U(t)[-X(t)] + \phi_{F,cap}(t)[\kappa S(t) - E_F(t)] + \phi_{F,0}(t)[E_F(t)] + \phi_{X,0}(t)[X(t)], \end{aligned} \tag{A.1}$$

$$[E_F] : \quad p_E(t) - c_F - \tau(t) = \mu_S(t) + [\phi_{F,cap}(t) - \phi_{F,0}(t)]; \tag{A.2}$$
$$\phi_{F,cap}(t)[\kappa S(t) - E_F(t)] = 0; \ \phi_{F,0}(t) E_F(t) = 0,$$

$$[X] : \quad \mu_S(t) = c_X(X(t), U(t)) + \mu_U(t) - \phi_{X,0}(t); \tag{A.3}$$
$$\phi_{X,0}(t) X(t) = 0,$$

$$[S] : \quad \frac{\dot{\mu}_S(t)}{\mu_S(t)} + \kappa \frac{\phi_{F,cap}(t)}{\mu_S(t)} = r, \tag{A.4}$$

$$[U] : \quad \frac{\dot{\mu}_U(t)}{\mu_U(t)} - \frac{\partial C_X(X(t), U(t)) / \partial U(t)}{\mu_U(t)} = r, \tag{A.5}$$

$$[TVC\ S] : \quad \lim_{t \to \infty} \mu_S(t) S(t) e^{-rt} = 0, \tag{A.6}$$

$$[TVC\ U] : \quad \lim_{t \to \infty} \mu_U(t) U(t) e^{-rt} = 0. \tag{A.7}$$

A.2 Renewable firm optimization

The renewable firm chooses the path of renewable energy production and investment in capacity, $[E_R(\nu), I(\nu)]_{\nu=t}^{\infty}$, that maximizes $\Pi_R(t) = \int_t^{\infty} \pi_R(\nu) e^{-r(\nu-t)} d\nu$, with instantaneous profits $\pi_R(t) = (p_E(t) - c_R) E_R(t) - C_I(I(t))$, subject to (6), (7) and $I(t), E_R(t) \geq 0$.

$$\begin{aligned} \mathscr{H}_R &= (p_E(t) - c_R) E_R(t) - C_I(I(t)) + \mu_K(t)[I(t) - \delta K(t)] \\ &\quad + \phi_{R,cap}(t)[K(t) - E_R(t)] + \phi_{R,0}(t)[E_R(t)] + \phi_{I,0}(t)[I(t)], \end{aligned} \tag{A.8}$$

$$
\begin{aligned}
[E_R] \quad &: \quad p_E(t) - c_R = [\phi_{R,cap}(t) - \phi_{R,0}(t)]\,; && \text{(A.9)}\\
& \quad \phi_{R,cap}(t)\,[K(t) - E_R(t)] = 0;\ \phi_{R,0}(t)E_R(t) = 0, &&\\
[I] \quad &: \quad \mu_K(t) = c_I(I(t)) - \phi_{I,0}(t);\ \phi_{I,0}(t)I(t) = 0, && \text{(A.10)}\\
[K] \quad &: \quad \frac{\dot{\mu}_K(t)}{\mu_K(t)} - \delta + \frac{\phi_{R,cap}(t)}{\mu_K(t)} = r, && \text{(A.11)}\\
[TVC] \quad &: \quad \lim_{t\to\infty} \mu_K(t)K(t)e^{-rt} = 0. && \text{(A.12)}
\end{aligned}
$$

A.3 Socially optimal allocation under a carbon budget

To determine the socially optimal allocation we maximize (19) subject to (1)-(7) and (20) and non-negativity constraints on exploration, extraction, undeveloped resources and remaining budget, $X(t), E_F(t), U(t), B(t) \geq 0\ \forall t$. This gives the following Hamiltonian with first order, complementary slackness and transversality conditions:

$$
\begin{aligned}
\mathscr{H} \quad = \quad & \int_0^{E(t)} (P(e) - p_E(t))\,de + p_E E_F(t) - c_F E_F(t) - C_X\,(X(t), U(t)) + p_E E_R(t)\\
& - c_R E_R(t) - C_I(I(t)) + \lambda_E^P(t)\,[E_F(t) + E_R(t) - E(t)] + \mu_S^P(t)\,[-E_F(t) + X(t)]\\
& + \phi_{F,cap}^P(t)\,[\kappa S(t) - E_F(t)] + \phi_{F,0}^P(t)\,[E_F(t)] + \phi_{X,0}^P(t)\,[X(t)] \qquad \text{(A.13)}\\
& + \mu_U^P(t)\,[-X(t)] + \mu_K^P(t)\,[I(t) - \delta K(t)] + \phi_{R,cap}^P(t)\,[K(t) - E_R(t)]\\
& + \phi_{R,0}^P(t)\,[E_R(t)] + \phi_{I,0}^P(t)\,[I(t)] + \mu_B^P(t)\,[-E_F(t)]\,,
\end{aligned}
$$

$$
\begin{aligned}
[E] \quad &: \quad P(E(t)) - p_E(t) = \lambda_E^P(t); && \text{(A.14)}\\
& \quad \lambda_E^P(t)\,[E_F(t) + E_R(t) - E(t)] = 0, &&\\
[E_F] \quad &: \quad p_E(t) - c_F + \lambda_E^P(t) - \mu_B^P(t) = \mu_S^P(t) + \left[\phi_{F,cap}^P(t) - \phi_{F,0}^P(t)\right]; && \text{(A.15)}\\
& \quad \phi_{F,cap}^P(t)\,[\kappa S(t) - E_F(t)] = 0;\ \phi_{F,0}^P(t)E_F(t) = 0, &&\\
[X] \quad &: \quad \mu_S^P(t) = c_X\,(X(t), U(t)) + \mu_U^P(t) - \phi_{X,0}^P(t); && \text{(A.16)}\\
& \quad \phi_{X,0}^P(t)X(t) = 0, &&\\
[E_R] \quad &: \quad p_E(t) - c_R + \lambda_E^P(t) = \left[\phi_{R,cap}^P(t) - \phi_{R,0}^P(t)\right]; && \text{(A.17)}\\
& \quad \phi_{R,cap}^P(t)\,[K(t) - E_R(t)] = 0;\ \phi_{R,0}^P(t)E_R(t) = 0, &&
\end{aligned}
$$

$$
\begin{aligned}
[I] \quad &: \quad \mu_K^P(t) = c_I(I(t)) - \phi_{I,0}^P(t);\ \phi_{I,0}^P(t)I(t) = 0, && \text{(A.18)}\\
[S] \quad &: \quad \frac{\dot{\mu}_S^P(t)}{\mu_S^P(t)} + \kappa\frac{\phi_{F,cap}^P(t)}{\mu_S^P(t)} = r, && \text{(A.19)}\\
[K] \quad &: \quad \frac{\dot{\mu}_K^P(t)}{\mu_K^P(t)} - \delta + \frac{\phi_{R,cap}^P(t)}{\mu_K^P(t)} = r, && \text{(A.20)}\\
[U] \quad &: \quad \frac{\dot{\mu}_U^P(t)}{\mu_U^P(t)} - \frac{\partial C_X(X(t),U(t))/\partial U(t)}{\mu_U^P(t)} = r, && \text{(A.21)}\\
[B] \quad &: \quad \frac{\dot{\mu}_B^P(t)}{\mu_B^P(t)} = r, && \text{(A.22)}\\
[TVC\ S] \quad &: \quad \lim_{t\to\infty} \mu_S^P(t)S(t)e^{-rt} = 0, && \text{(A.23)}\\
[TVC\ U] \quad &: \quad \lim_{t\to\infty} \mu_U^P(t)U(t)e^{-rt} = 0, && \text{(A.24)}\\
[TVC\ K] \quad &: \quad \lim_{t\to\infty} \mu_K^P(t)K(t)e^{-rt} = 0, && \text{(A.25)}\\
[TVC\ B] \quad &: \quad \lim_{t\to\infty} \mu_B^P(t)B(t)e^{-rt} = 0. && \text{(A.26)}
\end{aligned}
$$

B Proofs

B.1 Main proofs

B.1.1 Proof to Proposition 1

In equilibrium, $P(E(t)) = p_E(t)$, with $p_E^{ss} = \lim_{t\to\infty} p_E(t) = P(E^{ss})$ and $P(E^{ss})$ given by (18). From (A.2) this implies that we can write

$$
P(E^{ss}) - \lim_{t\to\infty} \tau(t) = c_F + \lim_{t\to\infty} \mu_S(t) + \left[\lim_{t\to\infty} \phi_{F,cap}(t) - \lim_{t\to\infty} \phi_{F,0}(t)\right], \tag{B.1}
$$

where by (12), $\mu_S(t) \geq 0\ \forall t$, with $\mu_S(t) > 0$ only if $\phi_{F,cap}(\nu) > 0$ for some $\nu \geq t$.

1. Consider first $P(E^{ss}) - \tau(t) > c_F$ for all t. As $\tau(t)$ is weakly increasing over time, this implies $P(E^{ss}) - \lim_{t\to\infty} \tau(t) > c_F$. Then (B.1) can only be satisfied if $\lim_{t\to\infty} \phi_{F,cap}(t) > 0$. From here it follows that the extraction constraint is binding in the long run: $E_F^{ss} = \kappa S^{ss}$. As $E^{ss} = E_R^{ss} > 0$ and thus $E_F^{ss} = 0$, this requires $S^{ss} = 0$.

2. Consider next $P(E^{ss}) - \tau(t) < c_F$ for some finite t. As $\tau(t)$ is weakly increasing over time, this implies $P(E^{ss}) - \lim_{t\to\infty} \tau(t) < c_F$, which by (B.1) implies $\lim_{t\to\infty} \phi_{F,0}(t) > 0$. As $\phi_{F,cap}(t)$ and

$\phi_{F,0}(t)$ cannot simultaneously be strictly positive, this gives $\lim_{t\to\infty}\phi_{F,cap}(t) = \phi^{ss}_{F,cap} = 0$ and $\lim_{t\to\infty}\mu_S(t) = \mu^{ss}_S = 0$. Using the following two lemmas we prove that this implies $S^{ss} > 0$.

Lemma B.1. *A necessary condition for $S^{ss} = 0$ is that for all finite t, there exists some $\nu > t$ such that $K(\nu) < K'(\nu)$, with $K'(\nu)$ satisfying $P(K'(\nu)) - \tau(\nu) = c_F$.*

Proof. First observe that by (3), $X(t) \geq 0$ and (4), $\dot{S}(t) \geq -\kappa S(t)$. Then by $S_0 > 0$, $S^{ss} = \lim_{t\to\infty} S(t) = 0$ requires that for all t, there exists some $\nu > t$ with $E_F(\nu) > 0$. As $p_E(\nu) = P(E(\nu))$. $E(\nu) = E_F(\nu) + E_R(\nu)$, $E_R(\nu) = K(\nu)$ and $P'(E(\nu)) < 0$, this requires $P(K(\nu)) - \tau(\nu) > c_F$, and thus $K(\nu) < K'(\nu)$. □

Lemma B.2. *There exists a finite t such that for all $\forall\nu \geq t$, whenever $K(\nu) \leq K'(\nu)$, $\dot{K}(\nu) > 0$.*

Proof. Consider some time t such that for all $\nu \geq t$, $P(E^{ss}) - \tau(\nu) < c_F$. By $P(E^{ss}) - \tau(t) < c_F$ for some finite t, and $\dot{\tau}(t) \geq 0$, this t must exist. Now suppose $K(\nu) \leq K'(\nu)$. Then by $P(K'(\nu)) - \tau(\nu) = c_F$ and $P(E^{ss}) - \tau(\nu) < c_F$, $K'(\nu) < E^{ss} = K^{ss}$ and thus $K(\nu) < K^{ss}$. Simultaneously, $K(\nu) \leq K'(\nu)$ implies $p_E(\nu) - \tau(\nu) \geq c_F$ and in turn $p_E(\nu) > P(E^{ss}) = c_R + c_I(\delta E^{ss})$. By the following, this implies $\dot{K}(\nu) > 0$.

Suppose $\dot{K}(\nu) \leq 0$, so $I(\nu) \leq \delta K(\nu) < \delta E^{ss}$. From (A.10) it then follows that $\mu_K(\nu) < c_I(\delta E^{ss})$. Combining (A.9) with (A.11) we obtain

$$\dot{\mu}_K(\nu) = c_R + c_I(\delta E^{ss}) - p_E(\nu) + (r+\delta)\left(\mu_K(\nu) - c_I(\delta E^{ss})\right) < 0.$$

From (A.10) this gives $\dot{I}(\nu) < 0$ and thus $K(\nu') < E^{ss}$ and $p_E(\nu') > c_R + c_I(\delta E^{ss})$ for all $\nu' \geq \nu$. Yet by (17), $p_E(\nu) > c_R + c_I(\delta E^{ss})$ is inconsistent with $\mu_K(\nu) < c_I(\delta E^{ss})$. Hence, we must have that $\dot{K}(\nu) > 0$. □

Finally note that as $K'(\nu)$ is implicitly defined by $P(K'(\nu)) - \tau(\nu) = c_F$, and $\dot{\tau}(\nu) \geq 0$, we must have $\dot{K}'(\nu) \leq 0$. With $\dot{K}(\nu) > 0$, K cannot be permanently below K', and thus $S^{ss} = \lim_{t\to\infty} S(t) = 0$ cannot hold. □

B.1.2 Proof to Lemma 1

A comparison of (A.14)-(A.21) to (A.2)-(A.5) and (A.9)-(A.11) reveals that the social optimum and decentralized equilibrium coincide if $\tau(t) = \mu_B^P(t)$. From (A.22), we then obtain

$$\frac{\dot{\tau}(t)}{\tau(t)} = \frac{\dot{\mu}_B^P(t)}{\mu_B^P(t)} = r.$$

(A.22) and (A.26) additionally imply that $\mu_B^P(t) = 0$ for all t, or $\lim_{t\to\infty} B(t) = 0$. □

B.2 Other proofs

B.2.1 $E_R(t) = K(t)\ \forall t$

By (6), $E_R(t) > K(t)$ is not feasible. Hence, $E_R(t) = K(t)\ \forall t$ unless $E_R(t) < K(t)$ for some t. From (A.9), $E_R(t) < K(t)$ implies $\phi_{R,cap}(t) = 0$. Suppose this is the case, then

$$p_E(t) = c_R - \phi_{R,0}(t)$$

and thus $p_E(t) \leq c_R$. By (A.2), $p_E(t) \leq c_R$ implies $\phi_{F,0}(t) > 0$ and thus $E_F(t) = 0$. Now define $\check{K}$ as the level of E that satisfies $P(\check{K}) = c_R$. Then $E_R(t) < K(t)$ requires $K(t) > \check{K}$.

We next show that $K(t) > \check{K}$ is not feasible. Recall that $K(0) = K_0$ is such that $E_F(0) > 0$. By (A.2), this requires $P(E(0)) = p_E(0) \geq c_F - \tau(0) > c_R$, and thus $E(0) < \check{K}$. This is consistent only with $K(0) < \check{K}$.

From here it follows that $K(t) > \check{K}$ for some t requires there exists some ν such that $K(\nu) = \check{K}$ and $\dot{K}(\nu) > 0$. By (7), the latter requires $I(\nu) > \delta K(\nu) = \delta\check{K}$. Then from (A.10), $\mu_K(\nu) \geq c_I(\delta\check{K}) > 0$ and by (A.11), $\dot{\mu}_K(\nu) > 0$. From here it follows that we must obtain $I(\nu') > \delta\check{K}$, $K(\nu') > \check{K}$ for all $\nu' > \nu$, and thus $p_E(\nu') = c_R$ for all $\nu' \geq \nu$. Yet by (A.9), the latter implies $\phi_{R,cap}(\nu') = 0$ for all $\nu' \geq \nu$, which from (A.12) gives $\mu_K(\nu) = 0$. Hence, $K(\nu) = \check{K}$ is inconsistent with $\dot{K}(\nu) \geq 0$, from which follows that $K(t) < \check{K}$ for all t, which in turn implies we never obtain $E_R(t) < K(t)$. □

B.2.2 Global stability of the long run equilibrium

From (A.9)-(A.11), we obtain that in steady state

$$p_E^{ss} = c_R + (r+\delta)\left[\lim_{t\to\infty} c_I(I(t)) - (r+\delta)\lim_{t\to\infty}\phi_{I,0}(t)\right] - \lim_{t\to\infty}\phi_{R,0}(t), \tag{B.2}$$

where $p_E^{ss} = \lim_{t\to\infty} p_E(t)$ and by $E_R(t) = K(t)$, $\lim_{t\to\infty} I(t) = \delta \lim_{t\to\infty} K(t) = \delta E_R^{ss}$. In equilibrium, $P(E(t)) = p_E(t)$ and thus $P(E^{ss}) = p_E^{ss}$. As $\lim_{E\to 0} P(E) > c_R$ and $E^{ss} = E_R^{ss} = K^{ss}$, we must obtain $\lim_{t\to\infty} \phi_{R,0}(t) = 0$ and $E_R^{ss} > 0$. $E_R^{ss} > 0$ requires a strictly positive renewable capacity $K^{ss} > 0$, and thus by (7), $I^{ss} = \delta K^{ss} > 0$. It then follows that $\lim_{t\to\infty} \phi_{I,0}(t) = 0$. With (B.2), this gives (18).

To then prove global stability, we first prove

Lemma B.3. *$K(t) \leq E_R^{ss}$ for all t*

Proof. As we assume $K(0) < E_R^{ss}$, $K(t) > E_R^{ss}$ is feasible only if for some $\nu < t$, $K(\nu) = E_R^{ss}$ and $I(\nu) > I^{ss} = \delta E_R^{ss}$ (see (7)). From (A.9), $K(\nu) \geq E_R^{ss}$ and $K(t) = E_R(t)$ for all t (see Appendix B.2.1), implies $p_E(\nu) \leq p_E^{ss}$. Yet $I(\nu) > I^{ss}$, requires $\mu_K(\nu) > \mu_K^{ss}$ from (A.10), and from (A.11) and $p_E(\nu) \leq p_E^{ss}$, it then follows that $\dot{\mu}_K(\nu) > 0$ and thus $\mu_K(\nu') > \mu_K^{ss}$ for all $\nu' \geq \nu$. This entails that $I(\nu') > I^{ss}$ and $K(\nu') > E_R^{ss}$ for all $\nu' > \nu$, and thus $p_E(\nu) \leq p_E^{ss}$ for all $\nu' \geq \nu$. However from (A.9) and (16), $p_E(\nu) \leq p_E^{ss}$ for all $\nu' \geq \nu$ is incompatible with $\mu_K(\nu) > \mu_K^{ss}$. Hence, $K(0) < E_R^{ss}$ implies that we cannot obtain $K(t) > E_R^{ss}$ for any $t > 0$. □

Next define $Z(t) \equiv U(t) + S(t)$. As we require $U(t) \geq 0$ and $S(t) \geq 0$ for all t, $Z(t) \geq 0$ for all t. In addition, $\dot{Z}(t) = \dot{U}(t) + \dot{S}(t) = -E_F(t) \leq 0$. Then we can be in one of two situations.

1. There exists some finite t' such that $Z(\nu) = Z(t')$ for all $\nu \geq t'$. From here it follows that $E_F(\nu) = 0$ and $E(\nu) = E_R(\nu)$ for all $\nu \geq t'$. From $K(t) = E_R(t)$ for all t, Lemma B.3 implies $p_E(\nu) \geq p_E^{ss}$ for all $\nu \geq t'$. From (A.9), and $c_R < p_E^{ss}$, it follows that $\phi_{R,cap}(\nu) > 0$ for all $\nu > t'$ and (17) applies. This gives $\mu_K(\nu) \geq \mu_K^{ss}$ and, by (A.10), $I(\nu) \geq I^{ss}$ for all $\nu > t'$. By (7), for all $\nu > t'$, whenever $K(\nu) < E_R^{ss} = E^{ss}$, $\dot{K}(\nu) > 0$. Together with Lemma B.3, this implies $\lim_{t\to\infty} K(t) = E^{ss}$.

2. There does not exist a finite t' such that $Z(\nu) = Z(t')$ for all $\nu \geq t'$. As $Z(t) \geq 0$ for all t, we must obtain $\lim_{t\to\infty} Z(t) = \bar{Z} \geq 0$ and thus $\lim_{t\to\infty} E_F(t) = 0$, and $E^{ss} = E_R^{ss}$. From Lemma B.3, $\lim_{t\to\infty} p_E(t) \geq p_E^{ss}$. From (A.9), and $c_R < p_E^{ss}$, $\lim_{t\to\infty} \phi_{R,cap}(t) > 0$ and from (17), $\lim_{t\to\infty} \mu_K(t) \geq \mu_K^{ss}$. By (A.10) and (7), $\lim_{t\to\infty} I(t) \geq I^{ss}$ and $\lim_{t\to\infty} K(t) \geq K^{ss}$. By $K^{ss} = E_R^{ss}$ and Lemma B.3 we must then obtain $\lim_{t\to\infty} K(t) = E^{ss}$.

□

B.2.3 Proof for condition for $U^{ss} > 0$.

To prove that $P(E^{ss}) - \tau(t) \leq c_F + (r+\kappa)\frac{c_X(0,0)}{\kappa}$ $\forall t$ is a necessary condition for $U^{ss} > 0$ we proceed as follows. We first establish an intermediate result that if $U^{ss} > 0$, $\lim_{t\to\infty} \mu_U(t) = 0$. Next, we establish that $\lim_{t\to\infty}\mu_U(t)=0$ if $z_F \geq \lim_{t\to\infty}[p(t)-\tau(t)]$, where we define $z_F \equiv c_F + (r+\kappa)\frac{c_X(0,0)}{\kappa}$. The observation that $\dot{\tau}(t)\geq 0$ then completes the proof.

From (A.5) and (A.6) we obtain:

Lemma B.4. *Either* $\lim_{t\to\infty}U(t)=0$*, or* $\lim_{t\to\infty}\mu_U(t)=0$*, or both.*

Proof. First rearrange (A.5) to

$$\dot{\mu}_U(t) = r\mu_U(t) + \frac{\partial C_X(X(t),U(t))}{\partial U(t)},$$

which allows us to write

$$\lim_{T\to\infty}\mu_U e^{-rT} = \mu_U(t)e^{-rt} + \int_t^\infty \frac{\partial C_X(X(\nu),U(\nu))}{\partial U(\nu)} e^{-r\nu} d\nu.$$

Next, observe that $\lim_{T\to\infty}U(T)=U^{ss}$. From (A.6) we must thus obtain

$$0 = U^{ss}\left[\mu_U(t)e^{-rt} + \int_t^\infty \frac{\partial C_X(X(\nu),U(\nu))}{\partial U(\nu)} e^{-r\nu} d\nu\right].$$

If $U^{ss}=0$, this condition is straightforwardly satisfied. If instead $U^{ss}>0$, we require

$$\mu_U(t) = -\int_t^\infty \frac{\partial C_X(X(\nu),U(\nu))}{\partial U(\nu)} e^{-r(\nu-t)} d\nu. \tag{B.3}$$

We know that $C_X(0,U(t))=0$, from which follows that $\partial C_X(0,U(\nu))/\partial U(\nu)=0$. In addition $\lim_{t\to\infty}X(t)=X^{ss}=0$. It then follows from (1) that $\lim_{t\to\infty}\mu_U(t)=0$. □

From (A.3) we can write

$$\lim_{t\to\infty}\mu_S(t) = \lim_{t\to\infty}c_X(0,U(t)) + \lim_{t\to\infty}\mu_U(t) - \lim_{t\to\infty}\phi_{X,0}(t).$$

where we use $\lim_{t\to\infty}X(t)=X^{ss}=0$. From (12) we obtain $\lim_{t\to\infty}\mu_S(t) = \frac{\kappa}{r}\lim_{t\to\infty}\phi_{F,cap}(t)$. With (A.2), this allows us to write

$$\begin{aligned}\lim_{t\to\infty}p_E(t) - \lim_{t\to\infty}\tau(t) \quad &= \quad z_F + \frac{r+\kappa}{\kappa}\left[\lim_{t\to\infty}\mu_U(t) - \lim_{t\to\infty}\phi_{X,0}(t)\right] \\ &\quad -\frac{r+\kappa}{\kappa}\left[c_X(0,0) - \lim_{t\to\infty}c_X(0,U(t))\right] - \lim_{t\to\infty}\phi_{F,0}(t),\end{aligned} \tag{B.4}$$

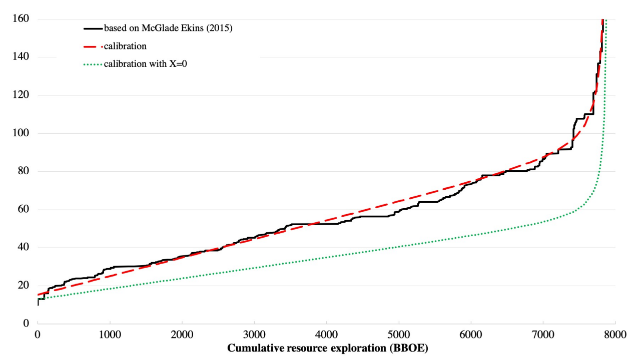
where by $\partial c_X(\cdot)/\partial U(t)\leq 0$, $c_X(0,0)-\lim_{t\to\infty}c_X(0,U(t))\geq 0$. From (18), $\lim_{t\to\infty}p_E(t)=P(E^{ss})$.

From here it directly follows that whenever $P(E^{ss}) - \lim_{t\to\infty} \tau(t) > z_F$, we must obtain $\lim_{t\to\infty} \mu_U(t) > 0$. Then, by Lemma B.4, $\lim_{t\to\infty} U(t) = 0$. In turn, Lemma B.4 states that a solution with $\lim_{t\to\infty} U(t) > 0$ requires $\lim_{t\to\infty} \mu_U(t) = 0$, which according to (B.4) requires $P(E^{ss}) - \lim_{t\to\infty} \tau(t) \leq z_F$. As $\tau(t)$ is weakly increasing over time, this condition is satisfied whenever $P(E^{ss}) - \tau(t) \leq z_F$ for some t.

C Quantitative analysis; further details

Calibration of the exploration cost function To calibrate the exploration cost function we use the 2010 distribution of oil and gas resources as presented in Figure 1 in McGlade and Ekins (2015).[31] To obtain a distribution of *undeveloped* resources, we adjust this data as follows. First, we proportionally reduce the stocks of resources labeled 'in production or planned to be in production' by 2010-2016 cumulative extraction of oil and gas reserves. Next, we subtract already-developed stock (S_0), where we assign 41% of S_0 to gas, and the remainder to oil, in line with 2017 use of oil and gas (IEA, 2019). Finally, we use CPI data from the US Bureau of Labor Statistics to convert the 2010 costs to 2017 USD. This gives the cost distribution of undeveloped resources as presented by the black curve in Figure C.1, where cumulative resource exploration is equivalent to $U_0 - U(t)$.

Figure C.1: Total resource cost ($/BOE) and cumulative resource exploration



To calibrate the parameters θ, ω and ρ, we proxy total resource costs from McGlade and Ekins (2015) by the simple sum of extraction and exploration cost: $c^{total} = c_F + c_X$. From (22), marginal exploration costs $c_X(\cdot)$ are a function not only of undeveloped stock $U(t)$, but also the exploration

[31] This data is available as supplementary material to McGlade and Ekins (2015).

level $X(t)$. For our calibration we fix $X(t)$ to the 2017 extraction level of 55.4.[32] We then obtain estimates for the parameters θ, ω and ρ by minimizing the squared deviation between c^{total} and the black curve in Figure C.1 from the minimum cost of $13.2 to $150.[33]

In this exercise, the parameter ψ is determined separately using estimates from Anderson et al. (2018). Anderson et al. (2018) obtain estimates of the elasticity of oil drilling rates and rig rental rates with respect to the oil price of 0.6 and 0.79 respectively. We combine these elasticities to obtain a short run elasticity of the rig rental rate with respect to the drilling rate of $0.79/0.6 = 1.32$. We consider this a proxy for the elasticity of c_X with respect to X and use this to determine ψ. The red curve in Figure C.1 depicts the resulting fit, parameter values are reported in Table C.1.

Our specification (22) implies marginal exploration costs $c_X(\cdot)$ increase in the level of contemparaneous exploration $X(t)$. In anticipation a fossil energy phaseout, exploration rates likely decline. To illustrate the sensitivity of our calibrated fossil costs to such lower exploration rates we additionally map the minimal c^{total} by setting $X(t) = 0$. The resulting relationship between resource costs and cumulative resource exploration is depicted by the green curve in Figure C.1. As can be observed from this curve, following an exploration trajectory with exploration levels close to the minimum level, would reduce resource cost by approximately up to a third.

Additional tables and figures Table C.1 presents the overview of parameter values used. Figures C.2 and C.3 present the results for the simulations with alternative estimates for the long run renewable costs.

Solution algorithm To numerically solve our model, we proceed as follows. We create an equally-spaced grid of the time horizon T. In our case, the model is solved over 1000 years, with quarterly intervals, which gives a grid of length $\Lambda = 4000$. We implement the following algorithm:

1. Determine μ_S^{ss}, μ_R^{ss} and μ_U^{ss} from the model.
2. Propose a series of prices $p_E^{\text{in}} = \{p_{E,0}, p_{E,1}, ..., p_{E,\Lambda-1}\}$ and exploration levels $X^{\text{in}} = \{X_0, X_1, ..., X_{\Lambda-1}\}$, and steady state $U^{ss,\text{in}} = U_\Lambda$.

[32]This implies that our calibration depicts exploration costs as a function of cumulative exploration, under the assumption that exploration is such that oil and gas extraction can be held constant at 2017 extraction levels. Though we have no data on actual exploration in 2010, we believe this value to be in line with actual 2010 exploration based on the following back of the envelope calculation. From the IEA energy use data, oil and gas extraction grew by 0.65% from 2010-2011, from 50.3 BBOE to 50.7 BBOE. In the context of our model, assuming constrained extraction, this implies $E_{F,2010} = \kappa S_{2010} = 50.3$ and $E_{F,2011} = \kappa S_{2011} = 50.7$. Then from $S_{2011} = S_{2010} - E_{F,2010} + X_{2010}$ this implies exploration X_{2010} equal to 54.8.

[33]Almost 99% of unexplored resources have cost below $150.

3. Impose $\mu_{S,\Lambda} = \mu_S^{ss}$, $\mu_{R,\Lambda} = \mu_R^{ss}$ and $\mu_{U,\Lambda} = \mu_U^{ss}$. Use the proposed prices, exploration levels and U^{ss} to backward-induce all shadow values. This gives a series of $\mu_S^{\text{out}} = \{\mu_{S,0}, \mu_{S,2}, ..., \mu_{S,\Lambda-1}\}$, $\mu_R^{\text{out}} = \{\mu_{R,0}, \mu_{R,1}, ..., \mu_{R,\Lambda-1}\}$, $\mu_U^{\text{out}} = \{\mu_{U,0}, \mu_{U,1}, ..., \mu_{U,\Lambda-1}\}$.

4. Use the shadow values from step 3, as well as initial conditions S_0, K_0 and U_0 to solve for a series of exploration and investment levels, $X^{\text{out}} = \{X_0, X_1, ..., X_{\Lambda-1}\}$ and $I^{\text{out}} = \{I_0, I_1, ..., I_{\Lambda-1}\}$, prices $p_E^{\text{out}} = \{p_{E,0}, p_{E,1}, ..., p_{E,\Lambda-1}\}$ and the steady state level of unexplored stock $U^{ss,\text{out}} = U_\Lambda$.

5. Evaluate the deviation of p_E^{in} from p_E^{out}, X^{in} from X^{out} , and $U^{ss,\text{in}}$ from $U^{ss,\text{out}}$ against a threshold.

    (a) If the series have not sufficiently converged: update p_E^{in}, X^{in} and $U^{ss,\text{in}}$ based on p_E^{out}, X^{out} and $U^{ss,\text{out}}$. Repeat from step 3.

    (b) If the series have sufficiently converged: an approximate solution has been found and the algorithm can be terminated.

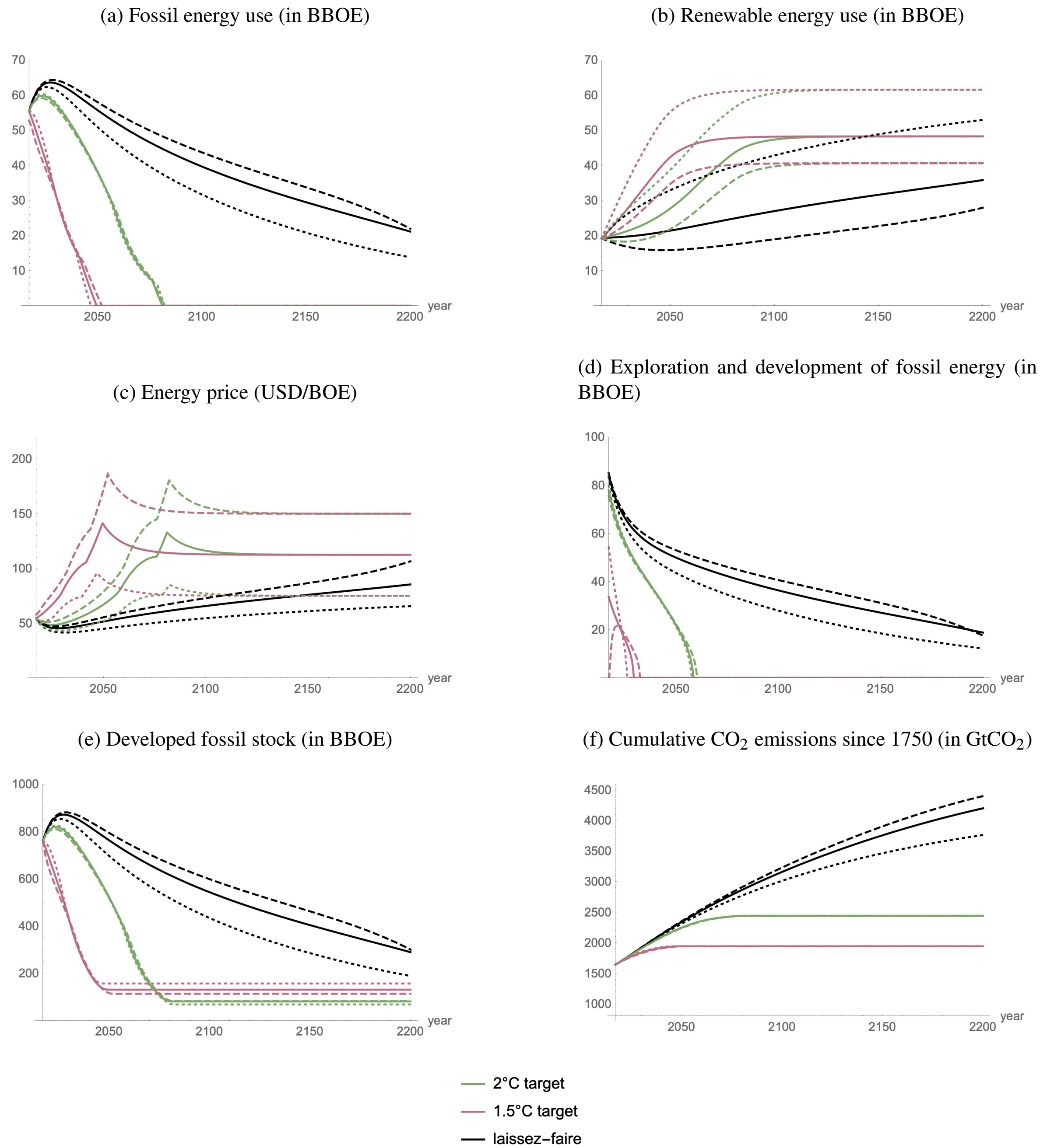
For our forward- and reverse-shooting procedures, we adopt a simple Euler approximation (see Judd, 1998, Chapter 10). The algorithm was implemented in Mathematica.[34]

Table C.1: Parameter values and initial conditions

Initial condition	Value	Parameter	Value	Parameter	Value
S_0	759	c_F	10	c_R	0
U_0	7903	κ	0.073	ξ	609.4
K_0	19.2	θ	2.8819	δ	0.045
		ω	$9.094 * 10^{-4}$	ε	0.6
		ρ	$5.191 * 10^{-3}$	χ	71976
		ψ	0.0512	r	0.04

[34]Further details and code are available upon request.

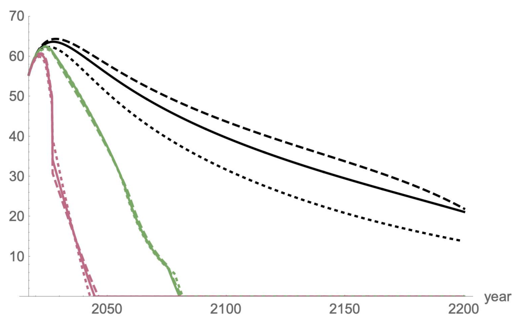
Figure C.2: Sensitivity to alternative renewable costs



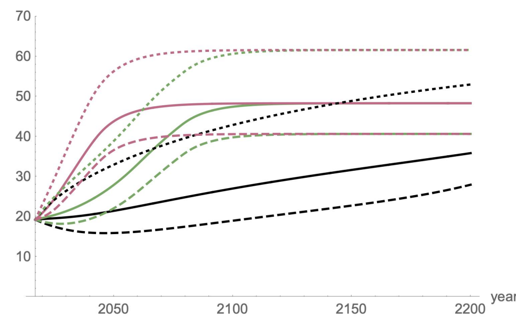
Dotted (dashed) curves indicate paths for long run renewable costs of \$75 (\$150). All trajectories are computed for the central budget estimates. For the $2°C$ target, 2017 emission taxes equal \$16, \$28 and \$39 per tCO_2under low, baseline and high renewable costs, respectively. For the $1.5°C$ target, these these values are \$75, \$103 and \$125 per tCO_2. Taxes subsequently increase at an annual rate of 4%.

Figure C.3: Sensitivity to alternative renewable costs, postponed policy implementation

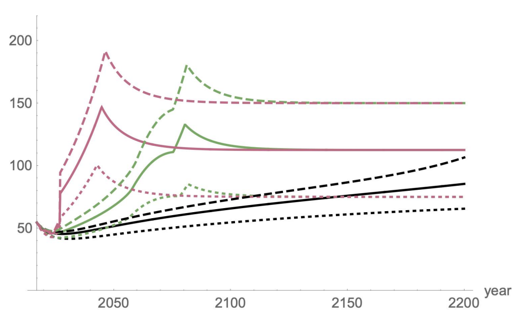
(a) Fossil energy use (in BBOE)



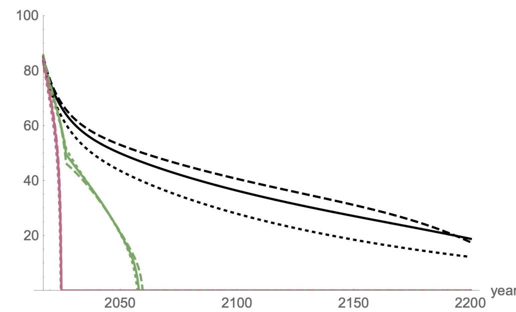
(b) Renewable energy use (in BBOE)



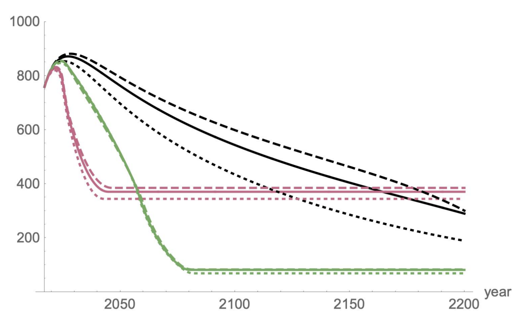
(c) Energy price (USD/BOE)



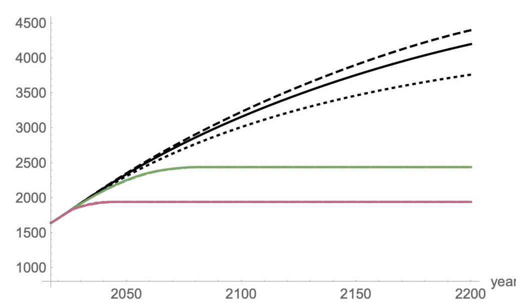
(d) Exploration and development of fossil energy (in BBOE)



(e) Developed fossil stock (in BBOE)



(f) Cumulative CO_2 emissions since 1750 (in $GtCO_2$)



Dotted (dashed) curves indicate paths for long run renewable costs of \$75 (\$150). All trajectories are computed for the central budget estimates. Emission taxes are zero from 2017-2026. For the $2°C$ target, 2027 emission taxes equal \$24, \$42 and \$56 per tCO_2under low, baseline and high renewable costs, respectively. For the $1.5°C$ target, these these values are \$138, \$193 and \$241 per tCO_2. Taxes subsequently increase at an annual rate of 4%.