



Closing wells: Fossil development and abandonment in the energy transition[☆]



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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 development activities. We provide conditions for when the fossil industry will abandon reserves, and establish that continued development of fossil resources is not incompatible with abandoning developed reserves. The first-best implementation of a carbon budget involves reserve abandonment, and thus development 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, development of new reserves is justified for another decade.

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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 over \$400 billion by 2020 (BloombergNEF, 2022).

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Still investment in fossil energy continues to be substantial. In 2021, investment in new and existing oil and natural gas fields amounted to \$380 billion, with planned investment for 2022 exceeding this figure (IEA, 2022). These investments raise concerns. Meeting climate targets requires forfeiting extraction of known oil and gas resources (McGlade and Ekins, 2015; Welsby et al., 2021). These resources can be classified as either undeveloped resources or developed reserves; the carbon emissions embedded in developed reserves alone currently close to the cumulative emission budget associated to the 1.5°C warming target (Rogelj et al., 2018; Trout et al., 2022). Unless fossil 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 transition towards renewable energy in a framework that (i) explicitly considers fossil development and the distinction between developed reserves and undeveloped resources, and (ii) assumes convex investment cost in renewable energy capacity. This setup allows us to rationalize new fossil 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 under a carbon budget always features development that pushes developed reserves in excess of the allowable budget. As revealed by our simulation exercises, optimal abandonment is non-negligible; 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 development of new fossil reserves and their subsequent extraction, 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 reserves, which need to be developed before they are available for extraction. Realistic limits on the rate at which reserves 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 development of additional fossil 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; this is due to the fact that limits on the maximal resource extraction rate preclude full extraction in finite time. Still, despite anticipated abandonment, a fossil energy firm may face positive incentives for fossil 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 reserves in excess of the allowable budget.

Our quantitative evaluation reveals that abandonment under the optimal implementation of a carbon budget is substantial: for the 2°C target, 68–97 billion barrels of oil-equivalent energy (BBOE) are abandoned, for the 1.5°C target this value increases to 120–146 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. Development of new reserves comes to an end 20–25 years prior to the fossil phase-out. Implementing the optimal phase-out trajectory requires 2017 fossil energy taxes equal to \$28 and \$104 per tCO₂ 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. The increase in abandonment and taxes caused by a delayed implementation is more severe when the introduction of the fossil energy taxes is unanticipated.

In our baseline framework, emission mitigation can only be achieved through a reduction in fossil energy use. We extend the model to allow for carbon capture and storage (CCS), and show that unless a 100% capture rate is sufficiently cheap, our results concerning (optimal) reserve abandonment also apply in this context. If instead full capture is relatively cheap, emissions will be fully mitigated through CCS, allowing for full extraction of developed reserves under a binding budget. Our simulations however reveal this is not the quantitatively relevant case; although CCS allows for greater development of fossil reserves and fossil energy use, abandonment remains substantial at an equivalent of 6–12% of initial reserves.

Our paper builds on various contributions on fossil resource exploration, development and extraction, in particular Venables (2014) and Anderson et al. (2018).¹ 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, field development activities are strongly price

¹ As an earlier version of this paper, the literature does not always make a clear distinction between resource exploration (the process of searching for and identifying deposits) and development (the process of putting a deposit in to production). Yet, similar to our analysis, the literature discussed in this section largely abstracts from uncertainty, and assumes exploration activities directly support extraction. As such it effectively characterizes the development process. Contrary, recent work by Ekeland et al. (2022) analyzes the implications of stochastic resource discoveries.

sensitive, which as highlighted by [Anderson et al. \(2018\)](#), is in line with empirical regularities.² A similar pattern 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.³ 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 development, and thereby does not distinguish between developed reserves and undeveloped resources.⁴ 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. Contrary to our paper, [van der Ploeg and Rezai \(2020\)](#) do not consider extraction constraints. Rather, firms are unconstrained to extract from total reserves, causing prices to follow a Hotelling rule. Exploration therefore serves a different purpose: it reduces extraction costs by increasing total remaining oil and gas reserves. 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, by when sufficient renewable energy capacity can be built (see also [Heal and Schlenker, 2019](#)). By assuming a convex cost of renewable energy capacity investments, our modeling approach does capture this distinction, and, thereby, simultaneously allows for the concurrent use of fossil and renewable energy.

Like [van der Ploeg and Rezai \(2020\)](#), [Dietz and Venmans \(2019\)](#) and [Gollier \(2021\)](#) consider the energy transition and emission mitigation policies in the presence of a carbon budget. They characterize the optimal carbon price to ensure cumulative CO₂ emissions remain within this budget. [Gollier \(2021\)](#) 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.

Finally, our paper contributes to the literature on stranded assets. The notion of stranded assets encompasses multiple phenomena, including ‘unburnable carbon’, underutilization and early write-off of fossil industry infrastructure due to anticipated climate policy, as well as the loss of value of (fossil) firm assets and other energy infrastructure due to an unanticipated introduction or tightening of emission mitigation policy ([Carbon Tracker and Grantham Institute, 2013](#); [Caldecott, 2017](#)). The first category includes the analyses by [Carbon Tracker and Grantham Institute \(2013\)](#), [McGlade and Ekins \(2015\)](#) and [Welsby et al. \(2021\)](#), who establish that, even with moderate climate targets, a large amount of carbon is ‘unburnable’. As our main analysis considers the amount of developed reserves that remain optimally unextracted under alternative climate targets, and does not hinge on the unexpected tightening of climate policy, it falls in this category. Contributions in the second category include [Rozenberg et al. \(2018\)](#), [Coulomb et al. \(2019\)](#), and [Baldwin et al. \(2020\)](#), who analyze the underutilization of fossil energy capital, such as coal and gas-fired power plants in the context of the energy transition. In these articles, underutilization is a consequence of the inability to relocate capital from the fossil to the renewable energy generation sector.⁵ Relatedly, [van der Ploeg and Rezai \(2020\)](#) consider the ‘stranding’ of capital goods used for fossil exploration. Here again, the inability to repurpose capital once full utilization is no longer preferred increases the cost of the energy transition. Such cost is further magnified by an unanticipated tightening of climate policy, and has the potential to cause substantial losses in the fossil energy industry. Capital write-offs due to sudden climate policy are also discussed in [Batten et al. \(2016\)](#) and analyzed by [Bretschger and Soretz \(2018\)](#).⁶

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](#), and the implications of CCS are evaluated in [Section 5](#). The quantitative analysis is presented in [Section 6](#). [Section 7](#) concludes. Derivations, proofs, additional calibration details and sensitivity analyses can be found in the Appendix.

2. Model

Energy is produced from fossil resources and renewable energy capital. Our setup for fossil energy supply bears close resemblance to the endogenous oil price model in [Anderson et al. \(2018\)](#). The extraction of fossil resources depletes developed

² The oil price swings during the COVID-19 pandemic also highlight the sluggish response of extraction to prices, and the corresponding importance of investment in field development. Pandemic-related closures initially caused a drop in oil demand. As supply did not instantly adjust, this led to a dramatic fall in oil prices in March and April 2019 ([Bureau of Labor Statistics, 2020](#)). The ensuing decline in investment in field development subsequently constrained supply, which contributed to the oil price spike as the global economy recovered in fall 2021 ([Bloomberg, 2021](#)).

³ An early contribution on fossil resource management that includes both extraction, and exploration and development decisions is [Pindyck \(1978\)](#); [Campbell \(1980\)](#) considers extraction capital determining maximal extraction levels. 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 and development, taking the extraction decision as exogenous. See for instance [Nystad \(1985\)](#) and [Thompson \(2001\)](#).

⁴ See for instance, [van der Ploeg and Withagen \(2015\)](#), [Rezai and van der Ploeg \(2017\)](#), and [van der Meijden and Smulders \(2017\)](#). [Heal and Schlenker \(2019\)](#) capture this distinction only by incorporating heterogeneous extraction costs that may depend on whether reserves have been previously developed or not.

⁵ One can argue that, conceptually, a similar mechanism is present in our framework: the inability to ‘undevelop’ or repurpose developed fossil reserves implies that developed reserves may be abandoned.

⁶ Contributions that identify and quantify climate policy-related losses include [Linn \(2010\)](#), [Delis et al. \(2018\)](#), [Atanasova and Schwartz \(2019\)](#), [Carattini and Sen \(2019\)](#), [Barnett \(2020\)](#), [Sen and von Schickfus \(2020\)](#), and [Fried et al. \(2021\)](#).

reserves. To replenish these reserves and expand extraction capacity, a fossil energy firm can invest in fossil 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 assume that 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 development activities that maximize firm value. The firm maximization problem in the renewable energy sector is similar, with the renewable energy firm 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:

$$E(t) = E_F(t) + E_R(t). \quad (1)$$

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, $S(t)$. This stock includes all reserves for which the necessary extraction infrastructure is already in place. To convert $E_F(t)$ units of fossil reserves into 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:

$$C_F(E_F(t)) = (c_F + \tau(t))E_F(t), \quad (2)$$

where we assume c_F is constant, allow taxes $\tau(t)$ to change over time, and require $E_F(t) \geq 0$.⁷

Fossil extraction is limited by the available extraction capacity. Akin to Anderson et al. (2018), we assume this extraction capacity is endogenously determined by the level of developed fossil reserves.⁸ This gives

$$E_F(t) \leq \kappa S(t), \quad (3)$$

with $\kappa > 0$. The parameter κ represents the maximum rate at which the developed reserves can be extracted. Conversely, κ determines the minimum amount of stock holdings required to extract a unit of fossil reserves 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 Darcy's law (Darcy, 1856) and the resulting decline curves in oil production (Höök et al., 2014).⁹ These curves relate well and field production rates to time since opening, assuming continued production at capacity. Equation (3) mimics this.¹⁰

The stock of developed reserves can be increased through development activities, which transform undeveloped resources U into developed reserves S . These activities include the drilling of production wells, and the installation of injection wells which allow for increased extraction from previously-developed deposits. Adding a flow $X(t)$ to the stock of developed reserves costs $C_X(X(t), U(t))$. The cost is convex and increasing in the flow of reserve additions: $\partial C_X(X(t), U(t))/\partial X(t) = c_X(X(t), U(t)) \geq 0$ and $\partial c_X(X(t), U(t))/\partial X(t) > 0$. This convexity 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. In the remainder we refer to the reserve additions, $X(t)$, as development, with $C_X(\cdot)$ development cost, and $c_X(\cdot)$ marginal development cost.¹¹ We take the development cost as equal to zero when development is zero, $C_X(0, U(t)) = 0$, and require $X(t) \geq 0$. We assume that the (marginal) cost of development increases as more reserves have been developed: $\partial C_X(\cdot)/\partial U(t) \leq 0$, and $\partial c_X(\cdot)/\partial U(t) \leq 0$; this captures that the most accessible, lowest-cost, resources are developed first (McGlade and Ekins, 2015).¹²

⁷ By assuming $C_F(\cdot)$ independent of the level of developed reserves, this specification is not subject to aggregation issues as discussed in Krautkraemer (1998) and Swierzbinski and Mendelsohn (1989).

⁸ See also Cairns (2014), Cairns and Davis (2001), and Thompson (2001).

⁹ Equation (3) resembles a simplified version Darcy's law, where the maximum production from a well is a function of a number of geological characteristics, such as, permeability and viscosity of the resource; these are captured by κ . Darcy's law also establishes that maximum extraction depends positively on the reservoir's pressure, which one can assume falls as the remaining stock S is depleted (Golan, 1992). From an aggregate perspective (3) is the theoretical counterpart of a global decline curve for oil (Höök et al., 2009, 2014). It is also consistent with the forecasted pattern of global oil production in the absence of additional upstream investment (Bentley et al., 2020; IEA, 2020b).

¹⁰ By taking the parameter κ as exogenous, (3) abstracts from investments that increase extraction capacity without expanding the stock of developed reserves, e.g., by installing additional wells in a given field. Instead, we implicitly assume that altering this extraction rate is infeasible or unprofitable. Note that, in the context of our framework, investment in techniques such as water or steam injection that increase the amount of reserves recoverable from a field are considered resource development.

¹¹ Realistically, the transformation of undeveloped resources into developed reserves requires the discovery and exploration of those resources to begin with. We focus on development only, implicitly assuming that the discovery and exploration expenses have already been incurred. This is motivated by the fact that observed upstream investment expenses mostly relate to development, a pattern that will continue to be reinforced as fossil fuels are phased out (IEA, 2021b).

¹² Though technological progress has dramatically reduced the cost of fossil 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 development $c_X(\cdot)$.

Given development $X(t)$ and fossil use $E_F(t)$, developed reserves $S(t)$ evolve according to

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

where the dot denotes the time derivative; we assume $S(0) = S_0 > 0$. We take the known stock of undeveloped reserves as given. This imposes the following limit on cumulative development:

$$\int_t^\infty X(\nu) d\nu \leq U(t), \quad (5)$$

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

$$E_R(t) \leq K(t). \quad (6)$$

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 variable operational or maintenance cost. Compared to the use cost of fossil energy, which includes the cost of extracting the fossil resource, c_R is likely small. In fact, the variable cost of most renewables is (near) zero (U.S. Energy Information Administration, 2019). In line with this we assume that $c_R < c_F$ in the remainder, which implies that the available renewable energy capacity is always utilized prior to fossil energy.

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. The convexity of the investment cost function captures that it is costly to rapidly expand renewable energy capacity and complementary services such as 'smart grids' and energy storage systems. This can be due to capital adjustment cost, for instance associated to acquiring new capital (Amigues et al., 2015). 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.¹³

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

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

with $K(0) = K_0 \geq 0$. As discussed in Section 3, depreciation of the capital stock in combination with the increasing marginal cost of investment, $\partial c_I(I(t))/\partial I(t) > 0$, imply that the marginal cost of sustaining a given level of renewable energy capacity is increasing in the capacity level.

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 $\lim_{E^D \rightarrow 0} P(E^D) = \infty$.

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 development, $[E_F(\nu), X(\nu)]_{\nu=t}^\infty$, 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 development (5), developed reserves evolution (4), and the non-negativity constraints on development and extraction, $X(t), E_F(t) \geq 0$. We discuss the most relevant firm tradeoffs 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 $E_F(t)$, which gives

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

¹³ Akin to development, we do not explicitly incorporate technological progress in renewable energy technology.

where $\mu_S(t)$ denotes the shadow value of $S(t)$, and $\phi_{F, \text{cap}}(t)$ and $\phi_{F,0}(t)$ are the shadow values of the extraction capacity and non-negativity 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 the extraction capacity constraint, $\phi_{F, \text{cap}}(t) > 0$. 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 non-negativity constraint on extraction will be positive, $\phi_{F,0}(t) > 0$.

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

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

where $\phi_{X,0}(t)$ denotes the shadow value of the non-negativity 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 development, $c_X(0, U(t)) + \mu_U(t)$, the firm will not find it optimal to develop, 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 development.

The value of developed stock can in turn be determined from the first-order condition with respect to $S(t)$, (A.4), and the transversality condition (A.6):¹⁴

$$\mu_S(t) = \kappa \int_t^\infty \phi_{F, \text{cap}}(\nu) e^{-r(\nu-t)} d\nu. \quad (10)$$

This expression states that the value of developed reserves is equal to the present value of relieving future extraction capacity constraints and thus allowing for additional extraction. Hence, 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 development 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, $[E_R(\nu), I(\nu)]_{\nu=t}^\infty$, 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 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 most relevant tradeoffs below. The decision to supply renewable energy is characterized by the first order condition with respect to $E_R(t)$, which gives:

$$p_E(t) - c_R = [\phi_{R, \text{cap}}(t) - \phi_{R,0}(t)], \quad (11)$$

where $\phi_{R, \text{cap}}(t)$ and $\phi_{R,0}(t)$ are the shadow values of the renewable energy capacity and non-negativity 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 ($\phi_{R, \text{cap}}(t) > 0$). 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. As the use cost of renewable capacity lies below the use cost of fossil, $c_R < c_F$, renewable capacity is always used first and, in equilibrium, $p_E(t) \geq c_R$. From here it follows that whenever a positive amount of fossil energy is used, renewables must be used at full capacity: $E_R(t) = K(t)$ and $\phi_{R,0}(t) = 0$.¹⁵ In the remainder of the paper we assume that this is the case.

Investment can relieve the capacity constraint on renewable energy generation. The FOC with respect to $I(t)$ 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 $\mu_K(t)$:

$$\mu_K(t) = c_I(I(t)) - \phi_{I,0}(t), \quad (12)$$

where $\phi_{I,0}(t)$ is the shadow value of the non-negativity constraint on investment. Using equations (11), (A.11) and the transversality condition (A.12) we obtain the following solution for $\mu_K(t)$:

$$\mu_K(t) = \int_t^\infty [p_E(\nu) - c_R] e^{-(r+\delta)(\nu-t)} d\nu. \quad (13)$$

Equation (13) 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, $\mu_K(t)$ is positive and captures the present value of adding a unit of renewable capacity. The level of renewable investment is then implicitly determined by (12); in the numerical exercise we assume $c_I(0) = 0$, which implies that renewable investment is always strictly positive.

¹⁴ This solution recognizes that the presence of the renewable substitute imposes an upper bound on the long-run energy price (see discussion below). This rules out a long run that features both full depletion ($\lim_{t \rightarrow \infty} S(t) = 0$) and a non-binding extraction constraint ($\lim_{t \rightarrow \infty} \phi_F(t) = 0$) as by (8) and (A.4) this would require $\lim_{t \rightarrow \infty} p_E(t) = \infty$.

¹⁵ In fact, as we show in Appendix B.2.1, whenever a strictly positive amount of fossil energy is used at $t = 0$, $E_R(t) = K(t) \forall t$.

3. Equilibrium: development and reserve abandonment

Section 2.2 characterizes the fossil and renewable firm extraction, development 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 development and the conditions under which the firm will abandon developed reserves.

Throughout this section, we define an equilibrium as paths $[E_F(t), X(t), E_R(t), I(t), S(t), U(t), K(t), p_E(t)]_{t=0}^{\infty}$ such that, for a given tax trajectory $[\tau(t)]_{t=0}^{\infty}$, the fossil and renewable firms maximize the net present value of profits taking the path of prices as given, and the energy market clears, $E(t) = E^D(t)$ for all t . In turn, we define the long-run equilibrium as the equilibrium that will prevail as $t \rightarrow \infty$. 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. More generally, this assumption implies that the analysis below is applicable to many different fossil fuel tax trajectories, including a strictly positive and weakly increasing tax ($\tau(t) > 0$, $\dot{\tau}(t) \geq 0$ for all t), the delayed implementation of a weakly increasing tax ($\tau(t) = 0$ up to some t' and $\tau(t) > 0$, $\dot{\tau}(t) \geq 0$ for all $t > t'$), and simply the absence of fossil fuel taxation ($\tau(t) = 0$ for all t).

Due to the finiteness of total resources, $U_0 + S_0$, a long run equilibrium with strictly positive fossil use is not feasible; in the long run, energy use must be fully renewable (or zero). From (7) and (11)–(13) this gives the following implicit solution for long-run equilibrium energy use and the corresponding energy price:¹⁶

$$P(E^{ss}) = c_R + (r + \delta)C_I(\delta E^{ss}), \quad (14)$$

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: $\dot{K}^{ss} = \delta E^{ss}$. As $\partial c_I(t)/\partial I(t) > 0$, (14) 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 resources, 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 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: $S^{ss} = 0$.¹⁷ 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 resources. 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 resources: $P(E^{ss}) - \tau(t) \leq c_F + (r + \kappa) \frac{c_X(0,0)}{\kappa}$ (see proof in Appendix B.2.3). 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, $(r + \kappa) \frac{c_X(0,0)}{\kappa}$.¹⁸

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 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 develop whenever the shadow value of developed fossil reserves, $\mu_S(t)$, is positive. From (9), this in turn leads to positive development whenever the value of fossil reserves exceeds the marginal cost of developing the first unit: $\mu_S(t) > c_X(0, U(t))$. As explained in Section 2.2, $\mu_S(t)$ is positive only if extraction is

¹⁶ Appendix B.2.2 establishes that the long run equilibrium is globally stable.

¹⁷ 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.

¹⁸ $c_X(0, 0)$ is the minimum cost of developing the last unit of undeveloped resources. 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 $r + \kappa$.

constrained at some future point, i.e., if $\phi_{F, \text{cap}}(t) > 0$ for some t . From (8), it then follows that, at time t , fossil development incentives are absent only if energy prices net of taxes are below the use cost along the *entire* transition: $P(E(\nu)) - \tau(\nu) \leq c_F$ for all $\nu \geq t$.¹⁹

As developed reserves 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 development’ is more demanding than the condition for ‘developed reserves abandonment’. Hence, an anticipated abandonment of developed reserves does not automatically rule out positive development.

A combination of elements of the framework explain why positive development in the short run is not incompatible with 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 reinforced 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. Development 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.

Hence relieving the extraction constraint provides a rationale for development despite the anticipated abandonment of developed reserves. If the fossil firm would have been able to freely extract from developed reserves, as it is the assumption in a conventional Hotelling framework, the firm would never develop more than it eventually extracts, unless development provides alternative benefits, such as extraction cost reductions or insurance against economic shocks.

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 development cost, is already sunk.

Below, we establish that the abandonment of developed reserves is part of the phase-out strategy under the optimal implementation of 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 CO₂ 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 CO₂ emissions, and independent of the exact timing of those emissions (Allen et al., 2009; Allen, 2016; Matthews et al., 2009; Rogelj et al., 2016; Stocker et al., 2014).²⁰

We define the allocation that optimally implements a carbon budget, $B(t)$, as the allocation that maximizes the present value sum of consumer and producer surplus, $\int_t^\infty \left[\int_0^{E(t)} (P(e) - p_E(t)) de + \pi_F(t) + \pi_R(t) + \Omega(t) \right] e^{-r(\nu-t)} d\nu$, where $\Omega(t)$ captures lump sum recycling of taxes, subject to (1)–(7) and cumulative emissions remaining below the carbon budget:

$$\int_t^\infty E_F(\nu) d\nu \leq B(t), \quad (15)$$

where we take $B(0) = B_0$ as strictly positive and finite.

The first order conditions corresponding to the optimal implementation of a budget are presented in Appendix A.3. From these first order conditions, we establish the following result regarding the optimal implementation of a carbon budget:

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

Proof. See Appendix B.1.2. \square .

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 (15) is met. When a carbon budget is optimally implemented, this tax is equal to the shadow value of the remaining budget. This shadow value in turn captures the increase in total surplus that can be obtained by relaxing the binding carbon budget constraint.

¹⁹ 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, $\mu_S(t) = 0$ 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.

²⁰ 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.

Along the tax trajectory that optimally implements the budget, 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.²¹

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 optimal implementation of a carbon budget features abandonment of developed reserves ($S^{ss} > 0$) if the budget is binding.

Proof. Follows from Proposition 1 and Lemma 1. \square .

Proposition 2 states that the optimal implementation of 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, $B(t)$.²² An immediate implication of this is that whenever developed reserves are equal to or below the remaining budget, development must be strictly positive at some future point in time. More generally, positive development may be observed even if $S(t) > B(t)$. The intuition behind this is akin to discussed in the previous section: development allows the fossil energy firm to increase extraction in the near future, which may generate sufficient return to justify development, even if part of the developed reserves are eventually abandoned. With reserve development acting as a lever on extraction, the path of reserve development may follow a stop-and-go sequence: if the fossil capacity constraint is not binding in the near future, for instance due to the high fossil fuel taxation, there will be no development until (part of) the excess capacity is depleted.

Whether the optimal implementation of a carbon budget results in positive development requires a quantitative assessment. In Section 6, we calibrate the model, and quantitatively evaluate time paths of fossil development and extraction, and renewable energy investment under the budgets corresponding to the 2°C and 1.5°C warming targets. In addition to the optimal implementation, we assess the implications of delaying the introduction of the fossil energy tax.

As a final remark, it is worthwhile highlighting that in Proposition 2 abandonment is driven by increasing fossil fuel taxation. Yet, the result that abandonment is positive, and that anticipating this does not preclude continued development in the short run, generalizes to alternative settings where policy or technology cause a fossil phase-out in finite time.

5. Extension: reserve abandonment with carbon capture and storage

The baseline model does not explicitly take into account the possibility of reducing emissions from fossil fuels through carbon capture and storage (CCS). In recent years, momentum has been building for the deployment of CCS technologies, and CCS is considered as a core element in the decarbonization of several sectors (IEA, 2021a; IPCC, 2022). In this section we extend our framework to include CCS, and generalize our propositions in this context. We focus on the main results below and refer the reader to Appendices A.4 and A.5 for a discussion and interpretation of the maximization problem and first order conditions.

Suppose that the fossil energy firm has access to a CCS technology such that fossil energy emissions now read $E_F(t) - H(t)$, with $H(t)$ the amount of carbon captured and stored (for infinite time thereafter) at time t . We assume the tax $\tau(t)$ is levied based on net emissions, i.e., the firm faces a tax bill equal to $\tau(t)(E_F(t) - H(t))$. The aggregate CCS cost curve is assumed to be convex in $H(t)$:

$$C_H(H(t), E_F(t)) = [\varsigma + f(h(t))]H(t), \quad (16)$$

with $h(t) \equiv H(t)/E_F(t)$ the CCS intensity, $\varsigma > 0$, $f(0) = 0$ and $\partial f(h(t))/\partial h(t) \geq 0$. We restrict $0 \leq h(t) \leq 1$.²³ This cost function can be considered a generalization of the linear CCS cost function adopted in Moreaux and Withagen (2015) and Moreaux et al. (2022), and is also consistent with the estimated convexity of CCS cost (Johnsson et al., 2020; IEA, 2021a). However, for tractability, it abstracts from the fact that a large part of CCS costs are capital costs to build the necessary CCS capacity. In our numerical analysis, we account for this time-to-build-up by assuming CCS only becomes available after 2027.

In the presence of CCS with cost function (16), Proposition 1 generalizes to

Proposition 3. If $P(E^{ss}) - c_F < 0$, then developed fossil reserves will be abandoned in the long run ($S^{ss} > 0$) for any $\tau(t) \geq 0$.

²¹ As noted by Gollier (2021), “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, 2021, 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 Coulomb et al. (2019), Dietz and Venmans (2019) and van der Ploeg and Rezai (2020).

²² 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 $t \geq T$, $E_F(t) = 0$.

²³ CCS by definition cannot exceed 100% of emissions; Johnsson et al. (2020) use maximal capture rates of 90–95% for current CCS technologies. Achieving net negative emissions necessitates the use of carbon dioxide removal (CDR) technologies. More so than CCS, CDR technologies are still at early stages of development and high-cost, making it highly uncertain whether mass deployment is feasible (Jacobsen, 2020b; IEA, 2021a).

If $0 \leq P(E^{ss}) - c_F < \varsigma + f(1)$, then there exists some finite level $\bar{\tau} > 0$ such that (i) if $\tau(t) > \bar{\tau}$ for some t , then developed fossil reserves will be abandoned in the long run ($S^{ss} > 0$), and (ii) if $\tau(t) < \bar{\tau}$ for all t , then all developed fossil reserves will be extracted in the long run ($S^{ss} = 0$). If $P(E^{ss}) - c_F > \varsigma + f(1)$, then all developed reserves will be extracted in the long run ($S^{ss} = 0$).

Proof. See [Appendix B.1.3](#). \square .

In the absence of CCS, the abandonment of developed reserves in the long run depends on whether extracting previously-developed reserves is sufficiently cheap; if the fossil energy tax is too high, developed reserves will be abandoned. CCS allows firms to avoid paying this tax, by instead paying for carbon capture. CCS thus places an upper bound on the cost of using fossil reserves. We then establish that if full capture ($h(t) = 1$) is sufficiently cheap, developed reserves are never be abandoned. In intermediate cases where CCS may be used, but full capture is not economical, there remains a maximum tax level $\bar{\tau}$, such that if $\tau(t) > \bar{\tau}$ in the long run, developed reserves will remain unextracted ($S^{ss} > 0$).

With CCS, the carbon budget evolves according to

$$\dot{B}(t) = -E_F(t) + H(t). \quad (17)$$

One can then straightforwardly verify that [Lemma 1](#) still applies (see [Appendix A.5](#) for details), from which follows the generalization of [Proposition 2](#):

Proposition 4. If $P(E^{ss}) - c_F < \varsigma + f(1)$, the optimal implementation of a carbon budget features abandonment of developed reserves ($S^{ss} > 0$) if the budget is binding.

Proof. Follows from [Proposition 3](#) and [Lemma 1](#). \square .

[Proposition 4](#) reveals that with CCS technologies, abandonment is only part of the optimal implementation of a carbon budget if full capture is too costly. For the quantitative analysis in [Section 6.2](#), we parameterize the CCS cost function based on the literature, and confirm that this is indeed the quantitatively relevant scenario.

6. 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 global warming targets of 2°C and 1.5°C as well as a laissez-faire baseline. We assess equilibrium trajectories starting in 2017, when policy is optimal and immediately introduced, or postponed by 10 years.

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.

The model specification and parameterization are discussed in [Section 6.1](#), and the results from the simulations, including the extended model with CCS and sensitivity analyses, are presented in [Section 6.2](#). Further details regarding the parameterization, numerical strategy and sensitivity 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.²⁴ All prices and taxes are expressed in 2017 USD, and emissions in GtCO₂.

6.1. Specifications and baseline parameterization

Energy demand: We adopt the following specification for the inverse energy demand:²⁵

$$P(E(t)) = \chi E(t)^{-\frac{1}{\varepsilon}}. \quad (18)$$

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. Here, and in the remainder of the section, we rely on IEA data for supply estimates ([IEA, 2019](#)).²⁶

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, 2018](#)).²⁷ Based on this, and the fact that a shift to higher-cost reserves is anticipated ([IEA, 2018](#)), we set $c_F = 10$.

²⁴ To convert all units into BBOE we use conversion factors from [BP \(2018\)](#).

²⁵ As we abstract from coal, (18) represents demand for residual, non-coal, energy. This specification reflects that both gas and renewables are substitutes for coal in power generation.

²⁶ This price is close to the 2015–2019 average Brent crude oil price of \$57.2.

²⁷ We assign administrative costs and production costs to use costs. Any capital costs will be assigned to development costs as explained below.

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 rates for 880 ‘post-peak’ fields. They find a production-weighted average of 7.3%. Based on this we set $\kappa = 0.073$.²⁸ 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 $S_0 = 759$.²⁹

To parameterize our development 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 eventually extracting these resources. To reproduce their distribution of global resources, we adopt the following specification for development costs:

$$C_X(X(t), U(t)) = \left[\frac{\theta}{1 - e^{-\omega U(t)}} + \rho(U_0 - U(t)) \right] [X(t) + [e^{\psi X(t)} - 1]]. \quad (19)$$

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 development 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 20–25 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 decommissioning 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 (near) zero (U.S. Energy Information Administration, 2019). To reflect this we set $c_R = 0$. Hence, all costs associated to renewable energy are due to investment, where we adopt a quadratic investment cost function:

$$C_I(I(t)) = \frac{\xi}{2} I(t)^2. \quad (20)$$

The investment cost parameter ξ is set to match the long-run cost of renewables. We formulate three scenarios 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 levelized cost of energy (LCOE) associated to solar photovoltaic, while for the lower bound we adopt the current LCOE for hydroelectric and nuclear power. Using global weighted averages 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. 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 CO₂ emissions, impacts of non-CO₂ greenhouse gas emissions and earth system feedbacks such as greenhouse gas emissions from wetlands and permafrost thawing. For this reason, instead of considering a single value for the budget, we adopt a central value $\pm 25\%$.³⁰ The central values are consistent with a 2/3 probability of staying below the temperature target, and are equal to 1170 and 420 GtCO₂ for 2°C and 1.5°C, respectively (Rogelj et al., 2018). These budgets apply to all CO₂ 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 CO₂ emissions, most importantly coal. Yet, coal is a major contributor of CO₂ emissions, and ignoring this would cause a substantial overestimation 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 804 GtCO₂ for the 2°C target, and a budget of 304 GtCO₂ for the 1.5°C target, which amount to 2298 and 869 BBOE, respectively.^{31, 32}

²⁸ These rates are similar to the global average annual decline rate of ‘roughly 8%’ for both oil and gas reported by the IEA (2020a).

²⁹ Hence, at the level of 2017 extraction, developed reserves amount to $759/55.4 \approx 14$ years of extraction. This figure for initial developed reserves is in line with estimates by Laherrère et al. (2022) and Rystad Energy (2022).

³⁰ 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.

³¹ 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 GtCO₂/BBOE. Conversely, $S_0 = 759$ gives 266 GtCO₂ embodied in initially developed oil and gas reserves.

³² Our approach does not explicitly model emissions from coal and land use changes. Greater use of e.g., 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.

6.2. Results

In this section we present the results of the 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 (15) is met. Next, 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. We subsequently present the results for a sensitivity analysis as well as results for the extended model including CCS.

6.2.1. 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.³³ The implementation of the carbon budget requires a tax with an initial value of \$28 and \$104 per tCO₂ for the central estimates of the 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. [Fig. 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 development of new fossil reserves (panel d).³⁴ Initial 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, development is notably lower, and fully terminated between 2024 and 2034. For this target, initial development is rather sensitive to the value of the budget, ranging between 0% and 62% of *laissez-faire* development levels.

As explained in [Section 3](#), the fossil firm's incentive to engage in 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 development in the short run are sizeable. 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 development.^{35, 36}

The optimal implementation of a budget entails the abandonment of developed reserves, which implies that development activities necessarily induce reserve development in excess of what can ultimately be extracted under the budget. At first glance, if one would not take into account that abandonment is part of the fossil firm's profit-maximizing strategy, some of this development would be deemed excessive. We compute this 'excessive development' as a fraction of the budget net of the 266 GtCO₂ embedded in initially developed reserves.³⁷ We find that excessive development 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 development, with a central value of 5%. For the 1.5°C target, 27% and 55% of development 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 development can be deemed excessive.

³³ It is worth noting that our *laissez-faire* scenario results in a more conservative evolution of renewables than the baseline scenarios produced by more detailed energy system models, for instance [BP \(2020\)](#) and [IEA \(2021b\)](#). This can be primarily explained by the fact that these baseline scenarios already presume either the presence of an increasing carbon tax ([BP, 2020](#)), or future implementation of 'stated policies' ([IEA, 2021b](#)). Nonetheless, the penetration of renewable energy in our *laissez-faire* scenario is consistent with [BP \(2020\)](#) and [IEA \(2021b\)](#).

³⁴ Further sensitivity analysis reveals that this result is generally robust: in [Appendix C.3.2](#) we find positive development for all 2°C scenarios and for 9/10 of the 1.5°C scenarios with alternative budgets and key parameter values. See [Tables C.2 and C.3](#) for summary statistics of the sensitivity checks.

³⁵ Additionally, marginal development costs rise as undeveloped resources fall. While this mechanism contributes to the fall in fossil development, and subsequent use under *laissez-faire* (panels b and c), it has little additional effect on the trajectories in the budget scenarios.

³⁶ The same intuition applies to the inverted-U shaped trajectory of development under the lower bound of the 1.5°C target. Here, high energy taxes cause extraction to be unconstrained initially, which diminishes development incentives. The absence of development implies rapidly falling fossil energy capacity, which in this particular case, causes extraction to become constrained in the short run, creating incentives for fossil development. This effect is however only temporary; over time, rising taxes and renewable energy supply will reduce incentives for fossil development, and cause a fossil phase-out.

³⁷ Put differently, we compute the share of newly-developed reserves that would remain unextracted under the budget, if all previously-developed reserves would be extracted.

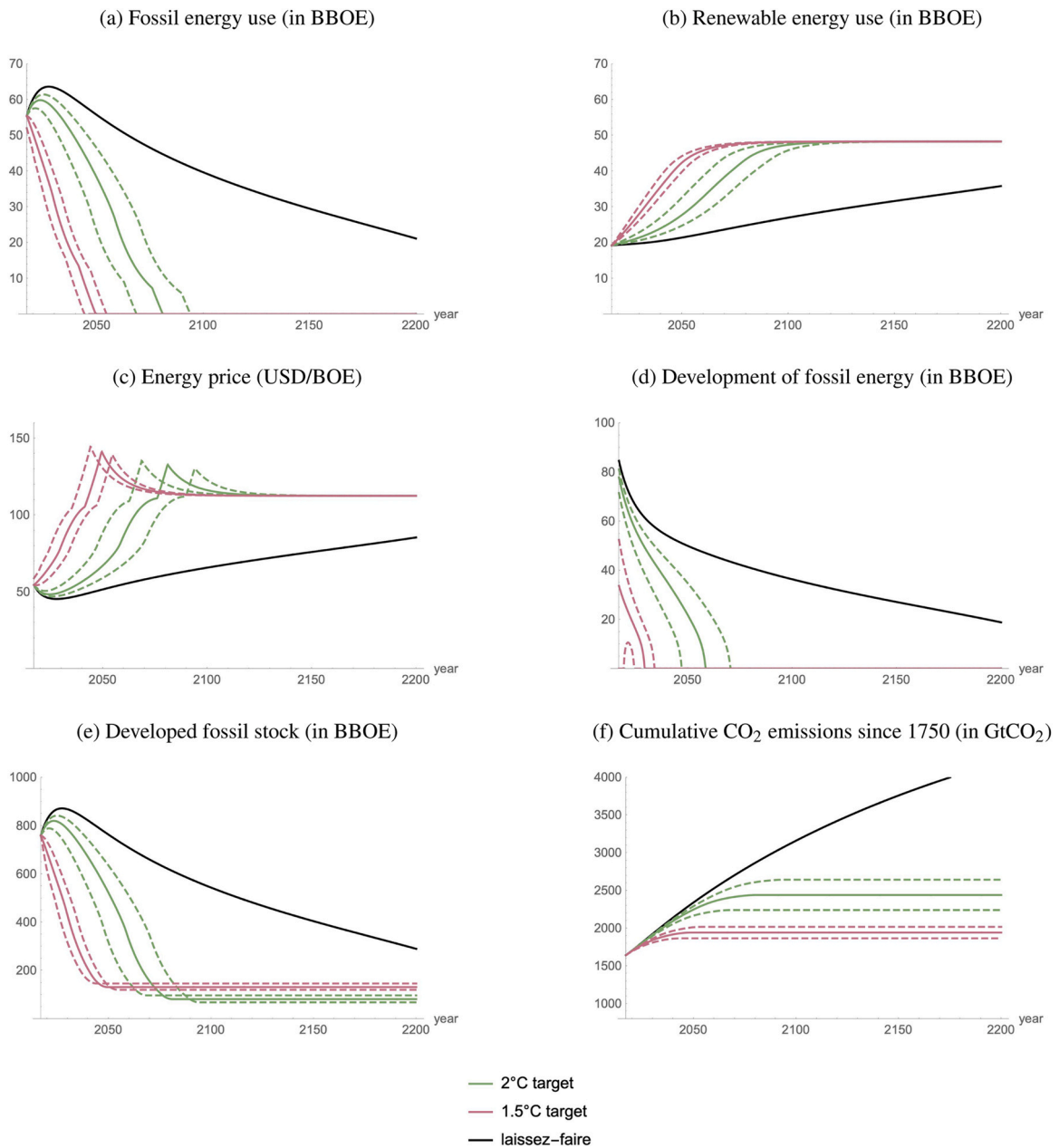


Fig. 1. Results, carbon budget and laissez-faire. Solid (dashed) curves indicate paths for the central (alternative) estimates for the oil and gas budget. 2017 emission taxes equal \$28 per tCO₂ for the central budget of the 2°C target (\$16 and \$46 for the upper and lower budget bound, resp.) and \$104 per tCO₂ 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%.

While the trajectories for fossil 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.³⁸ 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

³⁸ A similar price pattern emerges in Amigues et al. (2015), where the energy price peak is also a consequence of a gradual build up of renewable capacity and a finite time phase out of fossil energy due to exhaustion.

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 development and extraction of fossil resources (stage I). Next, 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.

6.2.2. 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, and this policy change is anticipated. 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 (14).

The results from the simulations show the tax delay has little effect on the energy transition for the 2°C target. A comparison of Figs. 1 and 2 reveals that price paths are nearly identical under an immediate or delayed introduction of the tax (panel c). 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 development levels in the first decade, lower subsequent development levels cause cumulative development 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 tCO₂, as compared to a 2027 tax of \$41 per tCO₂ when the 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 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 tCO₂ 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 development on par with the laissez-faire level, as the tax introduction draws nearer, development 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 possible despite the delayed introduction, the higher initial 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 on abandonment, it causes significantly higher levels of abandonment for the 1.5°C target.

As the introduction and future path of the tax are anticipated, these substantial levels of abandonment are not a by-product of unexpected policy changes. To assess the effect of an unexpected policy tightening on the energy transition, we simulate an alternative delayed policy scenario where the introduction of the tax on fossil use in 2027 is fully unanticipated. The results are presented in Fig. C.2 in Appendix C. In this alternative policy scenario, the remaining carbon budget in 2027 is positive for all six estimates of the initial budget. However, as emissions follow the laissez-faire path for the first decade, policy needs to be more aggressively introduced to meet a given target. For the central estimates, the required tax level in 2027 is \$51 and \$242 per tCO₂ to meet the 2°C and 1.5°C target, respectively. Meeting the 1.5°C target, while possible, may be infeasible in practice. Using the lower budget bound, the required tax level in 2027 exceeds \$600 per tCO₂. As development investments are not adjusted prior to the introduction of the tax, more developed reserves are eventually abandoned. For the central budget estimate of the 2°C target abandoned reserves amount to 102 BBOE, 25% more than under optimal implementation. Under the 1.5°C target abandonment totals 630 BBOE for the central budget estimate, which is about five times the abandonment under optimal implementation. For the lower budget bound the 1.5°C target, abandonment even exceeds the initial level of developed reserves and amounts to 845 BBOE. Thus, the differential effect of delaying the introduction of the tax on the level of abandonment under different targets is reinforced when the policy is not anticipated.

6.2.3. Sensitivity analysis

We perform sensitivity analysis around 5 model parameters. These parameters specify the cost of renewables (ξ), maximum extraction rate (κ), elasticity of energy demand (ϵ) and cost of developing new reserves (θ and ψ). As our results show little sensitivity to our alternative parameterizations of the energy demand elasticity and cost of developing new reserves, we discuss only the former two sensitivity analyses in detail.

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 per BBOE at baseline parameterization of energy demand. Results for the central budget

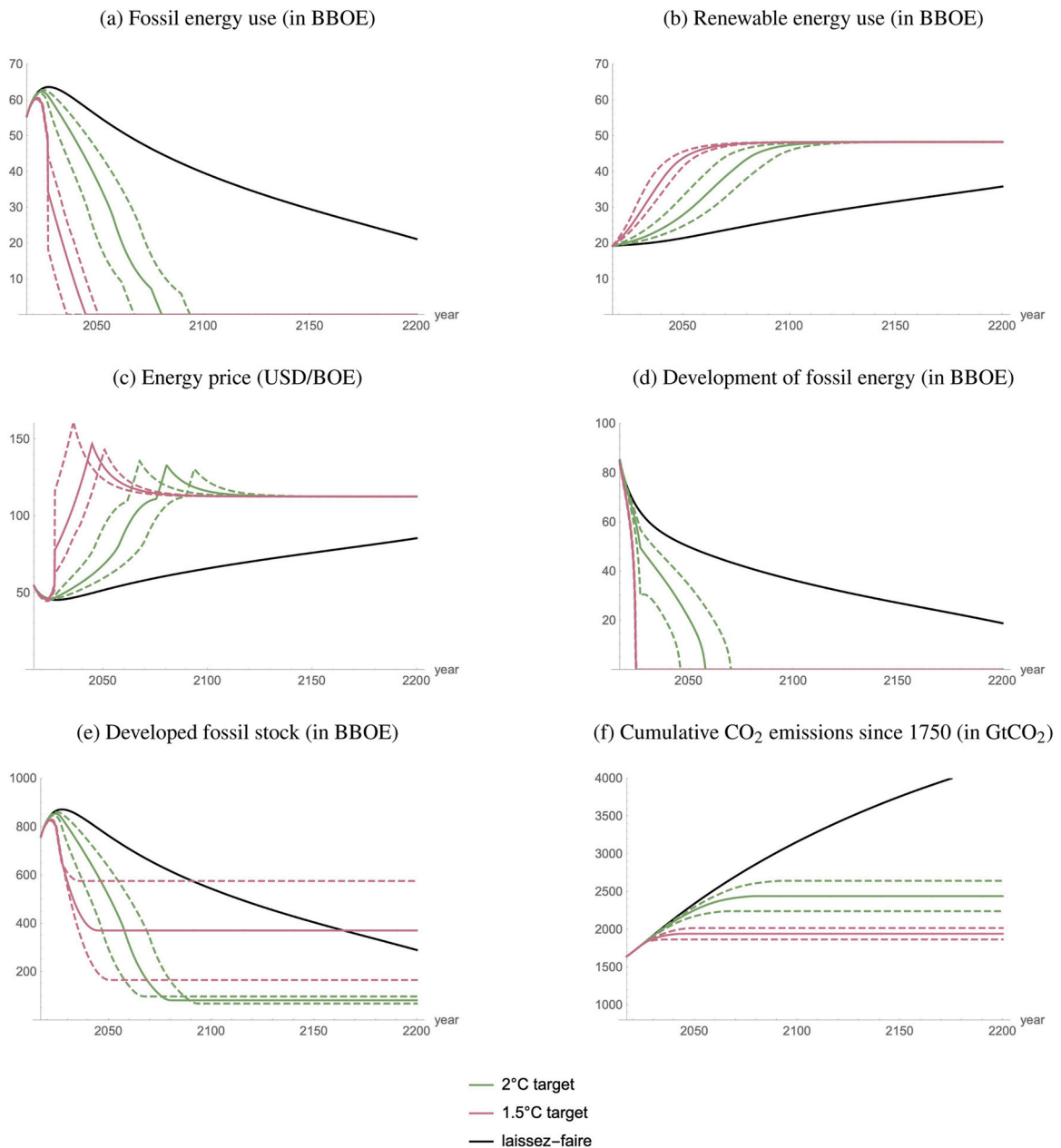


Fig. 2. Results, carbon budget and laissez-faire - delayed policy. Solid (dashed) curves indicate paths for the central (alternative) estimates for the oil and gas budget. Emission taxes are zero from 1717 to 2026. 2027 emission taxes equal \$42 per tCO₂ for the central budget of the 2°C target (\$24 and \$72 for the upper and lower budget bound, resp.) and \$193 per tCO₂ 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%.

estimates are presented in Fig. C.3 in Appendix C, alongside the results for our baseline calibration of \$112.5 per BBOE. 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 less costly, 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 tCO₂ 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 tCO₂ for the lowest and highest long run renewable cost estimates, with a baseline value of \$104 per tCO₂.

While cheaper renewable energy discourages fossil extraction, and hence development, lower carbon taxes have the opposite effect. Taken together, effects approximately cancel out, and the paths of fossil 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. An exception is fossil development under the 1.5°C target (panel d). Here, higher renewable costs are associated with a shift of development toward the future.

Maximum extraction rate: We next evaluate the sensitivity of our results to the maximum extraction rate. Fig. C.4 in Appendix C compares the results of the baseline calibration, with $\kappa = 0.073$, and two alternative specifications with values of κ around this baseline, for the central budget estimates. The lower bound for κ is set to the median depletion rate for all fields (0.059) and the upper bound is equal to the median for large fields (0.113) in Höök et al. (2014).³⁹ The initial tax required to optimally implement a given target is practically unaltered by the choice of κ . However, as κ determines how quickly developed reserves can be exploited before fossil energy is phased out, a higher κ results in lower reserve abandonment under both temperature targets and also reduces the sensitivity of abandonment to the stringency of the target. With $\kappa = 0.113$, the equivalent of 6% and 10% of initially developed reserves are abandoned under the 2°C and the 1.5°C target, respectively. With $\kappa = 0.059$, the corresponding abandonment figures are 14% and 22%.

Energy demand elasticity and cost of developing new reserves: Our remaining sensitivity analyses are as follows. First, in addition to the baseline parameterization $\varepsilon = 0.6$, which is based on the long-run value of the (absolute) price elasticity of energy demand, we consider $\varepsilon = 0.4$, which is closer to estimates of the price elasticity in the short run. Second, we perform two sets of sensitivity analyses to assess the implications of alternative parameterizations of the development cost function. For these analyses, we consider the baseline values of θ and $\psi \pm 25\%$. As can be concluded from Appendix Figs. C.5–C.7, our results are hardly affected by these alternative parameterizations. A lower energy demand elasticity implies higher long run energy use and prices. Slightly higher taxes are then required to implement the budget; combined with the higher energy price trajectory this implies little effect on the trajectories of development and reserve abandonment. Also lower marginal development costs (through lower θ or ψ) are associated with slightly increased optimal taxes, and virtually no net effect on total development or reserve abandonment. A lower ψ , which implies a lower elasticity of marginal development cost with respect to development $X(t)$, does bring forward development under the 2 degree scenario.

The sensitivity analyses above consider the effects of only varying one parameter at once. Tables C.2 and C.3 in Appendix C.3.2 additionally presents key statistics of a sensitivity analysis that simultaneously varies all of the above parameters, across all budget estimates. We find abandonment as a share of initially developed reserves between 2% and 17% for the 2°C target, and between 7% and 33% for the 1.5°C target. Except for the maximum extraction rate, and, to a lesser extent, the renewable cost, the effect of individual parameters on the shares of abandonment and excessive development is generally modest. We observe positive new reserve development across scenarios, except for some simulations with the lowest 1.5°C budget and lowest κ .

6.2.4. Carbon capture and storage

Finally, we consider the implications of including CCS as specified in Section 5. The parameterization is discussed in Appendix C.1.2; Figs. C.8 and C.9 in Appendix C.3.3 present the results. CCS does not prevent the abandonment of developed reserves; the calibrated CCS cost are such that in the long run, the cost of capture and storage of all CO₂ emissions from fossil energy use is too high to justify continued extraction of developed stocks.

Sufficiently high taxes on fossil fuel emissions are required to justify the use of CCS. Consequently, whereas CCS will be used as soon as possible under the (high tax) 1.5°C scenarios, the use of CCS is only economical between 2040 and 2060 under the 2°C targets. Over time, rising taxes on fossil fuel emissions further increase the share of emissions captured, resulting in capture rates of 60–70% at the time of fossil phase-out (see Fig. C.9). Fig. C.8 shows CCS allows for higher and more extended use of fossil reserves. Even though it encourages additional reserve development, it substantially reduces abandonment, to an equivalent of 6–12% of initial reserves, depending on budget scenario. This is a reduction of about 37% relative to the no-CCS baselines. As CCS allows for greater cumulative fossil use meeting the budget requires lower taxes: initial taxes are now \$27 per tCO₂ and \$99 per tCO₂ for the central estimates of the 2°C and 1.5°C targets, respectively.

7. Concluding comments

In this paper we build a dynamic model of the energy transition that explicitly considers the 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 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 involves developed reserves abandonment and thereby development of new fossil energy reserves in excess of the allowable budget. In a model extension with carbon capture and storage we establish that reserve abandonment can be avoided if 100% capture is sufficiently cheap, if not, the qualitative implications of the baseline model remain.

We calibrate the model to numerically investigate the transition path under the 2°C and 1.5°C warming targets. The optimal implementation leads to significant abandonment of developed reserves in the baseline model: equivalent to 9–19% of current

³⁹ Adjusting κ requires a recalibration of the initial value of developed reserves, S_0 , such that fossil extraction capacity coincides with actual use of energy from oil and gas: 55.4 BBOE; accordingly, the initial value of undeveloped resources, U_0 , is adjusted to keep total initial resources, $S_0 + U_0$, unchanged with respect to the baseline calibration.

developed reserves. Initial development is close to the laissez-faire under the 2°C target, yet declines rapidly, until it reaches zero in 2058. The more stringent 1.5°C target yields lower development levels, which remain positive until 2030. A delayed introduction of the tax brings forward 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 ambitious climate policy. Our results signal a large increase in reserves 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 development and reserves 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 development activities on the implementation of climate policy, and the incentives of the fossil industry to strategically engage in fossil development 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 development, the framework is particularly suited to analyze the scope for supply-side policies such as restrictions on development activities. Such policies have received increasing attention in recent years, both in the academic literature (Harstad, 2012; Asheim, 2019; Ahlvik et al., 2022), and the policy debate (Lazarus and van Asselt, 2018).

Data Availability

No data was used for the research described in the article.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Optimization problems

A.1. Fossil firm optimization

The fossil firm chooses the path of fossil extraction and development, $[E_F(v), X(v)]_{v=t}^{\infty}$, that maximizes $\Pi_F(t) = \int_t^{\infty} \pi_F(v) e^{-r(v-t)} dv$, 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:

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

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

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

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

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

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

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

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 $I(t), E_R(t) \geq 0$.

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

$$[E_R]: p_E(t) - c_R = [\phi_{R,cap}(t) - \phi_{R,0}(t)]; \phi_{R,cap}(t)[K(t) - E_R(t)] = 0; \quad \phi_{R,0}(t)E_R(t) = 0, \quad (A.9)$$

$$[I]: \mu_K(t) = c_I(I(t)) - \phi_{I,0}(t); \quad \phi_{I,0}(t)I(t) = 0, \quad (A.10)$$

$$[K]: \frac{\dot{\mu}_K(t)}{\mu_K(t)} - \delta + \frac{\phi_{R,cap}(t)}{\mu_K(t)} = r, \quad (A.11)$$

$$[TVC]: \lim_{t \rightarrow \infty} \mu_K(t)K(t)e^{-rt} = 0. \quad (A.12)$$

A.3. Optimal allocation under a carbon budget

To determine the optimal allocation under a carbon budget we maximize $\int_t^{\infty} \left[\int_0^{E(t)} (P(e) - p_E(t)) de + \pi_F(t) + \pi_R(t) + \Omega(t) \right] e^{-r(\nu-t)} d\nu$ subject to (1)–(7) and (15) and non-negativity constraints on extraction, development, 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:

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

$$[E]: P(E(t)) - p_E(t) = \lambda_E^P(t); \lambda_E^P(t)[E_F(t) + E_R(t) - E(t)] = 0, \quad (A.14)$$

$$[E_F]: p_E(t) - c_F + \lambda_E^P(t) - \mu_B^P(t) = \mu_S^P(t) + [\phi_{F,cap}^P(t) - \phi_{F,0}^P(t)]; \phi_{F,cap}^P(t)[\kappa S(t) - E_F(t)] = 0; \quad \phi_{F,0}^P(t)E_F(t) = 0, \quad (A.15)$$

$$[X]: \mu_S^P(t) = c_X(X(t), U(t)) + \mu_U^P(t) - \phi_{X,0}^P(t); \phi_{X,0}^P(t)X(t) = 0, \quad (A.16)$$

$$[E_R]: p_E(t) - c_R + \lambda_E^P(t) = [\phi_{R,cap}^P(t) - \phi_{R,0}^P(t)]; \phi_{R,cap}^P(t)[K(t) - E_R(t)] = 0; \quad \phi_{R,0}^P(t)E_R(t) = 0, \quad (A.17)$$

$$[I]: \mu_K^P(t) = c_I(I(t)) - \phi_{I,0}^P(t); \quad \phi_{I,0}^P(t)I(t) = 0, \quad (A.18)$$

$$[S]: \frac{\dot{\mu}_S^P(t)}{\mu_S^P(t)} + \kappa \frac{\phi_{F,cap}^P(t)}{\mu_S^P(t)} = r, \quad (A.19)$$

$$[K]: \frac{\dot{\mu}_K^P(t)}{\mu_K^P(t)} - \delta + \frac{\phi_{R,cap}^P(t)}{\mu_K^P(t)} = r, \quad (A.20)$$

$$[U]: \frac{\dot{\mu}_U^P(t)}{\mu_U^P(t)} - \frac{\partial C_X(X(t), U(t)) / \partial U(t)}{\mu_U^P(t)} = r, \quad (A.21)$$

$$[B]: \frac{\dot{\mu}_B^P(t)}{\mu_B^P(t)} = r, \quad (A.22)$$

$$[TVC S]: \lim_{t \rightarrow \infty} \mu_S^P(t)S(t)e^{-rt} = 0, \quad (A.23)$$

$$[TVC U]: \lim_{t \rightarrow \infty} \mu_U^P(t)U(t)e^{-rt} = 0, \quad (A.24)$$

$$[\text{TVC } K]: \lim_{t \rightarrow \infty} \mu_K^P(t) K(t) e^{-rt} = 0, \quad (\text{A.25})$$

$$[\text{TVC } B]: \lim_{t \rightarrow \infty} \mu_B^P(t) B(t) e^{-rt} = 0. \quad (\text{A.26})$$

A.4. Fossil firm optimization with CCS

The fossil firm chooses the path of fossil extraction, development and CCS, $[E_F(\nu), X(\nu), H(\nu)]_{\nu=t}^{\infty}$, that maximizes $\Pi_F(t) = \int_t^{\infty} \pi_F(\nu) e^{-r(\nu-t)} d\nu$, with instantaneous profits $\pi_F(t) = (p_E(t) - c_F - \tau(t))E_F(t) - C_X(X(t), U(t)) - C_H(H(t), E_F(t))$, subject to (3)–(5), $X(t), E_F(t) \geq 0$, (16) and $H(t) \in [0, E_F(t)] \forall t$. This gives the following Hamiltonian with first order, complementary slackness and transversality conditions:

$$\begin{aligned} \mathcal{H}_F = & [p_E(t) - c_F - \tau(t)]E_F(t) + \tau(t)H(t) - C_X(X(t), U(t)) - C_H(H(t), E_F(t)) \\ & + \mu_S(t)[-E_F(t) + X(t)] + \mu_U(t)[-X(t)] + \phi_{F, \text{cap}}(t)[\kappa S(t) - E_F(t)] \\ & + \phi_{F,0}(t)[E_F(t)] + \phi_{X,0}(t)[X(t)] + \phi_{H,0}(t)[H(t)] + \phi_{H, \text{cap}}(t)[E_F - H(t)], \end{aligned} \quad (\text{A.27})$$

$$\begin{aligned} [E_F]: & p_E(t) - c_F - \tau(t) - \frac{\partial C_H(H(t), E_F(t))}{\partial E_F(t)} + \phi_{H, \text{cap}}(t) \\ & = \mu_S(t) + [\phi_{F, \text{cap}}(t) - \phi_{F,0}(t)]; \\ & \phi_{F, \text{cap}}(t)[\kappa S(t) - E_F(t)] = 0; \quad \phi_{F,0}(t)E_F(t) = 0, \end{aligned} \quad (\text{A.28})$$

$$\begin{aligned} [X]: & \mu_S(t) = c_X(X(t), U(t)) + \mu_U(t) - \phi_{X,0}(t); \\ & \phi_{X,0}(t)X(t) = 0, \end{aligned} \quad (\text{A.29})$$

$$\begin{aligned} [H]: & \tau(t) + \phi_{H,0}(t) - \phi_{H, \text{cap}}(t) = c_H(h(t)); \\ & \phi_{H,0}(t)H(t) = 0; \quad \phi_{H, \text{cap}}(t)[E_F - H(t)] = 0, \end{aligned} \quad (\text{A.30})$$

$$[S]: \frac{\dot{\mu}_S(t)}{\mu_S(t)} + \kappa \frac{\phi_{F, \text{cap}}(t)}{\mu_S(t)} = r, \quad (\text{A.31})$$

$$[U]: \frac{\dot{\mu}_U(t)}{\mu_U(t)} - \frac{\partial C_X(X(t), U(t)) / \partial U(t)}{\mu_U(t)} = r, \quad (\text{A.32})$$

$$[\text{TVC } S]: \lim_{t \rightarrow \infty} \mu_S(t) S(t) e^{-rt} = 0, \quad (\text{A.33})$$

$$[\text{TVC } U]: \lim_{t \rightarrow \infty} \mu_U(t) U(t) e^{-rt} = 0, \quad (\text{A.34})$$

where akin to $c_X(X(t), U(t))$, $c_H(h(t))$ is the marginal cost of CCS $H(t)$, which by (16) is equal to $c_H(h(t)) = \zeta + f(h(t)) + (\partial f(h(t)) / \partial h(t))h(t)$.

The fossil firm's tradeoff in extraction is now characterized by (A.28). Including CCS adds two terms. First, $-\partial C_H(H(t), E_F(t)) / \partial E_F(t)$ captures the benefit of increasing fossil energy use through reducing the cost of achieving a given level of CCS. This is due to the fact that with higher energy use, the CCS intensity is reduced. Second, $\phi_{H, \text{cap}}(t)$ is the shadow value of the constraint on the maximal CCS level: higher fossil energy use allows for higher levels of CCS when this constraint is binding.

In addition, the fossil energy firm now decides the level of CCS to use. The level is implicitly given by (A.30), with $\phi_{H,0}(t) = 0$ if $H(t) > 0$ and $\phi_{H, \text{cap}}(t) = 0$ if $H(t) < E_F(t)$. This condition states that the firm will equalize the marginal cost of CCS with its marginal benefit: the tax savings due to reduces emissions. Whenever the fossil fuel tax falls short of the marginal cost of emissions, CCS will be zero, and $\phi_{H,0}(t) > 0$. Similarly, if the fossil fuel tax exceeds the marginal cost of CCS at 100% CCS ($H(t) = E_F(t)$), $\phi_{H, \text{cap}}(t) > 0$.

A.5. Optimal allocation under a carbon budget with CCS

To determine the optimal allocation under a carbon budget we maximize $\int_t^{\infty} \left[\int_0^{E(t)} (P(e) - p_E(t)) de + \pi_F(t) + \pi_R(t) + \Omega(t) \right] e^{-r(\nu-t)} d\nu$ subject to (1)–(7), (16) and (17), and non-negativity constraints on extraction, development, CCS, undeveloped resources and remaining budget, $X(t), E_F(t), U(t), B(t) \geq 0$ and $H(t) \in [0, E_F(t)] \forall t$. This gives the following Hamiltonian with first order, complementary slackness and transversality conditions:

$$\begin{aligned}
\mathcal{H} = & \int_0^{E(t)} (P(e) - p_E(t))de + p_E E_F(t) - c_F E_F(t) - C_X(X(t), U(t)) + p_E E_R(t) \\
& - c_R E_R(t) - C_I(I(t)) - C_H(H(t), E_F(t)) + \lambda_E^P(t)[E_F(t) + E_R(t) - E(t)] \\
& + \mu_S^P(t)[-E_F(t) + X(t)] + \phi_{F, \text{cap}}^P(t)[\kappa S(t) - E_F(t)] + \phi_{F,0}^P(t)[E_F(t)] \\
& + \phi_{X,0}^P(t)[X(t)] + \phi_{H,0}^P(t)[H(t)] + \phi_{H, \text{cap}}^P(t)[E_F - H(t)] + \mu_U^P(t)[-X(t)] \\
& + \mu_K^P(t)[I(t) - \delta K(t)] + \phi_{R, \text{cap}}^P(t)[K(t) - E_R(t)] + \phi_{R,0}^P(t)[E_R(t)] \\
& + \phi_{I,0}^P(t)[I(t)] + \mu_B^P(t)[H(t) - E_F(t)],
\end{aligned} \tag{A.35}$$

$$\begin{aligned}
[E]: \quad & P(E(t)) - p_E(t) = \lambda_E^P(t); \\
& \lambda_E^P(t)[E_F(t) + E_R(t) - E(t)] = 0,
\end{aligned} \tag{A.36}$$

$$\begin{aligned}
[E_F]: \quad & p_E(t) - c_F - \frac{\partial C_H(H(t), E_F(t))}{\partial E_F(t)} + \phi_{H, \text{cap}}^P(t) + \lambda_E^P(t) - \mu_B^P(t) \\
= & \mu_S^P(t) + [\phi_{F, \text{cap}}^P(t) - \phi_{F,0}^P(t)]; \\
& \phi_{F, \text{cap}}^P(t)[\kappa S(t) - E_F(t)] = 0; \quad \phi_{F,0}^P(t)E_F(t) = 0,
\end{aligned} \tag{A.37}$$

$$\begin{aligned}
[H]: \quad & \mu_B^P(t) + \phi_{H,0}^P(t) = c_H(h(t)); \\
& \phi_{H,0}^P(t)H(t) = 0; \quad \phi_{H, \text{cap}}^P(t)[E_F - H(t)] = 0,
\end{aligned} \tag{A.38}$$

$$\begin{aligned}
[X]: \quad & \mu_S^P(t) = c_X(X(t), U(t)) + \mu_U^P(t) - \phi_{X,0}^P(t); \\
& \phi_{X,0}^P(t)X(t) = 0,
\end{aligned} \tag{A.39}$$

$$\begin{aligned}
[E_R]: \quad & p_E(t) - c_R + \lambda_E^P(t) = [\phi_{R, \text{cap}}^P(t) - \phi_{R,0}^P(t)]; \\
& \phi_{R, \text{cap}}^P(t)[K(t) - E_R(t)] = 0; \quad \phi_{R,0}^P(t)E_R(t) = 0,
\end{aligned} \tag{A.40}$$

$$[I]: \mu_K^P(t) = c_I(I(t)) - \phi_{I,0}^P(t); \quad \phi_{I,0}^P(t)I(t) = 0, \tag{A.41}$$

$$[S]: \frac{\dot{\mu}_S^P(t)}{\mu_S^P(t)} + \kappa \frac{\phi_{F, \text{cap}}^P(t)}{\mu_S^P(t)} = r, \tag{A.42}$$

$$[K]: \frac{\dot{\mu}_K^P(t)}{\mu_K^P(t)} - \delta + \frac{\phi_{R, \text{cap}}^P(t)}{\mu_K^P(t)} = r, \tag{A.43}$$

$$[U]: \frac{\dot{\mu}_U^P(t)}{\mu_U^P(t)} - \frac{\partial C_X(X(t), U(t)) / \partial U(t)}{\mu_U^P(t)} = r, \tag{A.44}$$

$$[B]: \frac{\dot{\mu}_B^P(t)}{\mu_B^P(t)} = r, \tag{A.45}$$

$$[\text{TVC } S]: \lim_{t \rightarrow \infty} \mu_S^P(t)S(t)e^{-rt} = 0, \tag{A.46}$$

$$[\text{TVC } U]: \lim_{t \rightarrow \infty} \mu_U^P(t)U(t)e^{-rt} = 0, \tag{A.47}$$

$$[\text{TVC } K]: \lim_{t \rightarrow \infty} \mu_K^P(t)K(t)e^{-rt} = 0, \tag{A.48}$$

$$[\text{TVC } B]: \lim_{t \rightarrow \infty} \mu_B^P(t)B(t)e^{-rt} = 0. \tag{A.49}$$

Following the same steps as the Proof to [Lemma 1](#), one can straightforwardly establish that [Lemma 1](#) continues to apply when allowing for CCS: the optimal implementation of a binding carbon budget involves setting a positive fossil fuel tax that is increasing at the rate of interest. From here, [Proposition 4](#) follows. Note that use of CCS will allow for greater levels of fossil energy use for a given level of the budget. As a consequence, the shadow value of the budget and hence the optimal tax level will be affected: our numerical assessment reveals a reduction in optimal tax levels by about 5% when including CCS.

B. Proofs

B.1. Main proofs

B.1.1. Proof to proposition 1

In equilibrium, $P(E(t)) = p_E(t)$, with $p_E^{ss} = \lim_{t \rightarrow \infty} p_E(t) = P(E^{ss})$ and $P(E^{ss})$ given by (14). From (A.2) this implies that we can write

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

where by (10), $\mu_S(t) \geq 0 \forall t$, 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 $P(E^{ss}) - \lim_{t \rightarrow \infty} \tau(t) > c_F$. Then (B.1) can only be satisfied if $\lim_{t \rightarrow \infty} \phi_{F, cap}(t) > 0$. 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 $P(E^{ss}) - \lim_{t \rightarrow \infty} \tau(t) < c_F$, which by (B.1) implies $\lim_{t \rightarrow \infty} \phi_{F, 0}(t) > 0$. As $\phi_{F, cap}(t)$ and $\phi_{F, 0}(t)$ cannot simultaneously be strictly positive, this gives $\lim_{t \rightarrow \infty} \phi_{F, cap}(t) = \phi_{F, cap}^{ss} = 0$ and $\lim_{t \rightarrow \infty} \mu_S(t) = \mu_S^{ss} = 0$. 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 $S_0 > 0$, $S^{ss} = \lim_{t \rightarrow \infty} S(t) = 0$ 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 $K(\nu) < K'(\nu)$. \square

Lemma B.2. There exists a finite t such that for all $\nu \geq t$, 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

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

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 (13), $p_E(\nu) > c_R + c_I(\delta E^{ss})$ is inconsistent with $\mu_K(\nu) < c_I(\delta E^{ss})$. Hence, we must have that $\dot{K}(\nu) > 0$. \square

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 $S^{ss} = \lim_{t \rightarrow \infty} S(t) = 0$ cannot hold. \square

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 optimal allocation under a carbon budget and the 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 $\lim_{t \rightarrow \infty} B(t) = 0$. \square .

B.1.3. Proof to Proposition 3

Proof. Following the Proof to Proposition 1 (see Appendix B.1.1), developed fossil reserves will be abandoned in the long run if $\lim_{t \rightarrow \infty} p_E(t) - c_F - \lim_{t \rightarrow \infty} Q(t) < 0$ with

$$Q(t) \equiv c_H(h(t)) + [\zeta + f(h(t)) - c_H(h(t))]h(t) - \phi_{H, 0}(t),$$

and $c_H(h(t))$ again defined as the marginal cost of CCS $H(t)$. By (16), this term is equal to $c_H(h(t)) = \zeta + f(h(t)) + f'(h(t))h(t)$, where for convenience we adopt the notation $f'(h(t)) \equiv \partial f(h(t))/\partial h(t)$. Conversely, all developed reserves will be extracted in the long run if $\lim_{t \rightarrow \infty} p_E(t) - c_F - \lim_{t \rightarrow \infty} Q(t) > 0$.

Suppose first that $P(E^{ss}) - c_F < 0$. Then abandonment occurs unless $\lim_{t \rightarrow \infty} Q(t)$ sufficiently negative. As $h(t) \leq 1$, this requires $\phi_{H, 0}(t) > 0$. Yet, $\phi_{H, 0}(t) > 0$ implies $h(t) = 0$, which gives $Q(t) = c_H(h(t)) - \phi_{H, 0}(t)$. From (A.30), we then obtain $c_H(h(t)) - \phi_{H, 0}(t) = \tau(t)$ and thus $Q(t) = \tau(t) \geq 0$. Hence, if $P(E^{ss}) - c_F < 0$, abandonment occurs for any $\tau(t) \geq 0$.

Suppose next $P(E^{ss}) - c_F \geq 0$. Then abandonment requires $\lim_{t \rightarrow \infty} Q(t)$ sufficiently positive. First suppose $\tau(t) \leq \zeta$ for all t . Then by (A.30), $h(t) = 0$ and $c_H(h(t)) - \phi_{H, 0}(t) = \tau(t)$ for all t . This gives $Q(t) = \tau(t)$ for all t and Proposition 1 applies. If instead, $\tau(t) > \zeta$ for some t , and $\tau(t) < \zeta + f(1) + f'(1)$ for all t . Then by (A.30), $\lim_{t \rightarrow \infty} h(t) \in (0, 1)$. Then we can use (A.30) to write $Q(t) = \tau(t) + [\zeta + f$

$(h(t) - \tau(t))h(t)$ with $h(t)$ is implicitly determined by $\tau(t)$: there exists some function $j(\tau(t))$ such that $h(t) = j(\tau(t))$. For this function, we know $j(\varsigma) = 0$. Hence $Q(t) = \varsigma$ if $\tau(t) = \varsigma$. Next, $\frac{dQ(t)}{d\tau(t)} = \frac{\partial Q(t)}{\partial \tau(t)} + \frac{\partial Q(t)}{\partial h(t)} \frac{\partial h(t)}{\partial \tau(t)} = 1 - h(t)$, which is strictly positive for $h(t) < 1$. Finally, for $\tau(t) = \varsigma + f(1) + f'(1)$, $h(t) = 1$ and $Q(t) = \varsigma + f(1)$. Hence, for $\lim_{t \rightarrow \infty} \tau(t) \in (\varsigma, \varsigma + f(1) + f'(1))$, $\lim_{t \rightarrow \infty} Q(t) \in (\varsigma, \varsigma + f(1))$ and strictly increasing in $\lim_{t \rightarrow \infty} \tau(t)$. The proposition then follows from the fact that $\tau(t)$ is non-decreasing over time.

Finally, observe that if $\lim_{t \rightarrow \infty} \tau(t) \geq \varsigma + f(1) + f'(1)$, by (A.30), $\lim_{t \rightarrow \infty} h(t) = 1$. We then obtain $\lim_{t \rightarrow \infty} Q(t) = \varsigma + f(1)$. Hence, with CCS, $Q(t)$ is at most $\varsigma + f(1)$; if $P(E^{ss}) - c_F > \varsigma + f(1)$, no abandonment occurs. \square .

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 $E_R(t) < K(t)$. \square .

B.2.2. Global stability of the long run equilibrium

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

$$p_E^{ss} = c_R + (r + \delta) \lim_{t \rightarrow \infty} c_I(I(t)) - (r + \delta) \lim_{t \rightarrow \infty} \phi_{I,0}(t) - \lim_{t \rightarrow \infty} \phi_{R,0}(t), \quad (\text{B.2})$$

where $p_E^{ss} = \lim_{t \rightarrow \infty} p_E(t)$ and by $E_R(t) = K(t)$, $\lim_{t \rightarrow \infty} I(t) = \delta \lim_{t \rightarrow \infty} K(t) = \delta E_R^{ss}$. In equilibrium, $P(E(t)) = p_E(t)$ and thus $P(E^{ss}) = p_E^{ss}$. As $\lim_{E \rightarrow 0} P(E) > c_R$ and $E^{ss} = E_R^{ss} = K^{ss}$, we must obtain $\lim_{t \rightarrow \infty} \phi_{R,0}(t) = 0$ 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 $\lim_{t \rightarrow \infty} \phi_{I,0}(t) = 0$. With (B.2), this gives (14).

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 (13), $p_E(\nu) \leq p_E^{ss}$ 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 $t > 0$. \square .

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 (13) 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 $\lim_{t \rightarrow \infty} K(t) = E^{ss}$.
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 $\lim_{t \rightarrow \infty} Z(t) = \bar{Z} \geq 0$ and thus $\lim_{t \rightarrow \infty} E_F(t) = 0$, and $E^{ss} = E_R^{ss}$. From Lemma B.3, $\lim_{t \rightarrow \infty} p_E(t) \geq p_E^{ss}$. From (A.9), and $c_R < p_E^{ss}$, $\lim_{t \rightarrow \infty} \phi_{R, cap}(t) > 0$ and from (13), $\lim_{t \rightarrow \infty} \mu_K(t) \geq \mu_K^{ss}$. By (A.10) and (7), $\lim_{t \rightarrow \infty} I(t) \geq I^{ss}$ and $\lim_{t \rightarrow \infty} K(t) \geq K^{ss}$. By $K^{ss} = E_R^{ss}$ and Lemma B.3 we must then obtain $\lim_{t \rightarrow \infty} K(t) = E^{ss}$. \square .

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 $U^{ss} > 0$, $\lim_{t \rightarrow \infty} \mu_U(t) = 0$. Next, we establish that $\lim_{t \rightarrow \infty} \mu_U(t) = 0$ if $z_F \geq \lim_{t \rightarrow \infty} [p(t) - \tau(t)]$, where we define $z_F \equiv c_F + (r + \kappa) \frac{c_X(0,0)}{\kappa}$. The observation that $\dot{z}(t) \geq 0$ then completes the proof.

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

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

$$\lim_{T \rightarrow \infty} \mu_U e^{-rT} = \mu_U(t) e^{-rt} + \int_t^\infty \frac{\partial C_X(X(v), U(v))}{\partial U(v)} e^{-rv} dv.$$

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

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

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

$$\mu_U(t) = - \int_t^\infty \frac{\partial C_X(X(v), U(v))}{\partial U(v)} e^{-r(v-t)} dv. \quad (\text{B.3})$$

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

From (A.3) we can write

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

where we use $\lim_{t \rightarrow \infty} X(t) = X^{ss} = 0$. From (10) we obtain $\lim_{t \rightarrow \infty} \mu_S(t) = \frac{\kappa}{r} \lim_{t \rightarrow \infty} \phi_{F,cap}(t)$. With (A.2), this allows us to write

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

where by $\partial C_X(\cdot)/\partial U(t) \leq 0$, $c_X(0, 0) - \lim_{t \rightarrow \infty} c_X(0, U(t)) \geq 0$. From (14), $\lim_{t \rightarrow \infty} p_E(t) = P(E^{ss})$. From here it directly follows that whenever $P(E^{ss}) - \lim_{t \rightarrow \infty} \tau(t) > z_F$, we must obtain $\lim_{t \rightarrow \infty} \mu_U(t) > 0$. Then, by Lemma B.4, $\lim_{t \rightarrow \infty} U(t) = 0$. In turn, Lemma B.4 states that a solution with $\lim_{t \rightarrow \infty} U(t) > 0$ requires $\lim_{t \rightarrow \infty} \mu_U(t) = 0$, which according to (B.4) requires $P(E^{ss}) - \lim_{t \rightarrow \infty} \tau(t) \leq z_F$. As $\tau(t)$ is weakly increasing over time, this condition is satisfied whenever $P(E^{ss}) - \tau(t) \leq z_F$ for some t . \square .

C. Quantitative analysis; further details

C.1. Calibration

C.1.1. Development cost function

To calibrate the development cost function we use the 2010 distribution of oil and gas resources as presented in Figure 1 in McGlade and Ekins (2015). 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 Fig. C.1, where cumulative resource development is equivalent to $U_0 - U(t)$.

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 development cost: $c^{total} = c_F + c_X$.⁴⁰ From (19), marginal development costs $c_X(\cdot)$ are a function not only of undeveloped stock $U(t)$, but also the development level $X(t)$. For our calibration we fix $X(t)$ to the 2017 extraction level of 55.4.⁴¹ We then obtain estimates for the parameters θ , ω and ρ by minimizing the squared deviation between c^{total} and the black curve in Fig. C.1 from the minimum cost of \$13.2 to \$150; in McGlade and Ekins (2015) this covers almost 99% of undeveloped resources.

⁴⁰ The oil and gas resources in McGlade and Ekins (2015) include resources labeled as undiscovered. As these resources are considered realistically available for extraction in the next few decades, we retain those resources, and attribute any cost associated to exploration to resource development instead. Further analysis reveals that the share of undiscovered resources in cumulative development is about 10% on average across the budget scenarios.

⁴¹ This implies that our calibration depicts development cost as a function of cumulative development, under the assumption that development is such that oil and gas extraction can be held constant at 2017 extraction levels. Though we have no data on actual development in 2010, we believe this value to be in line with actual 2010 development 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 to 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 development X_{2010} equal to 54.8.

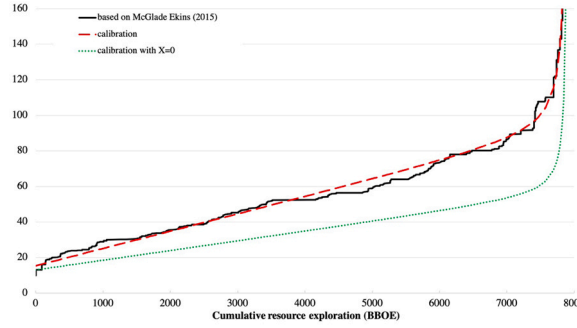


Fig. C.1. Total resource cost (\$/BOE) and cumulative resource development.

Table C.1

Baseline parameter values and initial conditions.

Initial condition	Value	Parameter	Value	Parameter	Value	Parameter	Value
S_0	759	c_F	10	c_R	0	ς	40
U_0	7903	κ	0.073	ξ	609.4	ς_h	330
K_0	19.2	θ	2.8819	δ	0.045		
		ω	$9.094 \cdot 10^{-4}$	ε	0.6		
		ρ	$5.191 \cdot 10^{-3}$	χ	71976		
		ψ	0.0512	r	0.04		

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 Fig. C.1 depicts the resulting fit, parameter values are reported in Table C.1.

Our specification (19) implies marginal development costs $c_X(\cdot)$ increase in the level of contemporaneous development $X(t)$. In anticipation a fossil energy phaseout, development rates likely decline. To illustrate the sensitivity of our calibrated fossil costs to such lower development rates we additionally map the minimal c^{total} by setting $X(t) = 0$. The resulting relationship between resource costs and cumulative resource development is depicted by the green curve in Fig. C.1. As can be observed from this curve, following a trajectory with development levels close to the minimum level, would reduce resource cost by approximately up to a third.

C.1.2. Carbon capture and storage

We parameterize (16) based on Johnsson et al. (2020) and IEA (2021a), who estimate convex marginal carbon capture and storage costs from about 40 USD/tCO₂ to 150 USD/tCO₂ depending on industrial process. The applications of CCS are electricity generation and industry, which account for about 64% of global emission, with maximal capture rates of 90% in these industries (Jacobsen, 2020a; Johnsson et al., 2020; IEA, 2021a). Based on this, we adopt $f(h(t)) = 0.5\varsigma_h h(t)^2$, which gives the marginal cost of CCS

$$c_H(h(t)) = \varsigma + \varsigma_h h(t)^2, \quad (C.1)$$

with $\varsigma = 40$ and $\varsigma_h = 330$. To account for the fact that current CCS capacity is low, we assume that CCS only becomes available after 2027.

C.1.3. Overview of baseline parameter values

Table C.1.

C.2. Solution algorithm

To numerically solve our model, we proceed as follows. We create an equally-spaced grid of the time horizon T . We solve the baseline calibration and individual sensitivity analysis (Section 6.2) over 750 years, with quarterly intervals, which gives a grid of length $\Lambda = 3000$. For the 2×486 sensitivity analyses in Tables C.2 and C.3 we use annual intervals. 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 $p_E^{\text{in}} = \{p_{E,0}, p_{E,1}, \dots, p_{E,\Lambda-1}\}$ and development levels $X^{\text{in}} = \{X_0, X_1, \dots, X_{\Lambda-1}\}$, and steady state $U^{\text{ss},\text{in}} = U_\Lambda$.

Table C.2

Sensitivity analysis; summary statistics for main variables.

Variable	Target	Mean	Min	25th pct	Median	75th pct	Max
Abandonment (share)	1.5°C	0.165	0.070	0.098	0.158	0.206	0.328
	2°C	0.093	0.023	0.060	0.095	0.120	0.172
Excessive development (share)	1.5°C	0.527	0.055	0.209	0.520	1	1
	2°C	0.054	0.005	0.021	0.042	0.082	0.171

This table reports results for 2×486 parameter combinations. The share of abandonment is defined as $\lim_{t \rightarrow \infty} S(t)/S_0$. The share of excessive development is reported for the remaining scenarios, and equal to 1 if $B(0) \leq S_0$, and $1 - (B(0) - S_0)/\int_0^\infty X(t)dt$ otherwise.

Table C.3

Sensitivity analysis of individual variables.

Parameter	Fixed value	Abandonment (share), median		Excessive development (share), median		Positive development (share)	
		1.5°C	2°C	1.5°C	2°C	1.5°C	2°C
ϵ , elasticity energy of demand	0.4	0.158	0.097	0.519	0.041	0.901	1
	0.6	0.159	0.092	0.520	0.042	0.914	1
	0.059	0.221	0.132	1	0.083	0.722	1
κ , maximum extraction rate	0.073	0.158	0.100	0.527	0.047	1	1
	0.113	0.086	0.054	0.103	0.014	1	1
	318.5	0.190	0.077	0.562	0.037	0.944	1
ξ , investment cost parameter	609.4	0.161	0.100	0.527	0.047	0.889	1
	965.6	0.141	0.105	0.494	0.050	0.889	1
	2.1614	0.165	0.09	0.532	0.044	0.926	1
θ , marginal development cost parameter	2.8819	0.159	0.094	0.525	0.042	0.907	1
	3.6024	0.153	0.091	0.517	0.038	0.889	1
	0.0384	0.159	0.097	0.520	0.044	0.907	1
ψ , marginal development cost curvature parameter	0.0512	0.158	0.094	0.520	0.041	0.907	1
	0.0640	0.156	0.091	0.518	0.038	0.907	1

This table reports results for 2×486 parameter combinations. Each row fixes one parameter value. The share of abandonment is defined as $\lim_{t \rightarrow \infty} S(t)/S_0$. The share of excessive development is reported for the remaining scenarios, and equal to 1 if $B(0) \leq S_0$, and $1 - (B(0) - S_0)/\int_0^\infty X(t)dt$ otherwise.

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, development levels and U^{ss} to backward-induce all shadow values. This gives a series of $\mu_S^{out} = \{\mu_{S,0}, \mu_{S,2}, \dots, \mu_{S,\Lambda-1}\}$, $\mu_R^{out} = \{\mu_{R,0}, \mu_{R,1}, \dots, \mu_{R,\Lambda-1}\}$, $\mu_U^{out} = \{\mu_{U,0}, \mu_{U,1}, \dots, \mu_{U,\Lambda-1}\}$.
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 development and investment levels, $X^{out} = \{X_0, X_1, \dots, X_{\Lambda-1}\}$ and $I^{out} = \{I_0, I_1, \dots, I_{\Lambda-1}\}$, prices $p_E^{out} = \{p_{E,0}, p_{E,1}, \dots, p_{E,\Lambda-1}\}$ and the steady state level of undeveloped stock $U^{ss,out} = U_\Lambda$.
5. Evaluate the deviation of p_E^{in} from p_E^{out} , X^{in} from X^{out} , and $U^{ss,in}$ from $U^{ss,out}$ against a threshold.
 - (a) If the series have not sufficiently converged: update p_E^{in} , X^{in} and $U^{ss,in}$ based on p_E^{out} , X^{out} and $U^{ss,out}$. 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. Further details and code are available in this link: [Code_REE_BijgaartRodriguez23.git](#)

C.3. Results

C.3.1. Carbon budget implementation with a delayed and unanticipated introduction of the carbon tax

Figure C.2.

C.3.2. Sensitivity analysis

Figures C.3, C.4, C.5, C.6, C.7 present the simulations for the sensitivity analysis as discussed in Section 6.2. In these figures, all but one parameter are fixed at their baseline levels, respectively, and we present estimates only for the central budget values. Finally, we combine all the sensitivity analyses across all budget values, resulting in $3 \times 2 \times 3^4 = 486$ model runs for both the 1.5°C and 2°C targets. Table C.2 presents key summary statistics for these model runs. Table C.3 summarizes results where we fix one parameter value at the time, allowing for a closer assessment of the sensitivity of our results to individual parameter values.

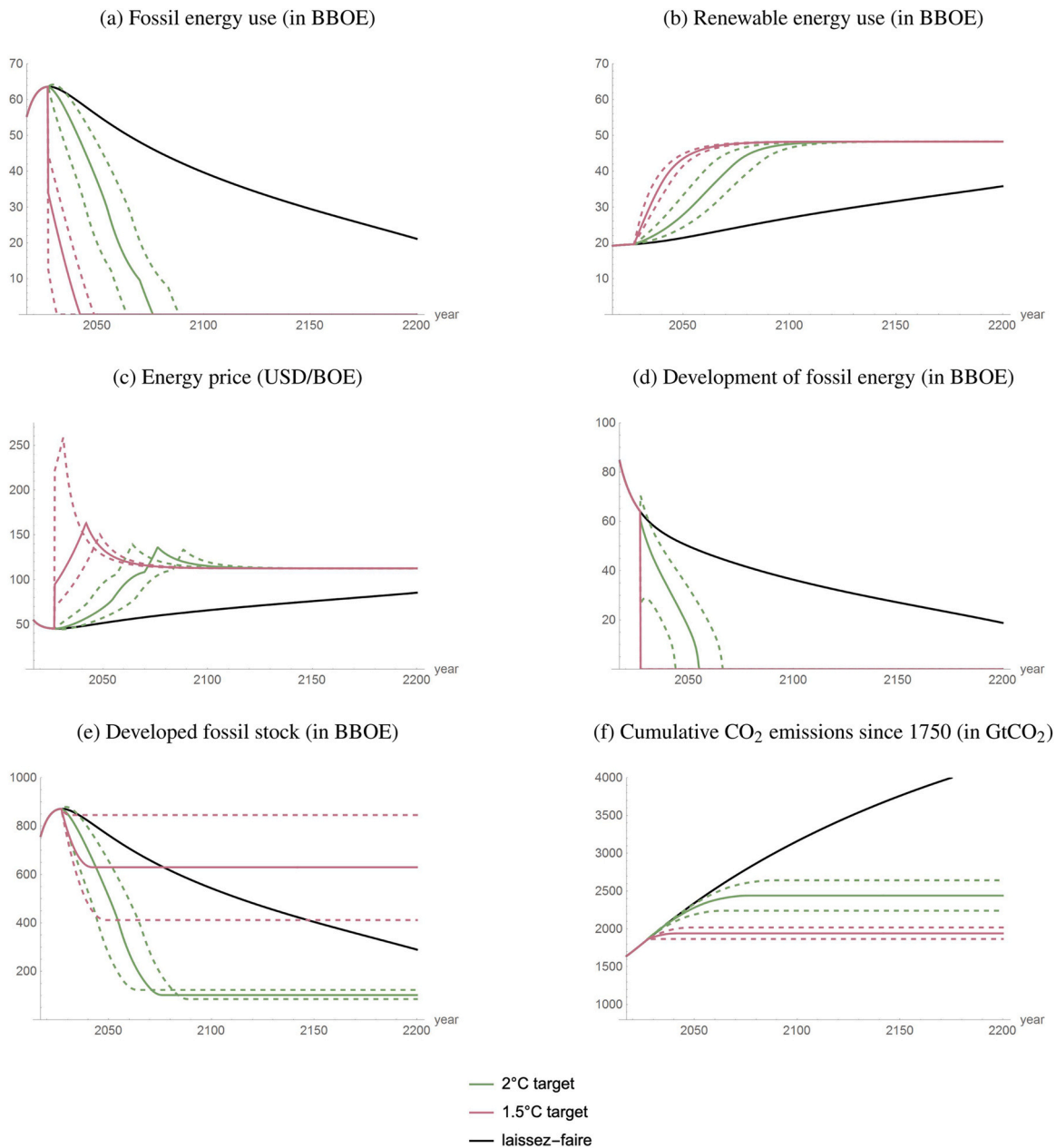


Fig. C.2. Results, carbon budget and laissez-faire - delayed and unanticipated policy. Solid (dashed) curves indicate paths for the central (alternative) estimates for the oil and gas budget. Emission taxes are zero from 2017 to 2026. 2027 emission taxes equal \$51 per tCO₂ for the central budget of the 2°C target (\$31 and \$85 for the upper and lower budget bound, resp.) and \$242 per tCO₂ for the central budget of the 1.5°C target (\$171 and \$605 for the upper and lower budget bound, resp.). Taxes subsequently increase at an annual rate of 4%.

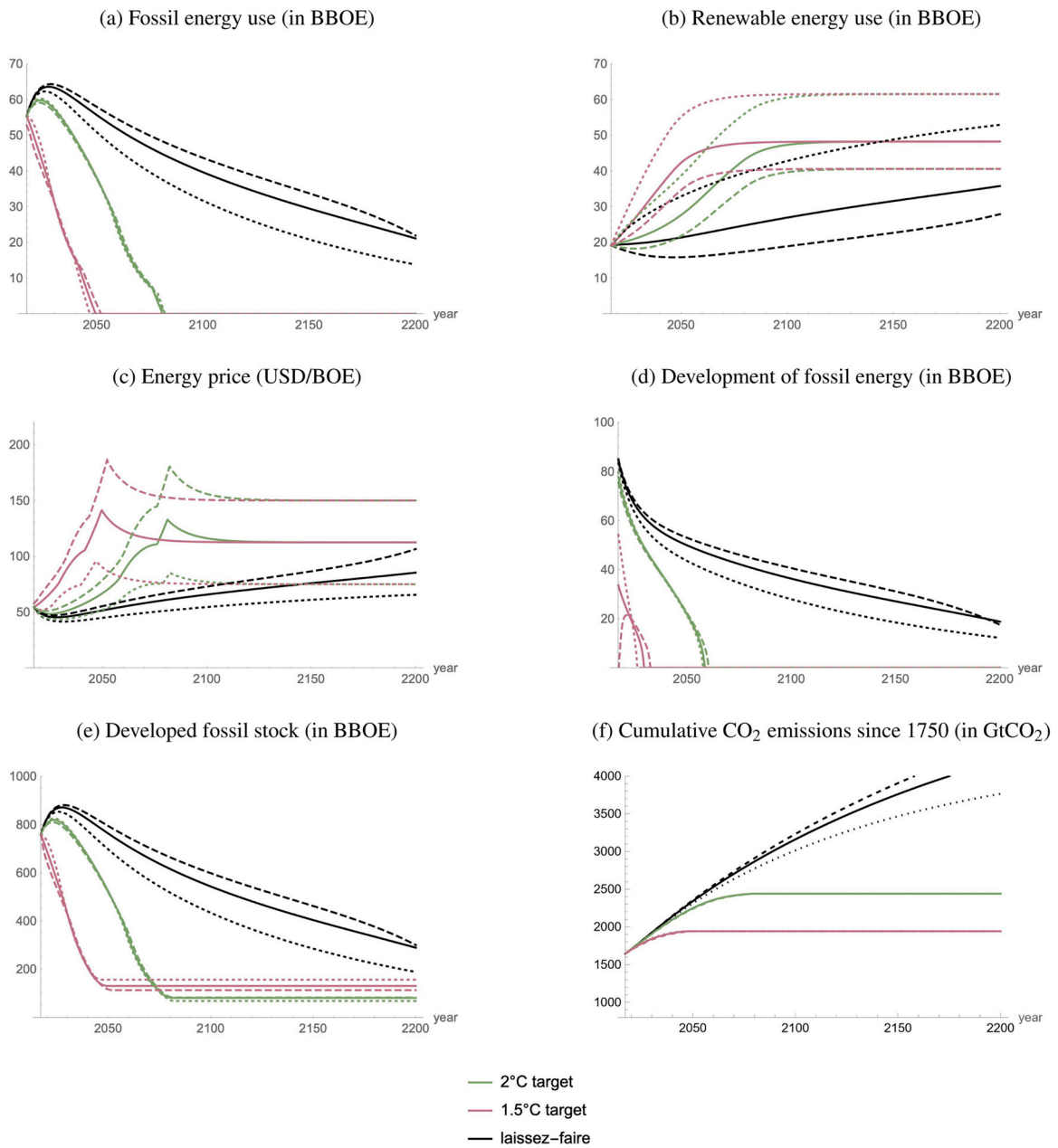


Fig. C.3. Sensitivity to renewable costs, ξ . Solid curves indicate paths for baseline calibration; dotted (dashed) curves indicate paths for long run renewable costs of \$75 (\$150). All trajectories are computed for the central budget estimates. For the 2°C target, 2017 emission taxes equal \$16, \$28 and \$39 per tCO₂ under low, baseline and high renewable costs, respectively. For the 1.5°C target, these values are \$75, \$104 and \$125 per tCO₂. Taxes subsequently increase at an annual rate of 4%.

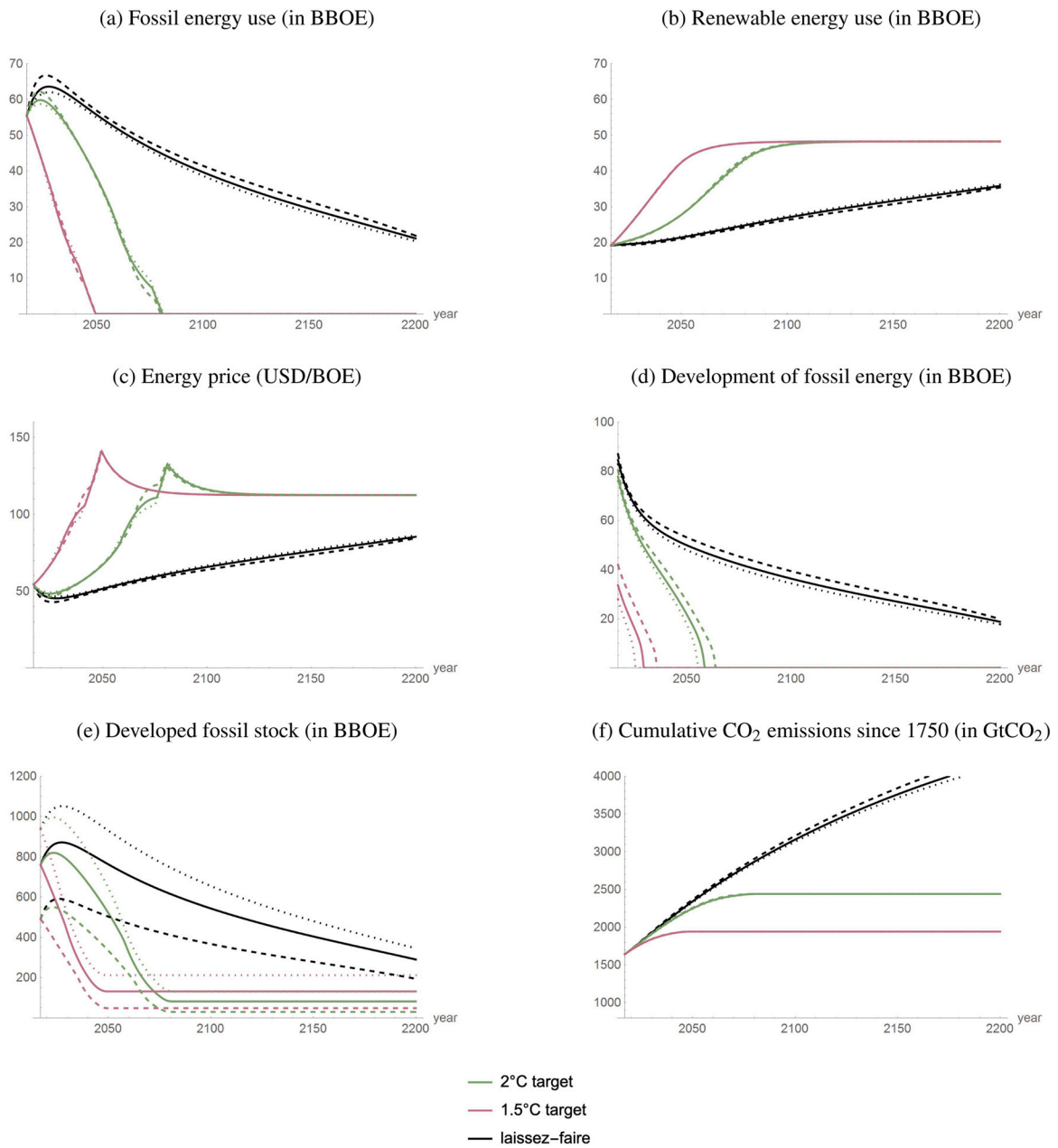


Fig. C.4. Sensitivity to maximum extraction rate, κ . Solid curves indicate paths for baseline calibration; dotted (dashed) curves indicate paths for maximum extraction rates of 5.9% (11.3%). All trajectories are computed for the central budget estimates. For the 2°C target, 2017 emission taxes equal \$27, \$28 and \$28 per tCO₂ under 5.9%, 7.3% and 11.3% maximum extraction rates, respectively. For the 1.5°C target, these values are \$104, \$104 and \$102 per tCO₂. Taxes subsequently increase at an annual rate of 4%.

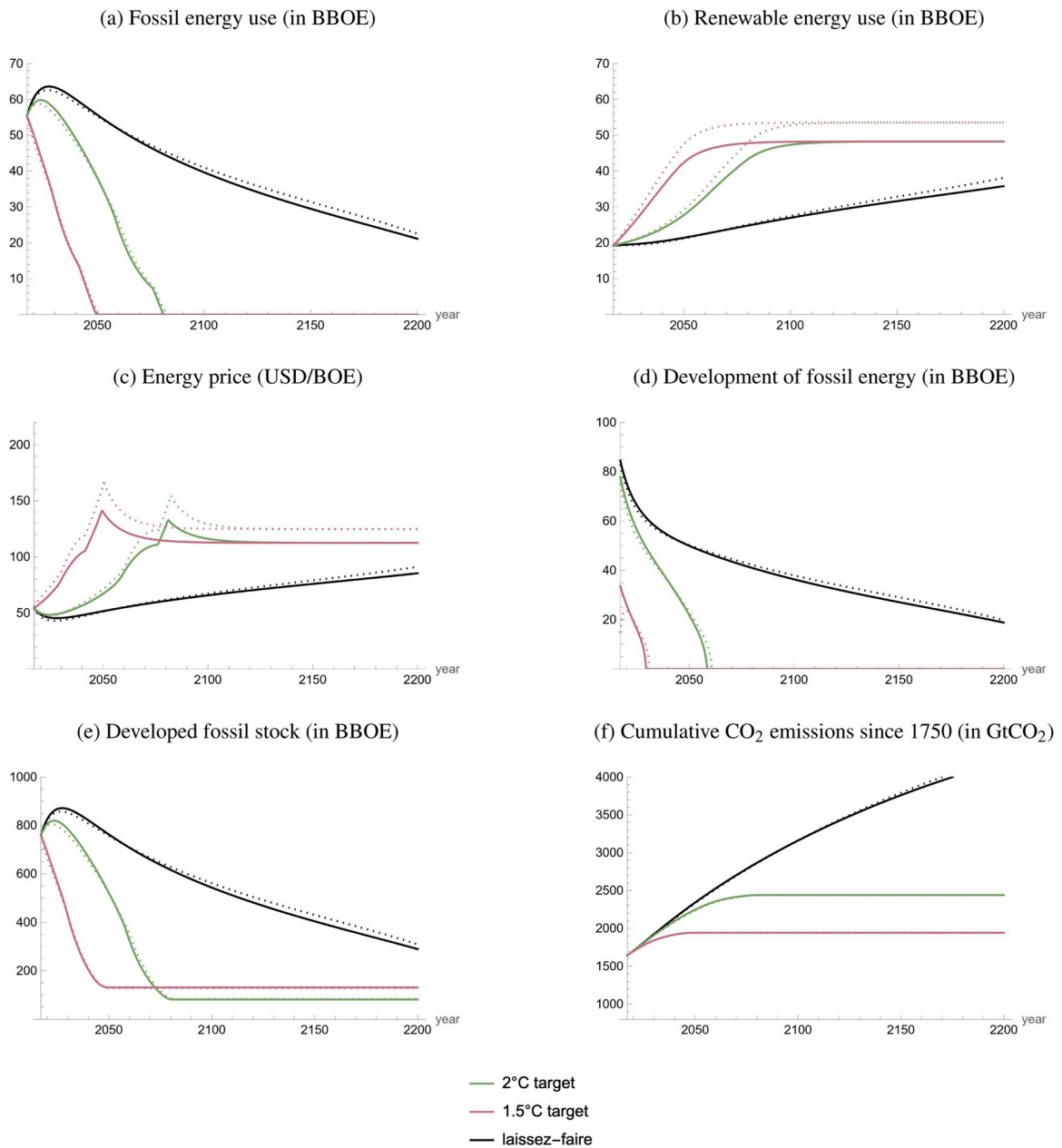


Fig. C.5. Sensitivity to elasticity of energy demand, ϵ . Solid curves indicate paths for baseline calibration; dotted curves indicate paths for absolute elasticity of energy demand $\epsilon = 0.4$. All trajectories are computed for the central budget estimates. For the 2°C target, 2017 emission taxes equal \$31 and \$28 per tCO₂ for $\epsilon = 0.4$ and $\epsilon = 0.6$, respectively. For the 1.5°C target, these values are \$118 and \$104 per tCO₂. Taxes subsequently increase at an annual rate of 4%.

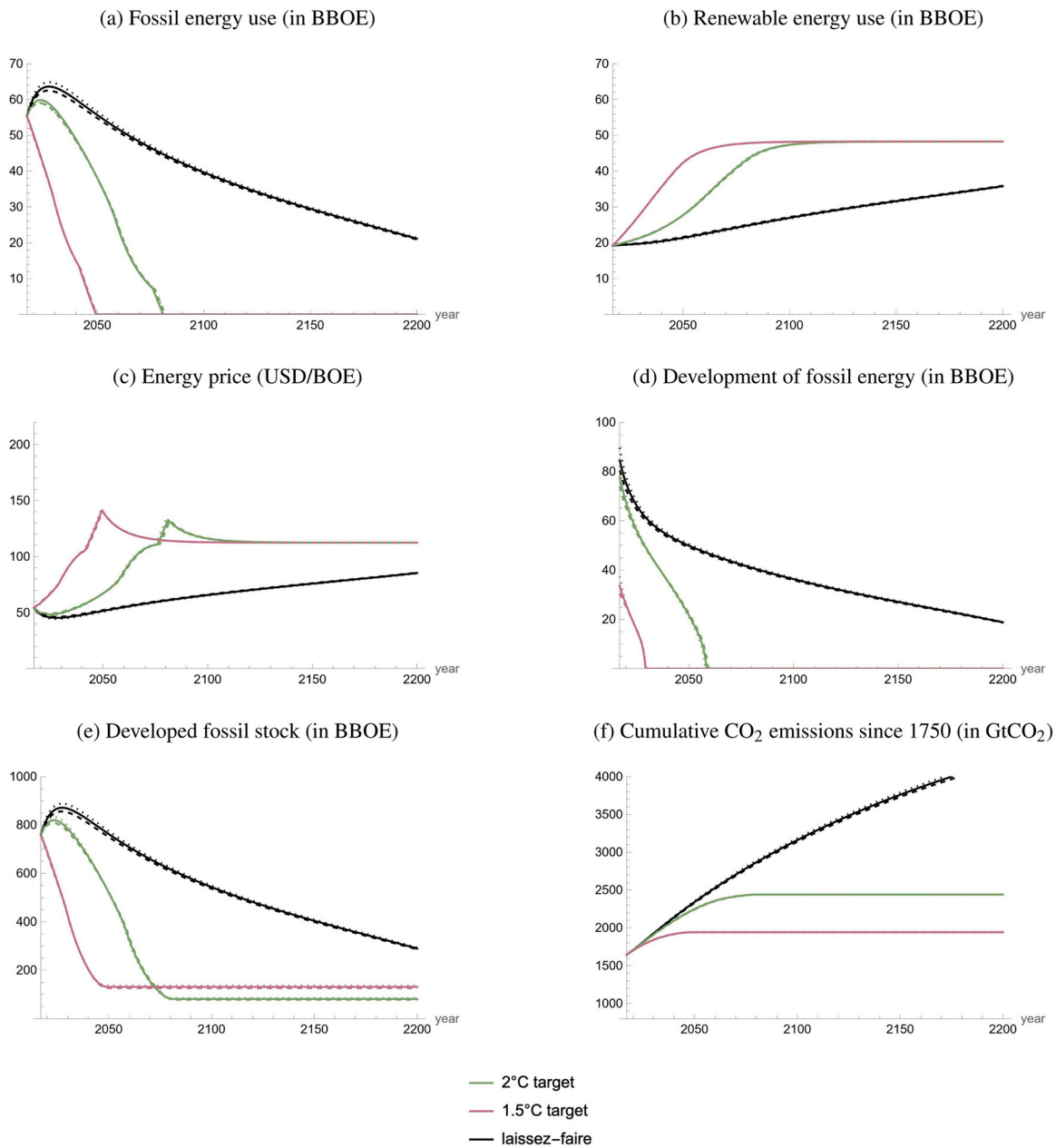


Fig. C.6. Sensitivity to marginal development cost, θ . Solid curves indicate paths for baseline calibration; dotted (dashed) curves indicate paths for $\theta = 2.1614$ ($\theta = 3.6024$). All trajectories are computed for the central budget estimates. For the 2°C target, 2017 emission taxes equal \$29, \$28 and \$26 per tCO₂ under $\theta = 2.1614$, $\theta = 2.8819$ and $\theta = 3.6024$, respectively. For the 1.5°C target, these values are \$105, \$104 and \$102 per tCO₂. Taxes subsequently increase at an annual rate of 4%.

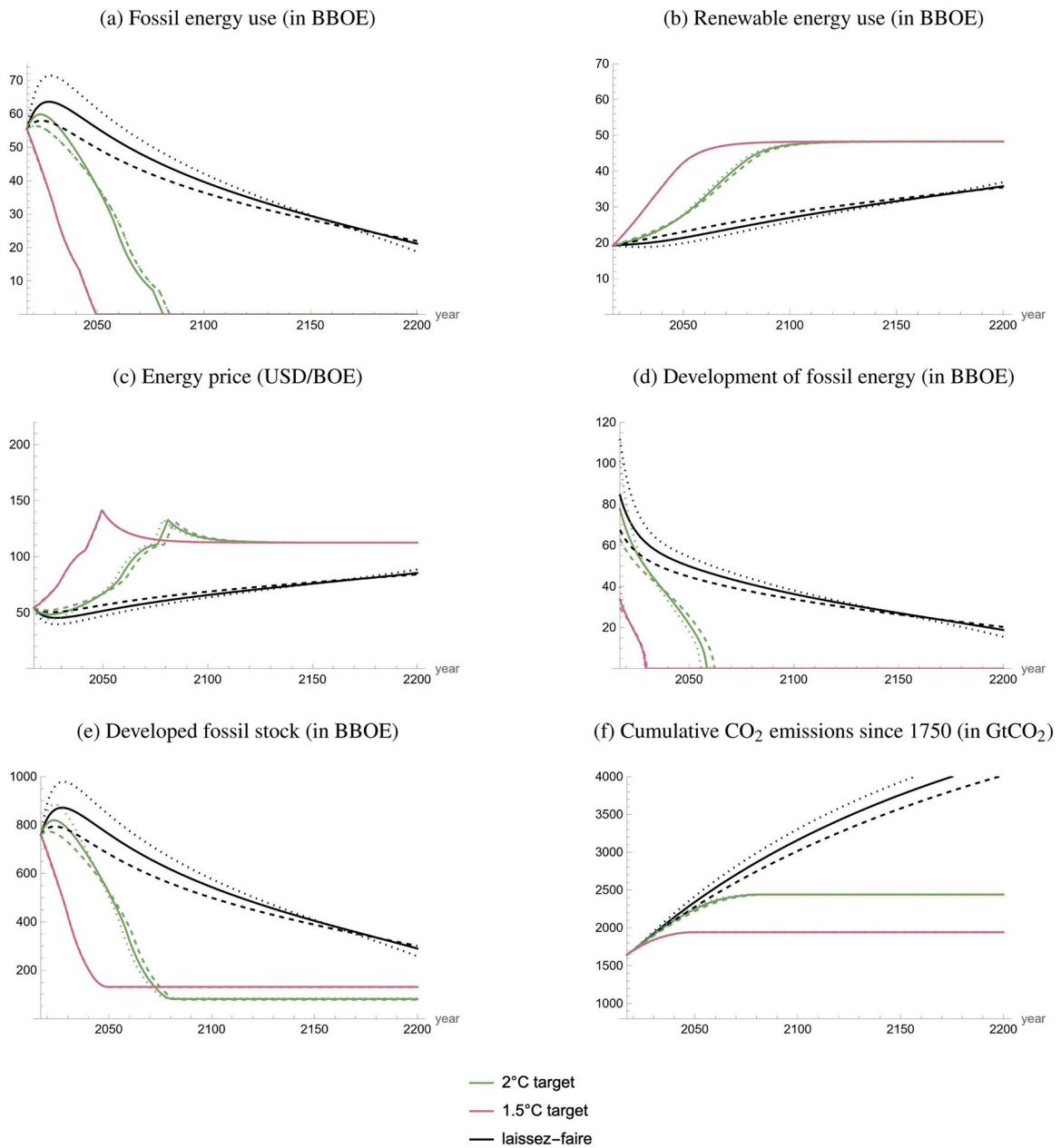


Fig. C.7. Sensitivity to marginal development cost curvature, ψ . Solid curves indicate paths for baseline calibration; dotted (dashed) curves indicate paths for $\psi = 0.0384$ ($\psi = 0.0640$). All trajectories are computed for the central budget estimates. For the 2°C target, 2017 emission taxes equal \$30, \$28 and \$24 per tCO₂ under $\psi = 0.0384$, $\psi = 0.0512$ and $\psi = 0.0640$, respectively. For the 1.5°C target, these values are \$104, \$104 and \$103 per tCO₂. Taxes subsequently increase at an annual rate of 4%.

C.3.3. Carbon capture and storage

Figures C.8, C.9.

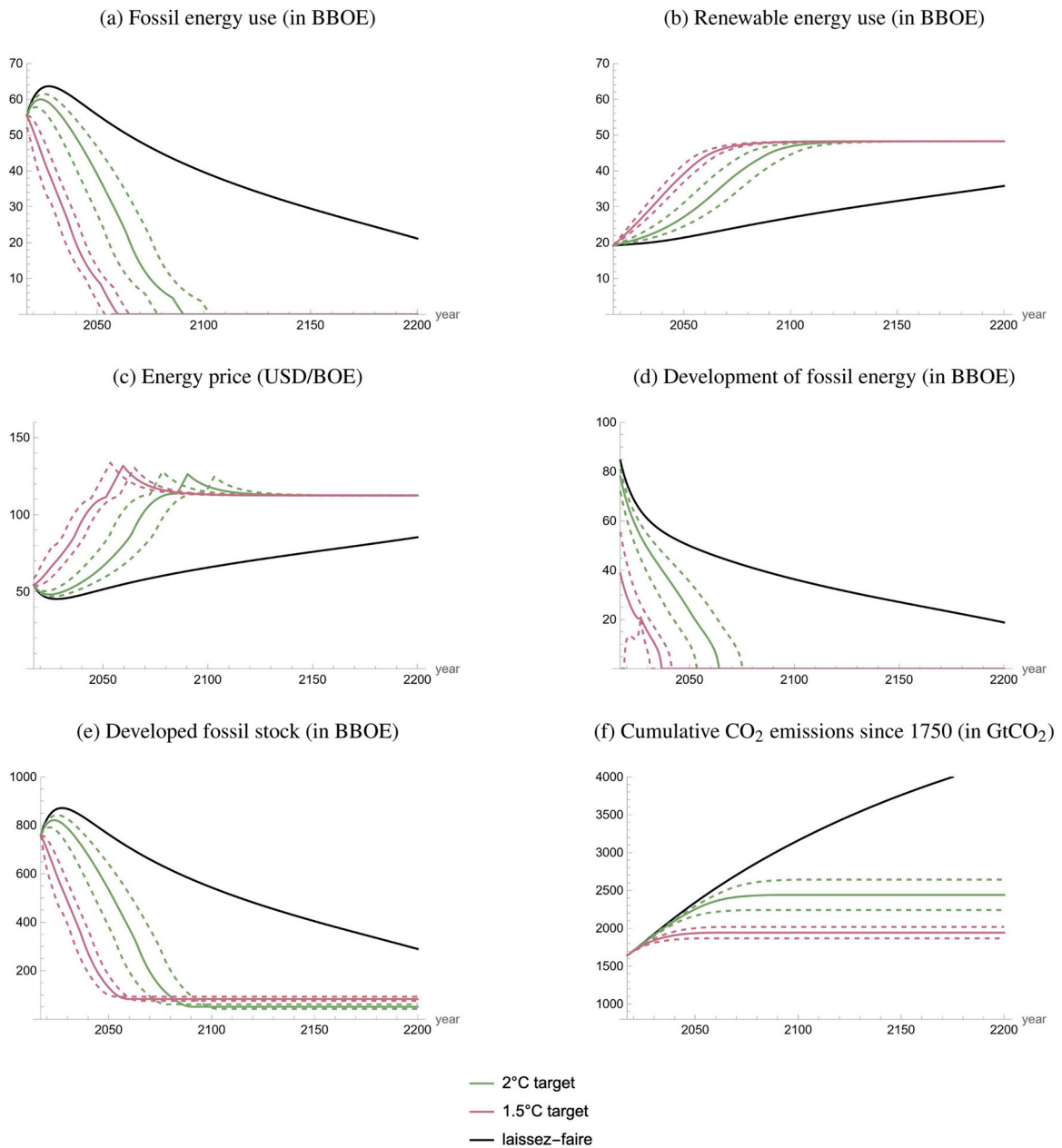


Fig. C.8. Results, carbon budget and laissez-faire - CCS. Solid (dashed) curves indicate paths for the central (alternative) estimates for the oil and gas budget. 2017 emission taxes equal \$27 for the central budget of the 2°C target (\$16 and \$44 for the upper and lower budget bound, resp.) and \$98 for the central budget of the 1.5°C target (\$78 and \$129 for the upper and lower budget bound, resp.). Taxes subsequently increase at an annual rate of 4%.

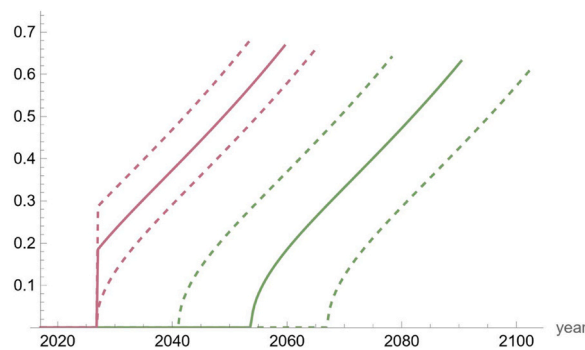


Fig. C.9. Share of emission captured. Solid (dashed) curves indicate paths for the central (alternative) estimates for the oil and gas budget. Shares are presented only for years with strictly positive fossil energy use.

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