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The Risk of Policy Tipping and Stranded Carbon Assets

Abstract

If global warming is to stay below 2°C, there are four risks of assets stranding. First, substantial fossil fuel reserves will be stranded at the end of the fossil era. Second, this will be true for exploration capital too. Third, unanticipated changes in present or expected future climate policy cause instantaneous discrete jumps in today's valuation of physical and natural capital. Fourth, if timing and intensity of climate policy are uncertain, revaluation of assets occurs as uncertainty about future climate policy is resolved. E.g. abandoning climate policy plans immediately boosts scarcity rent, market capitalization, exploration investment and discoveries. To explain and quantify these four effects, we use an analytical model of investment in exploration capital with intertemporal adjustment costs, depletion of reserves and market capitalization, and calibrate it to the global oil and gas industry. Climate policy implements a carbon budget commensurate with 2°C peak warming and we allow for different instruments: immediate or delayed carbon taxes and renewable subsidies. The social welfare ranking of these instruments is inverse to that of the oil and gas industry which prefers renewable subsidy and delaying taxes for as long as possible. We also pay attention to how the legislative "risk" of tipping into policy action affects the timing of the end of the fossil era, the profitability of existing capital, and green paradox effects.

JEL-Codes: D200, D530, D920, G110, H320, Q020, Q350, Q380, Q540.

Keywords: fossil fuel, exploration investment, discoveries, stranded carbon assets, stock prices, irreversible capital, adjustment costs, policy tipping, botched climate policies.

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"[*Investors] biggest fear is that oil demand growth is no longer a given in perpetuity, with some predicting that by the end of the next decade the industry could be facing a peak in consumption, as government policies try to curb the use of fossil fuels.*" (Financial Times, 26 October 2018)

1. Introduction

World leaders have agreed at the Paris International COP21 Conference on Climate Change to limit global warming to 2˚C with the goal of eventually lowering that further to 1.5˚C relative to pre-industrial temperatures. Even the 2˚C target only allows for a couple of hundred Giga-tons of carbon (GtC) of future emissions (the so-called carbon budget). But oil, gas, and coal reserves are about 3 or 4 (and for probable resources 10 to 11) times higher. McGlade and Ekins (2015) predict that one third of all oil reserves and half of gas reserves must be kept in the ground to meet the 2˚C target (McGlade and Ekins, 2015).[1] Burning *all* fossil fuel reserves induces global warming far higher than 2˚C and it is surprising that share prices of oil and gas majors hardly reacted to the news of the Paris agreement.[2]

Table 1 indicates that oil and gas companies are heavily exposed to the risk of being unable to burn all their reserves if climate policy becomes more ambitious. Total proven oil and gas reserves amount to over 300 GtC at current economic conditions and continue to increase (BP, 2017); including coal, this figure would more than double.

Table 1: The carbon underground of the Top 10 oil and gas companies

Potential emissions from reserves (GtCO2)	2015	2016	2017
Gasprom	43.9	44.1	43.9
Rosneft	23.2	16.8	17.5
PetroChina	8.6	8.1	7.7
ExxonMobil	8.2	8.0	7.0
Lukoil	7.0	7.1	6.6
BP	6.7	6.4	6.7
Royal Dutch Shell	16.7	6.4	4.3
Petrobas	5.4	4.4	4.0
Chevron	4.1	4.1	4.0
Novatek	3.9	3.9	3.9
Total	117.7	109.3	105.6

Source: http://fossilfreeindexes.com/research/the-carbon-underground/

[1] To meet the 2˚C target, four fifths of coal reserves should also be abandoned. All Canadian tar sands and Artic oil and gas reserves should be left in the ground (McGlade and Ekins, 2015).

[2] Share prices of coal companies such as Peabody Energy and Consol Energy Inc dropped by 11.3% and 4.9%, respectively. The U.S. oil and gas index fell by a mere 0.5%. On the other hand, renewable energy stocks rose after the Paris agreement. The MAC Global Solar Energy Index and the iShares Global Clean Energy Exchange Trade Fund rose by 1.9% and 1.4%, respectively. See Griffin et al. (2015) and Mukanjari and Sterner (2018) for econometric analyses.

Not only international companies are at risk, downstream business and producers of electricity and final goods that rely heavily on fossil fuel are strongly exposed to forced write-offs of their carbon assets. Oil-, gas- and coal-based economies are also at risk of sudden shifts in expectations about future prices for fossil fuels, often their most important source of foreign exchange, and financial markets are prone to instability emanating from policy-induced drops in the market values of fossil fuel based industries, much like during the financial crisis of 2007 which started in the relatively small residential U.S. real estate sector (Hjort, 2016; Battiston et al., 2017).

Our main objective is to gain an analytical and quantitative understanding of the determinants of stranded assets in the fossil-fuel industry. While the stranding of natural reserves assets has been studied widely, the stranding of financial assets is still little understood. Hence, we investigate the effects of different types and intensities of policy on market valuations, investments, and carbon resources and their scarcity rents belonging or accruing to international oil and gas companies, as well as the overall characteristics of the transition to the fossil-free era (e.g. transition time and the amount of locked-up carbon) and the overall cost of policy in terms of aggregate welfare.[3]

To gain a better understanding of what stranded assets in the context of climate policy means and to situate our research within the previous contributions, we distinguish the following four effects:

1. If climate policy is to keep global warming below 2˚C, a substantial proportion of fossil fuel reserves must be left in the crust of the earth at the end of the fossil era. This necessity of "unburnable carbon" arises because recent atmospheric insights suggest that a temperature cap implies a cap on cumulative carbon emissions (e.g. Meinshausen et al., 2009; Allen et al., 2009; Allen, 2016). These carbon assets under ground and their geographical distribution have been the focus of early studies of asset stranding in climate change economics (cf. Carbon Tracker Initiative, 2011; McGlade and Ekins, 2015; Rezai and van den Ploeg, 2017a; Millar et al., 2017; van der Ploeg, 2018; Dietz and Venmans, 2019; Aengenheyster et al., 2018).
2. Exploration capital and other physical assets industries that rely on burning fossil fuel and are costly to be put to a different use will be stranded at the end of the fossil era, too, if these investments are irreversible or costly to be used for another purpose. This aspect of economic obsolescence of physical capital in the resource, power generation, and transportation sectors follows quantitatively and qualitatively different dynamics from

[3] Since coal is abundant and the scarcity rent on coal is likely to be small, we limit our analysis to international oil and gas companies. We take temperature targets as given and abstract from global warming damages to aggregate production. Climate policy is thus always costly to the economy.

those of the stranding of natural capital (cf. Guivarch and Hallegatte, 2011; Carbon Tracker Initiative, 2013; Knoch and Bassen, 2013; Bertram et al., 2015; Pfeiffer et al., 2016; Baldwin et al., 2019; Coulomb et al., 2019; Rozenberg et al., 2019).

3. Unanticipated tightening of present or future climate policy leads to an immediate reduction in the market valuation of natural and physical capital. With lower current or future demand for fossil fuel, both the scarcity rent of fossil fuel and the price of capital drop instantaneously. With forward-looking rational expectations, these effects materialize as soon as new information becomes available, while stranding effects 1 and 2 above refer to the end of fossil era exclusively. Once climate policy is anticipated, less irreversible investments in, say, coal-fired power stations are undertaken, since policy lowers the profitability and valuation of capital (cf. Mukanjari and Sterner, 2018; Baldwin et al., 2019; Bretschger and Soretz, 2019; Kalkuhl et al. 2019; Rozenberg et al., 2019).
4. If the timing and forcefulness of climate policy is uncertain, additional revaluation of assets occurs once uncertainty is resolved at some future date. Once markets realize that climate policy will be enacted, capital and fossil reserves suffer a sudden loss in value while botching or cancelling an announced tightening of climate policy immediately boosts the scarcity rent and market capitalization of fossil fuel companies, leading to an investment boom in exploration and a surge in discoveries (cf. Bretschger and Soretz, 2019; Karydas and Xepapadeas, 2019).

Although the first two types of asset stranding have been studied in detail, the latter two are subject of ongoing research and we believe we are the first to formally analyse all four in a consistent analytical framework. To explain and quantify these effects, we adapt Pindyck's (1978) canonical model of exploration investment, discoveries, and depletion by introducing intertemporal adjustment costs for exploration investments. Exploration thus reacts to expectations about future changes in climate policy. To what extent exploration investments must be written off and stock market value is wiped out depends on how irreversible these investments are and how costly they are to adjust for other purposes. Without such intertemporal (or inter-sectoral) adjustment costs or some form of irreversibility in exploration investments, the risk of policy does not lead to discrete jumps in market capitalization and one cannot address the issue of stranded hydrocarbon and physical assets (Karp and Rezai, 2019).

Our focus is the effects of different climate policy instruments on asset stranding (cf. Goulder and Parry, 2008; Fischer and Newell, 2008; Fischer and Salant, 2017; Rozenberg et al, 2019). We compare the effects of certain and uncertain policies designed to keep global carbon warming below the Paris target of 2˚C. Certain policies include: (i) an immediately implemented carbon tax; (ii) a delayed but credibly announced carbon tax that necessarily has to be higher to achieve the same temperature target; and (iii) a renewable energy subsidy designed to stay below the temperature cap. We subsequently focus on the effects of uncertainty around the carbon budget and *uncertainty about the timing of climate policy* in two scenarios where politicians might wake up in the future and "tip" into action (we will refer to this as "policy tipping"): (iv) there is a risk that climate policy gets toughened to meet the temperature target at some future date (before it is too late); and (v) there is a risk as in (iv) but now it is eventually followed through at some even later date by a definite move to toughening climate policy to meet the temperature target in case the previous attempt at climate policy gets botched.

Policies (i) and (ii) give rise to a carbon tax that rises at a rate equal to the interest rate. Relative to the first-best policy (i), the delayed carbon tax (ii) speeds up fossil fuel extraction as companies try to avoid the burden of taxation. As a result, carbon emissions are brought forward thus accelerating global warming ahead of introducing the delayed carbon tax, which is the green paradox effect (cf. Sinn, 2008). To make up for the time wasted and the additional emissions due to the green paradox, the delayed carbon tax must be higher than an immediately implemented carbon tax to meet the same temperature target. The second-best climate policy (ii) shifts demand and carbon emissions to the near future and discourages costly exploitation investment and discoveries. This boosts the profitability of existing exploration capital stock and preserves some of the shareholder wealth lost under the immediate tax. Whether aggregate welfare increases or not depends on whether oil and gas supply is more responsive to prices than energy demand (van der Ploeg, 2016). A subsidy to renewable energy (iii) also accelerates fossil fuel use and global warming in the short run (green paradox) but curbs *cumulative* fossil use and emissions and warming in the long run. Investments in discovery and exploration are discouraged and more fossil fuel is locked up. Scenarios (iv) and (v) illustrate what the risk of policy tipping does to the market capitalization of oil and gas companies at various points in time: at the introduction of uncertainty, before the date at which policy tipping might take place, and after that date depending on whether the attempt to implement an announced climate policy is successful or abandoned (stranded assets effects 3 and 4 above).

Our model focuses on the oil and gas industry and reduces the role of renewable energies to that of a perfect substitute for fossil fuel, which can be produced at constant unit cost without requiring capital investments. This carbon-free source of energy drives out fossil fuel in a finite number of years.[4] We investigate these issues in a calibrated version of our model of exploration investment,

[4] Online Appendix A solves an analytical version of our model where fossil fuel is always needed and never phased out, either because renewable energy is initially not competitive or because renewable energy can never fully substitute for carbon-based energies. Due to the assumption of potentially prohibitive extraction

fossil fuel discoveries, climate policy, and stranded financial assets. Our focus is on exploration investment and discoveries of oil and gas reserves. Oil and gas companies must make substantial exploitation investments in rigs and similar infrastructure. With a risk of policy tipping or an unanticipated change in future climate policy, past exploitation investments become stranded and the share prices of oil and gas companies will drop. If previously announced attempts at policy are abandoned or botched, profitability and capitalization of these companies will rise.

Gollier (2019) discusses the effects of correlations between uncertainties in consumption growth and marginal abatement cost on the risk-adjusted discount rate to be used for the Hotelling path for the efficient carbon price, but we will abstract from such uncertainties and focus at policy uncertainties instead. Salant (2016) shows that the ongoing risk of future regulatory intervention increases the cost of maintaining a cap in the European Emissions Trading System even if no regulatory intervention occurs. We obtain a similar insight, but our aim is to show the different types of stranded assets effects caused by policy tipping in a general equilibrium framework. The novelty of our paper is to disaggregate the welfare effects of anticipated climate policies on the objective function of the oil and gas industry. We find that a delayed carbon tax compatible with staying below 2°C boosts market capitalization of the oil and gas industry relative to an immediately implemented carbon tax compatible with staying below 2°C, since it allows the industry to shift production towards the present and carbon taxation to the future. Given that there are adjustment costs to capital, this improves the profitability of the oil and gas industry as measured in the discounted stream of profits. The same reasoning applies to the cases of a renewable subsidy and risks of policy tipping. These second-best policies, however, come with deadweight loss for society.

Section 2 reviews empirical evidence on the drivers of discoveries and exploration investments showing that fossil fuel companies do not anticipate an end to their business model anytime soon and that the availability of fossil fuels is not a limiting factor on economic growth as purported by the "peak-oil" hypothesis. Section 3 sets up our model of exploration investments and discoveries of fossil fuel reserves and derives the first-best optimal allocations that are compatible with a temperature cap of 2˚C. Section 4 shows that the resulting first-best command optimum can be replicated in the market economy if policy makers implement a Hotelling path for the carbon tax with no need for a renewable energy subsidy. Section 5 discusses how second-best and policy-tipping scenarios can be calculated. Section 6 discusses our calibration to business as usual

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costs that rise as fewer fossil fuel reserves are left, it does not pay to fully deplete fossil fuel reserves but to invest and seek new ones. This version provides intuition how climate policy affects the investment in and valuation of exploration capital as well as the value of carbon under the ground and stock market value. Coulomb and Henriet (2018) and Coulomb et al. (2019) show that the inclusion of several energy sources and source-specific capital can avert the asset stranding for certain fossil fuel types at the expense of other.

and contrasts with first-best outcomes. Section 7 discusses the second-best outcomes. Section 8 shows how markets respond to probabilistic policy tipping. Stranded assets effects 1 and 2 occur in all scenarios, while second-best outcomes induce in addition effect 3. Effect 4 only occurs under probabilistic policy tipping in section 8. Sensitivity results are presented in section 9. Section 10 concludes and discusses stranded assets in other industries and policy implications.

2. Recent developments in oil and gas exploration investments and discoveries

The much-debated "peak-oil" hypothesis (Hubbert, 1956; Priest, 2014) has become irrelevant as globally there is still huge potential for further increases in the supply of fossil fuel. First, rapid advances in fracking technology such as horizontal drilling have led to rapid growth in production of unconventional oil and gas. This has turned the United States from an importer to an exporter of fossil fuel. Countries such as Poland and Algeria also have the potential to become large producers of shale gas. Despite the impressive technological progress in production of renewable energy (especially solar), the huge technology-driven boosts to the supply of unconventional fossil fuel have been a game changer in global energy markets. There is plenty of fossil fuel around and potential for a lot more. Still, renewable energies will benefit from sustained technical progress and climate policy, eventually ending the fossil fuel age (Helm, 2017). Rather than "peak-oil" the global fossil fuel industry is now more concerned about "peak-demand".

Second, proven reserves of crude oil have grown continuously over the past decades worldwide even before the shale gas revolution. Discoveries have shifted from high-income countries to emerging markets and developing economies. Giant discoveries in the developing world have increased oil supply for decades, thus narrowing the gap in (known) resource wealth between developed and developing countries. These have to a large extent been driven by efforts in emerging market and developing economies to attract foreign investment and improve institutions and the rule of law (Arezki et al., 2019). While this might have been a one-off surge in proven reserves, the producers are now sitting on more carbon than ever.

The coming to market of new technology and nurturing of an environment that encourages exploration investments reinforce each other and boost fossil fuel discoveries, especially in developing economies. The micro evidence of Bjørnland et al. (2017) for unconventional oil and Arezki et al. (2019) more generally suggests that exploration and discoveries are driven by the world price of oil too. A crash in the world oil price depresses exploration investments and curbs opening of new oil and gas reserves. Regardless of whether a global producer oil price drops due to falls in global energy demand or to more ambitious climate policy to drive out fossil fuel, discoveries will become less frequent and more oil and gas (and thus more carbon) will be locked up in the crust of the earth as a result. We conclude that any analysis of policy tipping and stranded fossil fuel assets must allow for endogenous exploration of oil and gas fields and of reserves to capture financial in addition to natural resource wealth.

3. First-best allocation for ensuring a temperature cap with exploration and discoveries

We first show how the cap on temperature translates into a cap on cumulative emissions and then derive the command optimum subject to the cumulative emissions cap.

3.1. A temperature ceiling requires a cap on cumulative emissions

Following insights in atmospheric science, we suppose that peak warming is determined by cumulative carbon emissions rather than by the stock of atmospheric carbon (e.g. Matthews et al., 2009; Allen et al., 2009, 2016). Denoting the deviation of peak global warming from pre-industrial temperature in degrees Celsius by *PW*, the constraint for the temperature cap becomes

(1) $$PW = \gamma_0 + \gamma_1 E(T) \leq 2^{\circ}\mathrm{C} \quad \text{or} \quad E(T) \leq \bar{E} \equiv (2^{\circ}\mathrm{C} - \gamma_0) / \gamma_1,$$

where E is cumulative fossil fuel use (measured in Giga tons of carbon or GtC), T is the end of the carbon era, and $\gamma_1 > 0$ denotes the transient climate response to cumulative carbon emissions (TCRCE). Cumulative carbon emissions at time t are measured from the present day, denoted by $t = 0$, and denoted by E. Denoting the rate of fossil use by R (measured in GtC), we have

(2) $$\dot{E}(t) = R(t), \quad E(0) = 0, \quad \text{and} \quad E(t) = \int_0^t R(s)ds.$$

3.2. Fossil fuel exploration and discoveries

The stock of fossil fuel reserves, S, increases due to discoveries at a rate D and is depleted at the rate R. Discoveries are an increasing and concave function of exploration capital, K, so that $D = \mathrm{D}(K)$ with $\mathrm{D}' > 0$ and $\mathrm{D}'' < 0$.[5,6] Exploration capital depreciates at the rate $\delta > 0$. The cost of exploration investment, I, increases in the investment-capital ratio due to internal adjustment costs. The unit cost is thus $1 + \phi I / 2K$, where $\phi > 0$ is the adjustment cost parameter. Only a

[5] Arrow and Chang (1982) analyse stochastic discoveries. In contrast, we capture the empirical fact that recent advances and cost reductions in the global oil and gas industry have led to discoveries of competitive discoveries as well as more costly finds, thus roughly mirroring the existing supply curve of fossil fuel resources. Alternatively, exploration investment can be modelled to extend the supply curve at the margin, yielding ever more expensive resources.
[6] Discoveries might fall with cumulative discoveries, C, so $D = \mathrm{D}(K, C)$ with $\mathrm{D}_C < 0$. Price-taking oil and gas companies would not internalise the adverse impact of cumulative discoveries on current discoveries but take C as given. We abstract from this effect of cumulative discoveries in light of little change in average extraction costs over the past decades.

fraction $1/(1+\phi I/2K)$ of total investment outlays thus translates into additional exploration capital. Extraction costs in units of foregone output increase as reserves diminish and thus less accessible, more costly fields must be drilled: i.e. $\mathrm{G}(S)R$ with $\mathrm{G}'>0$. The dynamic development of the stock of reserves and the stock of exploration capital is

$$(3) \qquad \dot{S}(t)=\mathrm{D}\big(K(t)\big)-R(t), \quad S(0)=S_0, \text{ and } \dot{K}(t)=I(t)-\delta K(t), \quad K(0)=K_0,$$

where S_0 and K_0 denote the initial stocks of reserves and exploration capital, respectively.

3.3. The carbon-free backstop energy source

Although fossil fuel is currently cheap, there comes a moment that full costs including the social cost of meeting the temperature cap have risen so much that it is optimal to switch to renewable energy. We suppose renewable energy is a backstop, *B*, which can be produced infinitely elastic at cost $b > 0$ per unit of energy (measured in terms of equivalent GtC). Due to technical progress, this cost declines over time. Once the full cost of fossil fuel has reached the exogenous cost of renewable energy, the fossil fuel era comes to an end. The duration of the fossil fuel era, *T*, is endogenous and depends on the cumulative emissions cap (i.e. the carbon budget), the cost of renewable energy, the drivers of the cost of fossil fuel, reserves, and past exploration activities.

3.4. Production and consumption

Let aggregate production of final goods be Y and utility of energy consumption be $\mathrm{U}(R+B)$, where U(.) is twice differentiable and concave and energy sources are perfect substitutes. Consumption of final goods, *Z*, is what is left of aggregate production after subtracting exploration investment costs including adjustment costs, fossil extraction cost and renewable production cost. With quasi-linear utility, total utility is

$$(4) \qquad \mathrm{U}(R+B)+Z \quad \text{with} \quad Z=Y-I-\frac{\phi}{2}\frac{I^2}{K}-\mathrm{G}(S)R-bB.$$

3.5. Maximizing welfare subject to the cap on cumulative emissions

The first-best optimal allocation corresponding to the command optimum follows from maximizing the intertemporal welfare function with risk-neutral utility function

$$(5) \qquad \int_0^\infty e^{-\rho t}\left[\mathrm{U}\big(R(t)+B(t)\big)+Z(t)\right]dt$$

subject to the peak-warming constraint (1), the dynamics of cumulative emissions (2), the dynamics of reserves and exploration capital (3), and consumption of final goods (4), where the social rate of time preference is denoted by $\rho > 0$. We define the Hamiltonian function as

$$H \equiv \mathrm{U}(R+B)+Y-I-\frac{1}{2}\phi\frac{I^2}{K}-\mathrm{G}(S)R-bB-\lambda_E R+\lambda_S\left[\mathrm{D}(K)-R\right]+\lambda_K(I-\delta K),$$

where $-\lambda_E$, λ_S and λ_K denote the co-state variables corresponding to (2) and (3), respectively. The first-order conditions corresponding to Pontryagin's Maximum Principle are

(6a) $\quad \dfrac{\partial H}{\partial R} \le 0 \quad \text{or} \quad \mathrm{U}'(R+B) \le \mathrm{G}(S)+\lambda_S+\lambda_E \quad \perp \quad R \ge 0,$

(6b) $\quad \dfrac{\partial H}{\partial B} \le 0 \quad \text{or} \quad \mathrm{U}'(R+B) \le b \quad \perp \quad B \ge 0,$

(6c) $\quad \dfrac{\partial H}{\partial I} \le 0 \quad \text{or} \quad \lambda_K \le 1+\phi\dfrac{I}{K} \quad \perp \quad I \ge 0,$

(6d) $\quad \rho\lambda_E - \dot{\lambda}_E = -\dfrac{\partial H}{\partial E} = 0 \quad \text{or} \quad \dot{\lambda}_E = \rho\lambda_E,$

(6e) $\quad \rho\lambda_S - \dot{\lambda}_S = \dfrac{\partial H}{\partial S} = -\mathrm{G}'(S)R \quad \text{or} \quad \dot{\lambda}_S = \rho\lambda_S + \mathrm{G}'(S)R,$

(6f) $\quad \rho\lambda_K - \dot{\lambda}_K = \dfrac{\partial H}{\partial K} = \dfrac{1}{2}\phi\left(\dfrac{I}{K}\right)^2 + \mathrm{D}'(K)\lambda_S - \delta\lambda_K \quad \text{or} \quad \dot{\lambda}_K = (\rho+\delta)\lambda_K - \dfrac{1}{2}\phi\left(\dfrac{I}{K}\right)^2 - \mathrm{D}'(K)\lambda_S.$

We thus see from (6a) that, if fossil fuel use is positive, it equals $R = \Phi\big(G(S)+\lambda_S+\lambda_E\big)-B$ with $\Phi' = 1/\mathrm{U}'' < 0,$ so that fossil fuel use decreases in the social of cost of fossil fuel use, i.e. the sum of the extraction cost, $\mathrm{G}(S),$ the shadow value of fossil fuel reserves, λ_S, and the shadow cost of meeting the cumulative emissions cap, λ_E. Similarly, if renewable energy is in use, $B = \Phi\big(b\big)-R$ with $\Phi' = 1/\mathrm{U}'' < 0$ from (6b). There are three potential energy regimes: fossil only, renewable only, and simultaneous use. For the plausible case of low extraction costs and high but declining backstop price, the economy starts with a fossil only regime. Continued investment in exploration capital ensures that discoveries keep up with extraction and extraction costs stay low. If the backstop price drops below the point where investments become unprofitable and extraction costs large enough, the economy switches to a regime of renewable energy use. Since both energy types are perfect substitutes, simultaneous use occurs for at most an instance. Hence, in general we can write fossil fuel use as $R = \mathrm{R}(S, \lambda_S+\lambda_E)$ with $\mathrm{R}_S > 0,$ $\mathrm{R}_{\lambda_S+\lambda_K} < 0$ if B = 0.[7] Lower reserves

[7] In case of simultaneous use, $B = \Phi\big(b\big)-R$ and $G(S)+\lambda_E-b=-\lambda_S$. Depleting fossil fuel resources implies a rising unit extraction cost of fossil fuel, equation (6d) implies that the cost of satisfying the cap rises λ_E

thus drive up extraction costs and depress fossil fuel use. Equation (6c) indicates that, if the shadow value of exploration capital is high enough to cover the marginal cost of investment including adjustment costs, the optimal investment rate is non-negative and equals $I = \frac{1}{\phi}(\lambda_K - 1)K$. It increases in the shadow value of exploration capital, λ_K. Equation (6d) indicates that the shadow value of the emission cap grows with the rate of interest. Equations (6e) and (6f) state that the returns of extracting one extra unit of fossil fuel or investing an extra unit of exploration capital equals the return earned in the capital market (see more below).

If fossil fuel is competitive from the start, we get, using (1) from equations (2)-(3) and (6d)-(6f), the following two-point-boundary-value problem:

(7a) $\dot{E} = \mathrm{R}(S, \lambda_S + \lambda_E)$ given $E(0) = E_0, \quad E(T) = \bar{E}$,

(7b) $\dot{S} = \mathrm{D}(K) - \mathrm{R}(S, \lambda_S + \lambda_E)$ given $S(0) = S_0$,

(7c) $\dot{K} = \mathrm{Max}\left[\left(\frac{1}{\phi}(\lambda_K - 1) - \delta\right), -\delta\right]K$ given $K(0) = K_0$,

(7d) $\dot{\lambda}_E = \rho\lambda_E, \quad \lambda_E(0)$ free, $\lambda_E(T) = b - \mathrm{G}(S(T))$,

(7e) $\dot{\lambda}_S = \rho\lambda_S + \mathrm{G}'(S)\mathrm{R}(S, \lambda_S + \lambda_E), \quad \lambda_S(0)$ free, $\lambda_S(T) = 0$,

(7f) $\dot{\lambda}_K = (\rho + \delta)\lambda_K - \frac{1}{2\phi}(\lambda_K - 1)^2 - \mathrm{D}'(K)\lambda_S, \quad \lambda_K(0)$ free, $\lambda_K(T) = 0$.

The first three equations of this 6-dimensional system of differential equations give the dynamics for the predetermined (backward-looking) equations, which are pinned down by their initial conditions. The latter three equations give the dynamics for the jump (forward-looking) variables, which are pinned down at the end of the fossil fuel era by the two conditions that the shadow values of fossil fuel reserves and exploration capital have fallen to zero plus the condition that the social cost of meeting the cumulative emissions cap has to equal the cost difference between fossil fuel and the renewable backstop. Apart from these six boundary conditions, there is a seventh boundary condition $E(T) = \bar{E}$ which pins down the duration of the fossil fuel era.[8]

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over time as well, and b is either constant or falls due to technical progress. Hence, we see that during simultaneous use the scarcity rent λ_S must fall strong enough over time. Since simultaneous use only occurred once in our numerical simulations below, we do not discuss the case of simultaneous use any further.

[8] If the cap on cumulative emissions is not binding, then $\lambda_E = 0$ and $E(T)$ free with the terminal period of the fossil fuel era, T, from the no-arbitrage condition $b = \mathrm{G}(S(T))$.

4. Using carbon pricing to decentralize the command optimum in the market economy

We now demonstrate that the first-best optimal allocation derived in section 3.5 for the command economy can be replicated in the decentralized market economy. To see this, we distinguish final goods producers, fossil fuel and renewable energy producers, households, and the government in the market economy. The final goods market is in equilibrium if the exogenous output of final goods, *Y*, equals the demand for final goods from energy producers, $bB + \mathrm{G}(S)R + I + \phi I^2 / 2K,$ and from households for consumption, *Z*. For simplicity, we abstract from government demand for final goods. The government budget constraint states that public expenditure on renewable energy subsidies, $\sigma B,$ must equal lump-sum taxes, *L*, plus income from carbon tax revenue, $\tau R,$ where σ denotes the specific renewable energy subsidy and τ denotes the specific carbon tax.[9] The household budget constraint states that the cost of consuming final goods, *Z*, and energy, $(p+\tau)R + (b-\sigma)B,$ must equal net household income, $Y + \Pi^B + \Pi^R - L,$ where $\Pi^B = (p-b)B$ denotes profit income from renewable energy companies and $\Pi^R = pR - \mathrm{G}(S)R - I - \phi I^2 / 2K$ profits from fossil fuel companies. Household utility, $Z + \mathrm{U}(R+B),$ is quasi-linear, where U(.) is twice differentiable and concave. Inverse energy demand is $p + \tau = \mathrm{U}'(R+B),$ so global energy demand is $R + B = \Phi(p+\tau)$ with $\Phi' = 1/\mathrm{U}'' < 0.$ Consumers of energy also have access to an alternative renewable energy source. This perfect substitute for fossil fuel is infinitely elastically supplied at the cost *b*. Renewable energy producers maximize profits by setting the price equal to the cost of production, *p* = *b*, so that their profits are in equilibrium zero, $\Pi^B = 0.$

Fossil fuel producers choose investments in exploration capital and depletion rates to maximize their net worth, i.e. the present discounted value of current and future profits $V^R \equiv \int_0^\infty e^{-rt}\Pi^R dt$ subject to equations (2) and (3), where *r* now denotes the market rate of interest.[10] This gives optimal exploration investment $I = \frac{1}{\phi}(q-1)K$ if positive and *I* = 0 else, where *q* denotes the marginal market value of existing exploration capital (cf. Tobin's "Q" as in Hayashi,1982). It also gives $p = \mathrm{G}(S) + h,$ so that the price of fossil fuel should equal the user cost, viz. the marginal cost of extraction, $\mathrm{G}(S),$ plus the Hotelling or scarcity rent, *h*. The efficiency conditions for the

[9] We refer to carbon pricing as a "carbon tax", but it could equivalently be a price that is the outcome of a global competitive market for carbon emission permits or the shadow price of a quota policy.
[10] One can allow for the payment of royalties or a license fee for the right to exploit natural resources, but this does not affect our result about sustaining the command outcome in the market economy.

fossil fuel producers are $\dot{h} = rh + \mathrm{G}'(S)\mathrm{R}(S, h+\tau)$ and $\dot{q} + \frac{1}{2\phi}(q-1)^2 + \mathrm{D}'(K)h = (r+\delta)q.$ The stock market value of oil and gas companies vanishes at the end of the carbon era, so $V^R(T) = 0.$

The first efficiency condition is the Hotelling rule for the scarcity rent on in-situ reserves. It states that the return on holding, say, a marginal barrel of oil in the ground (the expected capital gains), must equal the net return of taking it out (the return on investing the proceeds of selling the oil minus the marginal increase in extraction costs resulting from depleting oil reserves by one unit). This implies that the scarcity rent equals the present discounted value of all future reductions in extraction cost resulting from keeping an additional unit of resources in the ground, $h(t) = \int_t^\infty \left[-G'\big(S(s)\big)R(s)\right]e^{-r(s-t)}ds$.[11] Global fossil fuel demand is $R = \Phi\big(h + \mathrm{G}(S) + \tau\big) - B$ $\equiv \mathrm{R}(S, h+\tau)$ with $\mathrm{R}_S = \Phi'\mathrm{G}' > 0$ and $\mathrm{R}_{h+\tau} = \Phi' < 0.$ A higher scarcity rent, fossil fuel extraction cost (caused by lower reserves) or carbon tax thus curb global demand for fossil fuel.

The second efficiency condition states that the expected capital gains plus marginal benefits from lowered adjustment costs and increased discoveries of having an additional unit of exploration capital must equal rental plus depreciation charges. The marginal value of exploration capital is $q(t) = \int_t^\infty \left[\mathrm{D}'\big(K(s)\big)h(s) + \frac{\phi}{2}\left(\frac{I(s)}{K(s)}\right)^2\right]e^{-(r+\delta)(s-t)}ds,$ which is the present discounted value of these two marginal benefits.[12]

In the fossil fuel regime, if fossil fuel is competitive and cheaper than renewable energy, $R = \Phi(p+\tau)$ with $p = \mathrm{G}(S) + h$ and $\Phi' = 1/\mathrm{U}'' < 0.$ Once the price of fossil fuel plus the carbon tax exceeds the user cost of renewable energy, fossil fuel is substituted in final goods production, the consumer energy price becomes $p = b - \sigma$ and global energy demand becomes $B = \Phi(p).$ This switch might be temporary if installed capital leads to continued discovery of new competitive reserves, which in turn lowers extraction costs and the user cost of fossil fuel. A sufficiently large drop in extraction cost could bring fossil fuels back, at least temporarily. If continued technological progress or a technological breakthrough lower the cost of renewables sufficiently (as we assume in our numerical simulations), fossil fuels are permanently phased out eventually. Fossil fuel companies then go bankrupt and global energy demand becomes

[11] Anderson et al. (2018) explain that the opening of new fields is governed by Hotelling-like rules, but the depletion of existing fields is governed by Darcy's law for the flow of fluid through a porous medium. Our model should thus be viewed as one for the opening of new fields to which Hotelling considerations apply.

[12] Since profits of fossil fuel companies are not homogenous of degree one, we do not have $V^R = hS + qK$ and thus need to evaluate the stock market numerically.

$B = \Phi(b - \sigma)$ indefinitely. At the end of the carbon era, at time T, the scarcity rent has fallen to zero, $h(T) = 0,$ and shares in fossil fuel companies are worthless, $q(T) = 0.$

Ricardian equivalence holds, so we can abstract from government debt and assume that the government always balances its books using lump-sum transfers. Households are infinitely lived and maximize $\int_0^\infty e^{-\rho t}\left[Z(t) + \mathrm{U}\left(R(t) + B(t)\right)\right]dt.$ Quasi-linear utility implies that $r = \rho$.

Proposition: *The first-best outcome can be sustained in the market economy if policy makers levy a carbon tax on final goods producers from time zero onwards according to*

(8) $$\tau(t) = e^{r(t-T)}\left[b(T) - \mathrm{G}\left(S(T)\right)\right], \quad t \geq 0,$$

rebate revenues in lump-sum manner, and offer no renewable energy subsidy, $\sigma(t) = 0,\ t \geq 0.$

Proof: To see that this proposition holds, note that $r = \rho$ and that the conditions for the command and market outcomes coincide if $\tau = \lambda_E$, $q = \lambda_K$, $h = \lambda_S$, and $\sigma = 0.$ The carbon tax thus satisfies $\dot{\tau} = r\tau$ with $\tau(T) = b(T) - \mathrm{G}\left(S(T)\right),$ which can be solved to give (8).

The first-best optimal carbon tax (8) must rise at a rate equal to the market rate of interest (i.e. a Hotelling path) to reflect the increasing social scarcity of fossil fuel as the carbon budget gradually gets exhausted. The carbon tax is tied down at the end of the fossil era by the difference in the market cost of the renewable and the extraction cost of fossil. In fact, the welfare-maximizing carbon tax path (8) also corresponds to the path that minimizes costs. Our Hotelling carbon tax path (8) extends earlier results on the optimal response in case of a temperature cap (e.g. Nordhaus, 1982; Tol, 2013; Bauer et al., 2015) by allowing for endogenous fossil fuel discoveries.[13] However, note that the discount rate in (8) does not include the rate of atmospheric decay as cumulative emissions (*not* the stock of atmospheric carbon) matters for global warming (e.g. Matthews et al., 2009; Allen et al., 2009; van der Ploeg, 2018; Dietz and Venmans, 2018).[14]

5. Second-best and policy-tipping scenarios versus first-best scenarios

Politicians have two main characteristics: first, they procrastinate and postpone implementation of unpopular policies to their successors, and, second, they prefer subsidies to taxes. Hence, the

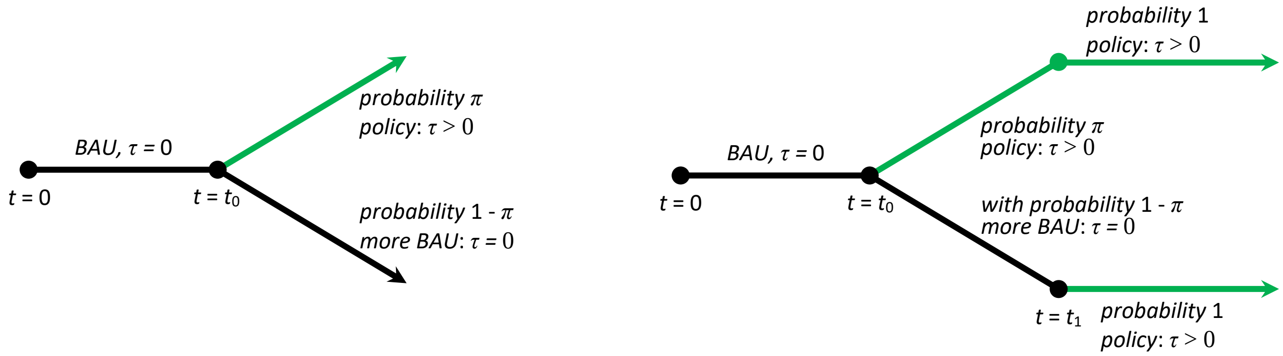
[13] Mattauch et al. (2018) discuss the equivalence between targets on temperature and cumulative emissions.
[14] In models such as that of Nordhaus (2017), global warming causes a loss in aggregate economic output in which case the welfare-maximising carbon tax is the discounted sum of marginal climate damages. If one combines this approach with a temperature ceiling, the optimal carbon price grows at a rate between the rate of economic growth and the real rate of interest (van der Ploeg, 2018; Dietz and Venmans, 2018).

first-best outcome is generally not attainable for political reasons. We therefore contrast the first-best policies of the proposition with the second-best policies of a delayed carbon tax and a renewable energy subsidy. Such policies cannot rely on (decentralizing) the command optimum as done in section 3, since the fundamental theorem of welfare economics no longer holds. Instead, policy makers must maximize welfare in (5) from time zero onwards taking full account of the market equilibrium conditions and the behaviour of households and all three types of firms described in section 4 (see section 5.1). We assume that policy makers can commit to all future policies announced at date zero. These second-best policies and their potential time inconsistency have been analysed before in a context where renewable energy production is subject to learning by doing (e.g. Rezai and van der Ploeg, 2017b), but here we abstract from this second type of market failure and assume exogenous technical progress in renewable energy production instead. We find that these second-best policies accelerate depletion and exacerbate short-run global warming also with endogenous discoveries.

To illustrate the issue of policy uncertainty, we also consider the risk of policy tipping. The market assigns a probability $0 < \pi < 1$ that policy makers change tack at some future date t_0 and from then on start conducting carbon pricing compatible with the internationally agreed upon temperature (and thus cumulative emissions) cap. The market assigns a probability $0 < 1 - \pi < 1$ that policy makers continue with business as usual. In this scenario, uncertainty involves whether at some future point of time a ceiling on cumulative emissions is imposed or not. An alternative is to allow for uncertainty about the timing of policy tipping given adherence to a known carbon budget compatible with the temperature cap. In such a modified scenario in which, policy makers with probability π tip into action at the anticipated date t_0 or with some probability 1-π they will wake up with certainty at a known later date, t_1, and do whatever it takes to keep temperature below the temperature target. These two alternative types of policy tipping are presented in Figure 1.

Figure 1: Two types of carbon tax tipping

(iv) Policy tipping I **(v) Policy tipping II**



We thus consider six scenarios:

(i) **First-best (immediate carbon tax):** Policy makers impose the first-best carbon tax (8) from time zero onwards. The carbon tax stays in place after the carbon era, so fossil fuel companies do not re-enter the market.

(ii) **Second-best I (delayed carbon tax):** Policy makers are credible and announce at time zero that at some future point in time $t_0 > 0$ a carbon tax is set to keep temperature below target from the perspective of time t_0, so policy makers commit to the announced policy and firms and households adjust.

(iii) **Second-best II (renewable energy subsidy):** Policy makers announce at time zero that they will offer a second-best renewable energy subsidy σ but levy no carbon tax. The size of this subsidy is chosen so that temperature stays below its ceiling. Firms and households find the announcement credible and take it fully into account in their decisions.

(iv) **Policy tipping I (safe or none):** Market participants know that carbon taxes stay zero until time $t_0 > 0$. With positive probability π policy makers set the optimal carbon tax for $t \geq t_0$ to keep cumulative emissions within the safe carbon budget, and probability 1-π the policy effort is abandoned at $t = t_0$ so that policy makers do nothing and continue with business as usual indefinitely.

(v) **Policy tipping II (safe or sorry):** As policy-tipping I scenario, but if the carbon tax is botched then at some later time $t_1 > t_0$ policy makers are sorry about their failed attempt and implement for $t \geq t_1$ the carbon tax path that is needed to keep temperature below its ceiling.

(vi) **Business as usual:** Policy makers never implement any climate policies.

Comparing the delayed with the immediate carbon tax, we will find that the later policy makers wake up, the higher the carbon tax must be. For scenario (iii), locked-up reserves, $S(T) = \mathrm{S}(b-\sigma)$ with $\mathrm{S}' = 1/\mathrm{G}' < 0,$ and cumulative discoveries, $\int_0^T D(t)dt = \bar{E} - S_0 + \mathrm{S}(b-\sigma),$ increase in the renewable energy subsidy, σ. A tighter carbon budget does not affect locked-up reserves but does demand fewer cumulative discoveries.

Our main interest is in the policy-tipping scenarios (iv) and (v). These allow for the impact of policy uncertainty on investment behaviour and market valuations.[15] If policy makers tip, the carbon taxes that, if successful, are implemented from $t = t_0$ onwards will be higher than what was hitherto expected by the market, and consequently there is a discrete drop in the share price

[15] The analysis of tipping risk is related to that of expropriation risk (e.g., Long, 1975; Bohn and Deacon, 2000; van Benthem and Stroebel, 2013).

and market value of the oil and gas companies. Some of the market value must be written off and this has been called stranded assets. If the attempt to introduce carbon taxes is botched, carbon taxes remain zero and the market value jumps up instantaneously. The expected carbon tax at $t = t_0$ in case of a botched attempt in the "safe or sorry" scenario jumps up, because more action must be taken to stay below the temperature cap if policy makers procrastinate further. Uncertainty also affects investment and market valuations *before* the tipping point. If an uncertain tax is announced, share prices drop but not as much as if the tax was certain to be implemented.

It is easy to allow for the probability of policy tipping to be endogenous; e.g. it could increase in cumulative carbon emissions or temperature. We can also allow for multiple potential tipping dates in which case the expected carbon path would be hiked up after every disappointment, but to keep the exposition and numerical challenges manageable we abstract from these modifications.

5.1. Finding optimal second-best policies

To find the optimal delayed carbon tax (ii), policy makers at time zero set $\tau(t) = 0,\, 0 \le t < t_0$ and $\sigma(t) = 0,\, 0 \le t$ and choose the carbon taxes $\tau(t),\, t \ge t_0 > 0$ with $t_0 < T$ to maximize welfare (5) subject to (4) with $I = \mathrm{Max}\left[\frac{1}{\phi}(q-1), 0\right]K$ and the anticipated market responses:

(10a) $\dot{S} = \mathrm{D}(K) - \mathrm{R}(S, h+\tau), \quad S(0) = S_0, \quad S(T) = \mathrm{S}\big(\tau(T) + \theta - b(T)\big),$

(10b) $\dot{K} = \mathrm{Max}\left[\left(\frac{1}{\phi}(q-1) - \delta\right), -\delta\right]K, \quad K(0) = K_0,$

(10c) $\dot{h} = rh + \mathrm{G}'(S)\mathrm{R}(S, h+\tau), \quad h(0) \text{ free}, \quad h(T) = 0,$

(10d) $\dot{q} = (r+\delta)q - \mathrm{D}_K(K)h - \frac{1}{2\phi}(q-1)^2, \quad q(0) \text{ free}, \quad q(T) = 0,$

(10e) $\dot{V}^R = rV^R - h\mathrm{R}(S, h+\tau) - \mathrm{Max}\big[(q-1)\big[1-(q-1)/2\big]K/\phi, 0\big], \quad V^R(T) = 0.$

where $G\big(S(T)\big) + \tau(T) = b(T) - \sigma(T)$ gives locked-up reserves $S(T) = \mathrm{S}\big(\tau(T) + \sigma(T) - b(T)\big)$ with S′ > 0. The stocks (S, K) are backward-looking, predetermined state variables and the asset prices and the market capitalization (h, q, V^R) are forward-looking, non-predetermined state variables. Equations (10) thus constitute a saddle-point system with a 2-dimensional stable manifold corresponding to the two predetermined state variables. The complete system has six boundary conditions. Five of these are the two initial conditions of the predetermined states and the three terminal conditions for non-predetermined states. The additional terminal condition in

(10a) gives the end of the carbon era *T*. The constraint $E(T) = \int_0^T \mathrm{R}\left(S(t), h(t) + \tau(t)\right) = \bar{E}$ corresponding to (1) gives cumulative emissions compatible with staying below the temperature ceiling. The optimal delayed carbon tax thus found does not correspond to the optimal directly implemented carbon tax (8), since the government will find it optimal to adjust to future taxes to compensate for the delay in implementation. To find the optimal renewable energy subsidy (iii), policy makers also maximize welfare (5) subject to (4) and the constraints of the market economy (10) and the infeasibility constraint on the carbon tax $\tau(t) = 0, 0 \le t.$ This gives the value of σ that ensures that the temperature cap is not violated.

5.2. Pasting conditions for the policy-tipping scenarios

The derivation of the policy-tipping scenarios is more complicated. Consider scenario (iv) "safe or none" first. We solve three saddle-point problems comprising the decentralized equilibrium conditions and stitch them together via appropriate pasting conditions. The first one is the optimization problem for the period $0 \le t \le t_0$. The second one is the optimization problem for the period $t \ge t_0$ in case the climate policy materializes, which is denoted by superscript *M*. The third one is the simulation problem for the period $t \ge t_0$ in case the climate policy is botched, which is denoted by superscript *B*. We have the pasting conditions: $S(t_0-) = S^M(t_0+) = S^B(t_0+),$ $K(t_0-) = K^M(t_0+) = K^B(t_0+),$ $h(t_0-) = \pi h^M(t_0+) + (1-\pi)h^B(t_0+),$ and $q(t_0-) = \pi q^M(t_0+) + (1-\pi)q^B(t_0+).$ Hence, the state variable *S* and *K* are not allowed to jump while the forward-looking variables *h* and *q* have to equal their respective expected values right before the tipping event at time t_0. The carbon tax jumps upward to its welfare-maximizing value if the policy materializes and stays zero else, and the scarcity rent and the marginal value of exploration capital jump down if policy materializes and up if it is botched. The extra pasting conditions for the policy-tipping scenario (v) "safe or sorry" at $t = t_1$ ensure no discrete jumps in any of the states including the scarcity rent, *h*, the marginal value of exploration capital, *q*, and V^R as the switch to a positive carbon tax (when policy makers are finally sorry) is fully anticipated.

6. Calibration to business-as-usual and first-best climate policy simulations

6.1. Calibration

We base our illustrative calibration on the following observations:

- Initial proven reserves are taken from BP (2016) and converted into GtC using the conversion factors listed in BP (2016). Proven reserves in 2015 of oil are 200.5 GtC and of natural gas 104 GtC. This gives $S_0 = 304.5$ GtC.[16] We scale the stock of exploration capital to the global capital stock of \$ 150 trillion, so that $K_0 = \$12$ trillion as fossil fuel companies account for 8% of global market capitalization (Bullard, 2014). We set the depreciation rate δ to 5% per year.

- Extraction costs in 2015 account for \$30/barrel (T\$0.3/GtC) in 2015 while oil prices in 2015 average around \$55/barrel (T\$0.6/GtC) implying a scarcity value of \$25/barrel (T\$0.25/GtC) (Arezki et al. 2017; BP, 2016). Prices for natural gas move in tandem with oil prices. With extraction costs $\mathrm{G}(S) = \chi_0 (S_0 / S)^{\chi_1}$, we have $\chi_0 = \mathrm{G}(S_0) = 0.3$ T\$/GtC. Only 12% of the world economy prices carbon emissions and the average price charged is only \$8/tCO2 or \$29/tC (Fischer and Pizer, 2019). For simplicity, we thus assume that initially carbon emissions are not priced at all, so $p(0) = G(S_0) + h_0 = 0.55$ T\$/GtC. We calibrate the exponent of the extraction cost function to ensure that this relation holds for the business-as-usual simulation. This gives $\chi_1 = 1.25$.

- We suppose that world GDP is given by a simple trend, $Y(t) = Y(0)(1+g)^t$, where initial GDP in 2015 $Y(0)$ equals \$75.5 trillion and the trend rate of annual economic growth g is 2% and the real interest rate 4% per year. Carbon emissions from oil and gas amounted globally to 5.9 GtC in 2015 (BP, 2016). We specify iso-elastic global energy demand $\Phi(p+\tau) = AY(p+\tau)^{-\varepsilon}$, where the price elasticity ε is set to 0.8 and the income elasticity to 1. These price and income elasticities are in line with those reported by Fouquet (2014, Figure 4) for the period 1950-2010.[17] Utility from energy is $\mathrm{U}(R+B) = AY^{1/\varepsilon}(R+B)^{1-1/\varepsilon} / (1-1/\varepsilon)$ with $A = 5.9 \times 0.55^{0.8} / 75.5 = 0.048$ to match current oil and gas use. This implies an oil/gas energy share in final goods output of 4.3%.

- Investment in the oil and gas industry amounts to \$1 trillion in 2015 (IEA, 2018) and discoveries matched extraction of 5.9 GtC as growth in reserves in 2015 was negligible. With discoveries $\mathrm{D}(K) = \alpha_0 K^{\alpha_1}$, we calibrate $\alpha_0 = 0.915$ and $\alpha_1 = 0.75$ so that business-as-usual investment and discoveries match their 2015 values, given that we set the adjustment cost parameter ϕ to 0.1 (Hall, 2004) and $K_0 = 12$.

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[16] Together with 366 GtC of proven coal reserves, BP estimates total proven reserves of 670 GtC (2,456 GtCO2) which deviates somewhat from the 791 GtC (2,900 GtCO2) in McGlade and Ekins (2015). We abstract from coal and focus at oil and gas exploration.
[17] This study suggests that the income elasticities for domestic heating and passenger transport are roughly one, but a little less for lighting. The price elasticities for recent decades are somewhat lower than 0.8.

- We set the initial production cost of renewable energy prohibitively high at 2 T$/GtCe. We assume that in 2200 a technological breakthrough makes renewable energy competitive and forces the oil and gas companies out of business. This assumption allows us to assume a distant but finite horizon even under business as usual. In contrast to the oil and gas industry, the renewable energies industry has no scarcity rents and does not generate profits.

- The remaining carbon budget is 400 GtC (200 GtC) for a temperature target of 2° (1.5°C) (Millar et al., 2017; Goodwin et al., 2018).[18] Since these carbon budgets include emissions from coal as well, we rely on McGlade and Ekins (2015) who state that 100 GtC of coal are burnt under a 2°C target. Hence, our carbon budget for oil and gas only is $\bar{E} = 300$ GtC (or 150 GtC).[19] This is less than initial reserves of 304.5 GtC and implies that some proven oil and gas must remain under ground even if exploration ceases immediately. We follow Allen (2016) and van der Ploeg (2018) and use a TCRCE of 2°C per trillion ton of C, we have γ_1 = 0.002. The above is consistent with equation (1) if we set γ_0 = (2 – 0.002 x 400) = 1.2°C.

Our calibration is summarized in Table 2.

We solve the model numerically using the CONOPT of GAMS for 190 periods which is sufficiently long to include the end of the fossil fuel era. Given that after this point all state variables remain constant, we do not need to allow for continuation values.

Table 2: Calibration summary

Interest rate, depreciation rate, adjustment cost parameter	r = 0.04/year, δ = 0.05/year, ϕ = 0.1
Exploration: $\mathrm{D}(K,C) = \alpha_0 K^{\alpha_1} \exp(-\alpha_2 C)$	α_0 = 0.915, α_1 = 0.75, K_0 = \$12 trillion
Extraction: $\mathrm{G}(S) = \chi_0 (S_0 / S)^{\chi_1}$	χ_0 = 0.3, χ_1 = 1.25 and S_0 = 304 GtC
Demand: $\Phi(p+\tau) = AY(p+\tau)^{-\varepsilon}$	A= 0.048, Y = 75.5 T$/year, g = 2%/year, ε = 0.8
Cost of renewable energy $b(t) = b_0$	$b_0 = 2$
Peak warming: $PW = \gamma_0 + \gamma_1 E$	$\gamma_0 = 1.2$ °C, $\gamma_1 = 0.002$ °C /GtC, $PW \leq 2$ °C

6.2. Business as usual: steadily growing exploration and excessive warming

With no climate policy, fossil fuel remains competitive for an extended period and fossil fuel companies invest heavily into exploration of new fossil fuel reserves. As depicted in Figure 2

[18] Pricing carbon will shut off most of coal, so most of this relates to cumulative emissions of oil and gas.
[19] This is consistent with McGlade and Ekins (2015) who state that proven resources are about the same as the carbon budget for a 2°C target. Their headline finding that 50% of oil and gas and 80% of coal in situ must be abandoned to keep global mean temperature below 2˚C, refers to estimates of probable reserves which will become available over the century. We endogenize exploration and hence set initial reserves to proven reserves in 2015.

(black, solid) sustained investment implies continued growth of discoveries and reserves, matching recent historical trends. Growing reserves make fossil fuel more abundant and lower extraction costs. The scarcity rent continues to increase, however, as demand is growing rapidly as well. The fossil fuel era last until 2200 at which point (by our choice of calibration) the cost for renewable energy drops to a sufficiently low level to force fossil fuels out of the energy market. The reserves and stock of exploration capital become economically obsolete. As reported in Table 3, a total of 18 GtC and $272 trillion are abandoned since their user value has diminished to zero. These are examples of the stranded assets effect 1 and 2 mentioned in the introduction. Since this twilight of the oil and gas companies is still nearly two centuries away and exponentially increasing fossil demand bolsters their coffers, these companies are valued at $29 trillion today. In total, the oil and gas companies discover 8,887 GtC in new reserves and extract and sell 8,600 GtC, 1,366 GtC of which are extracted in this century. This is more than three times the total carbon budget for a 2°C target (including coal) and implies warming of more than 4°C by the end of this century, illustrating the size of the climate policy challenge. Stranded asset effects 3 and 4 do not occur under business as usual because policy is absent. Since climate policy is imposed in the absence of any modelled damages from climate change, social welfare increases by a total of $87.5 trillion, relative to welfare under the first-best tax.

Table 3: Summary results of first- and second-best policy simulations

	Business as usual	First-best tax	Second-best I (delayed tax)	Second-best II (ren. subsidy)
Switch to carbon-free era, T	2200	2068	2066	2053
Locked-up carbon, $S(T)$	18 GtC	170 GtC	168 GtC	171 GtC
Cumulative oil and gas discoveries	8,600 GtC	165 GtC	163 GtC	166 GtC
Cumulative emissions, $E(T)$	8,887 GtC	300 GtC	300 GtC	300 GtC
Final stock exploration capital, $K(T)$	272.1 $T	1.3 $T	1.3 $T	2.9 $T
Initial stock market value, $V(0)$	29.0 $T	21.9 $T	25.4 $T	28.2 $T
Initial value of capital, $q(0)$	1.009	0.924	0.987	1.006
Initial exploration investment, $I(0)$	1.1 $T/yr	0.0 $T/yr	0.0 $T/yr	0.7 $T/yr
Initial scarcity rent on oil and gas, $h(0)$	245 $/tC	192 $/tC	223 $/tC	241 $/tC
Social welfare, difference to first-best	87.5 $T	0 $T	- 2.4 $T	- 119.7 $T

Key: All scenarios except business as usual limit cumulative carbon emissions to 300 GtC.

6.3. First best: Immediate implementation of carbon tax to keep global warming below 2°C

To limit global warming and curb demand for fossil fuel, the government can impose a carbon tax which limits cumulative emissions to 300 GtC. Cost-efficient policy immediately implements a carbon tax of $180 per tC ($ 49 per tCO2) which grows exponentially at a rate equal to the

Figure 2: Policy simulations for first- and second-best policies

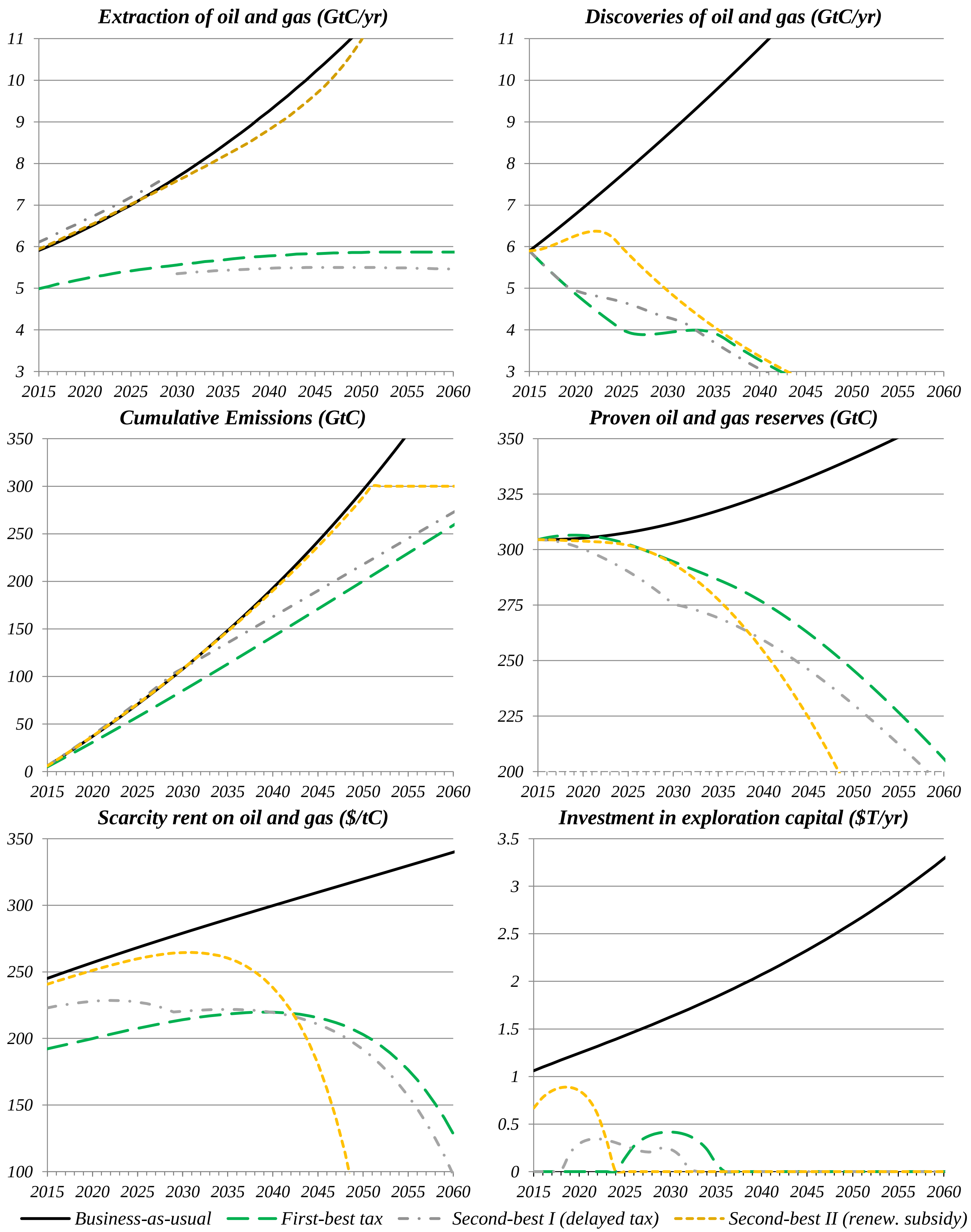
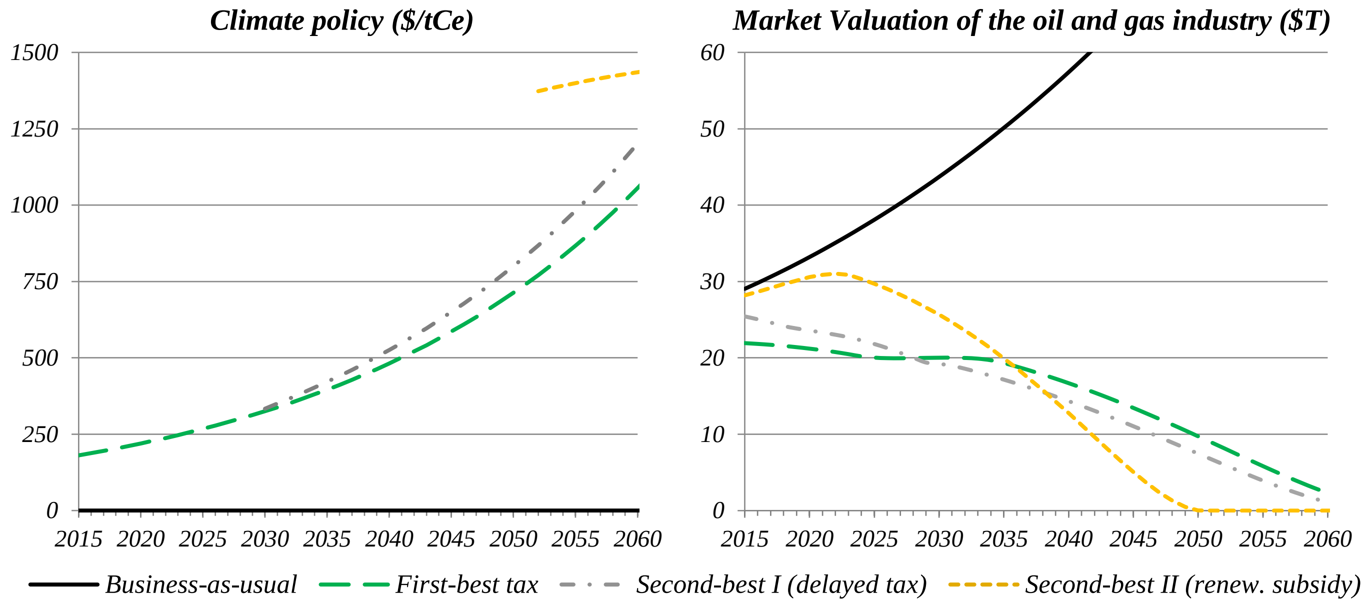


Figure 2 (*con't*): Policy simulations for first- and second-best policies



market rate of interest (4% per year) until fossil fuel is priced out of the market in 50 years' time.[20] After the end of the fossil era only a maintenance tax is required which moves in tandem with the cost for renewable and fossil energy, maintaining a wedge such that fossil fuel remains uncompetitive despite any occasional discoveries in oil and gas reserves which might occur in the future. This forceful pricing of carbon shifts downward the demand for fossil fuel and the extraction trajectory in Figure 2 (green, long-dashed). As a result, investment in exploration capital grinds to a halt, lowering the stock of exploration capital and the rate of new discoveries. Once the oil and gas companies have adjusted to the new policy environment, exploration investment briefly resumes to provide new discoveries which keep extraction costs at optimally low levels. This plateauing of discoveries at 4 GtC per year only last a brief period as the carbon budget is nearly used up and, anticipating the end of its business, the oil and gas companies slowly wind down capital and reserves before they finally close shop. A total of 170 GtC and $1.3 trillion of natural and physical assets are abandoned (stranded assets effect 1 and 2). Carbon pricing and its intended consequence of lower cumulative use immediately bite into the scarcity rent on existing reserves (which falls by 22 percent to $192). This drop of $53 per tC is more than compensated by the carbon tax of $180 per tC and demand falls. The current value of oil and gas companies drops by $7 trillion or 25% to $22 trillion under the first-best carbon tax (stranded asset effect 3).

[20] Using the DICE2016R model of Nordhaus (2017), we obtain a price of $236 per tC when setting mitigation prior to 2015 to zero, limit anthropogenic emissions from the start of the fossil era to 1000 GtC, and account for annual inflation of 2 percent.

7. Second-best climate policy simulations

7.1. Keeping temperature below 2°C with a delayed carbon tax

Politicians like to kick the can down the road and pass an increasingly hard problem to their successors. To capture this aspect of climate policy, we allow for 15 years of inaction followed by a credible, albeit hard commitment to doubled-down policy efforts which still ensure that cumulative emissions are kept below 300 GtC. In anticipation of carbon pricing and depressed demand, the scarcity rent on fossil reserves falls by $22 per tC, increasing demand by 0.2 GtC (3.4 percent) relative to business as usual (grey, dot-dashed in Figure 2). This comparatively small green paradox effect is due to virtually all existing fossil fuel reserves remaining burnable and policy only impacting the scarcity rent indirectly through the lower future demand. The announced policy also decreases the price of and investment in exploration capital.

The delay in policy shifts the reductions in demand from today to future, where they must be more forceful due to green paradox effects. This protects the business model of oil and gas companies initially but clobbers it later. Due to positive discounting and depreciation of existing assets over time, delayed implementation of climate policy protects profitability of the oil and gas companies and softens the reduction in market capitalization from $7.1 trillion (under first-best) to $3.6 trillion but the value of the oil and gas companies still drops to $25.4 trillion (by 12% from its business-as-usual value). While investment in exploration capital is halted initially, it resumes at low levels for a brief period to soften the decline in discoveries relative to business as usual. The carbon budget is used up in 2066, slightly earlier than under the first-best carbon tax due to the weak green paradox effect in this second-best scenario. Cumulative fossil fuel discoveries and the amounts of abandoned reserves and capital are akin to those in the first-best case. The overall welfare cost of delaying the imposition of the carbon tax equals $2.4 trillion.

7.2. Keeping temperature below 2°C with a renewable energy subsidy

While the "stick" of the carbon tax is the efficient instrument to curb fossil fuel use in the light of climate change, the "carrot" of the renewable energy subsidy might be more appealing. Here, we study the effect of such an inefficient (but perhaps necessary due to political constraints) second-best subsidy to oil and gas companies (yellow, short-dashed in Figure 2). If the announcement of this renewable subsidy is credible, it only leads to a slight drop in the scarcity rent (of $4 per tC) and a miniscule increase in extraction which increases (by less than 1% relative to business as usual in the next three decades – the green paradox effect). Investment falls by one third and, due to lower exploration, the rate of discoveries also falls below business as usual. The initial market capitalization is curbed by a mere $0.8 trillion (a 3% reduction). Unhampered growth in fossil fuel demand combined with an abrupt shift to carbon-free renewables leaves a high amount of physical assets stranded ($2.91 trillion). This shift to renewable energy would be less abrupt if substitution between the two energy types would be imperfectly elastic. Comparing policy designs, the second-best policy which delays a reduction in fossil fuel demand for as long as possible is the preferred option for the oil and gas companies as this allows a higher utilization of existing reserves and capital assets for longer, thereby minimizing the reduction in their current wealth and market capitalization. The welfare cost of using a renewable subsidy, however, is very large, amounting to $119.7 trillion.

8. Policy-tipping simulations and stranded assets

So far, we have assumed that policies once announced will be implemented with certainty. In this section we study (and plot in Figure 3) the case where policy makers vow not to exceed the safe carbon budget by implementing policy in 15 years but due to the election cycle, odious rent-seeking by the fossil fuel industry, or some other political constraints only manage to do so with some probability π, which is set to 50 percent in our simulations. Thus, there is a 50-50 chance in the scenario labelled "safe or none" that either a tax will indeed be implemented in 2030 or business as usual continues indefinitely. In a variant of this scenario, we move uncertainty about policy from the carbon budget itself (i.e. to tax or not to tax carbon) to the timing of policy implementation. In the scenario labelled "safe or sorry" policy makers manage to keep within the carbon budget but the timing of the introduction of climate policy is uncertain. Carbon pricing is implemented with a 50-50 chance either in 15 years' time or business is usual is permitted to continue for another 15 years at which point policy makers are sorry and forcefully price fossil fuels out of the market. We call this second branch of the decision tree the "sorry branch" in Figure 3. The introduction of uncertainty allows us to study the repricing of assets once uncertainty is removed (stranded asset effect 4) in addition to the effect that uncertainty has on current pricing (stranded asset effect 3) and the amount of natural and physical assets abandoned at the end of the fossil era (stranded assets effect 1 and 2). Since the "safe or none" scenario reduces to business as usual with $\pi = 0$ and to the "second-based I (delayed tax)" scenario with $\pi = 1$, we take these from Figure 2 and include them in Figure 3 as well.[21] Table 4 gives a summary outcome of the policy-tipping scenarios.

If policy makers announce future climate policy which materializes only with 50 percent chance (i.e. the "safe or none" scenario), firms and households and especially the oil and gas companies

[21] The formatting of Figure 3 combines colour coding (blue for "safe or none", red for "safe or sorry", and as before black for business as usual and grey for a certain but delayed tax) and different styles (solid for pre-tipping, long-dashed for tipping into immediate carbon taxing, short-dashed into no taxing, and dot-dot-dashed into delayed taxing).

adjust their expectations with the announcement. With safe carbon taxation materialized (blue, long-dashed in Figure 3), fossil fuel use drops sharply while a botched policy attempt (the “none” branch) allows unfettered growth in fossil fuel use. Even before the tipping point in 2030, these future developments are captured already in today’s forward-looking prices (the scarcity rent and the marginal value of exploration capital) and thus in exploration investment and the market capitalization too. With the announcement of uncertain climate policy, the scarcity rent jumps down below its business-as-usual value. However, the drop is less than in the “second-best I (delayed tax)” scenario, since there is still a 50 percent chance that the announcement turns out to be an empty promise.

Table 4: Summary results of policy-tipping simulations

	Business-as-usual	Safe or none, tax applied	Safe or none, tax botched	Safe or sorry, tax applied	Safe or sorry, tax delayed
Switch to carbon-free era, T	2200	2066	2200	2066	2060
Locked-up carbon, S(T)	18 GtC	183 GtC	18 GtC	174 GtC	170 GtC
Cumulative discoveries	8600 GtC	179 GtC	8589 GtC	169 GtC	165 GtC
Cumulative emissions, E(T)	8887 GtC	300 GtC	8876 GtC	300 GtC	300 GtC
Final stock of capital, K(T)	272.1 $T	1.4 $T	272.1 $T	1.3 $T	1.9 $T
Initial stock market value, V(0)	29.0 $T	26.6 $T	26.6 $T	26.4 $T	26.4 $T
Initial value of capital, q(0)	1.009	1.001	1.001	0.998	0.998
Initial investment, I(0) ($T/year)	1.1 $T	0.1 $T	0.1 $T	0.0 $T	0.0 $T
Initial scarcity rent, h(0)	245 $/tC	234 $/tC	234 $/tC	230 $/tC	230 $/tC
Social welfare, diff. to first-best	87.5 $T	-2.2 $T	86.9 $T	-2.2 $T	-7.4 $T

Key: All scenarios except business as usual and policy tipping I (botched carbon tax) limit cumulative carbon emissions to 300 GtC.

Once uncertainty is resolved in 2030, the paths diverge for the two branches of the diagram in Figure 1. In case the carbon tax materializes, the scarcity rent drops discretely, while it jumps up if plans for carbon pricing are scrapped (stranded asset effect 4). In the latter case, the scarcity rent jumps above the business-as-usual level as policy uncertainty lowers exploration investments before the tip and proven reserves in 2030 are scarcer than under business as usual. The scrapping of carbon pricing leads to a boom in exploration investment (which amounts to $4.9 trillion in 2030, outside the panel of Figure 3).

Discoveries surge and proven reserves gradually approach the business-as-usual growth path. With the viability of the oil and gas industry’s business model confirmed, market valuation of oil and gas companies jumps from $23.7 to $33.4 trillion. At the tipping point, oil and gas extraction jump upward in the case where the carbon tax is abandoned but do not reach the business-as-usual level due to the higher scarcity rent and higher extraction cost of fossil fuel. As time progresses, newly funded discoveries replenish the stock of proven reserves, extraction approaches the

Figure 3: Policy simulations under the risk of policy tipping

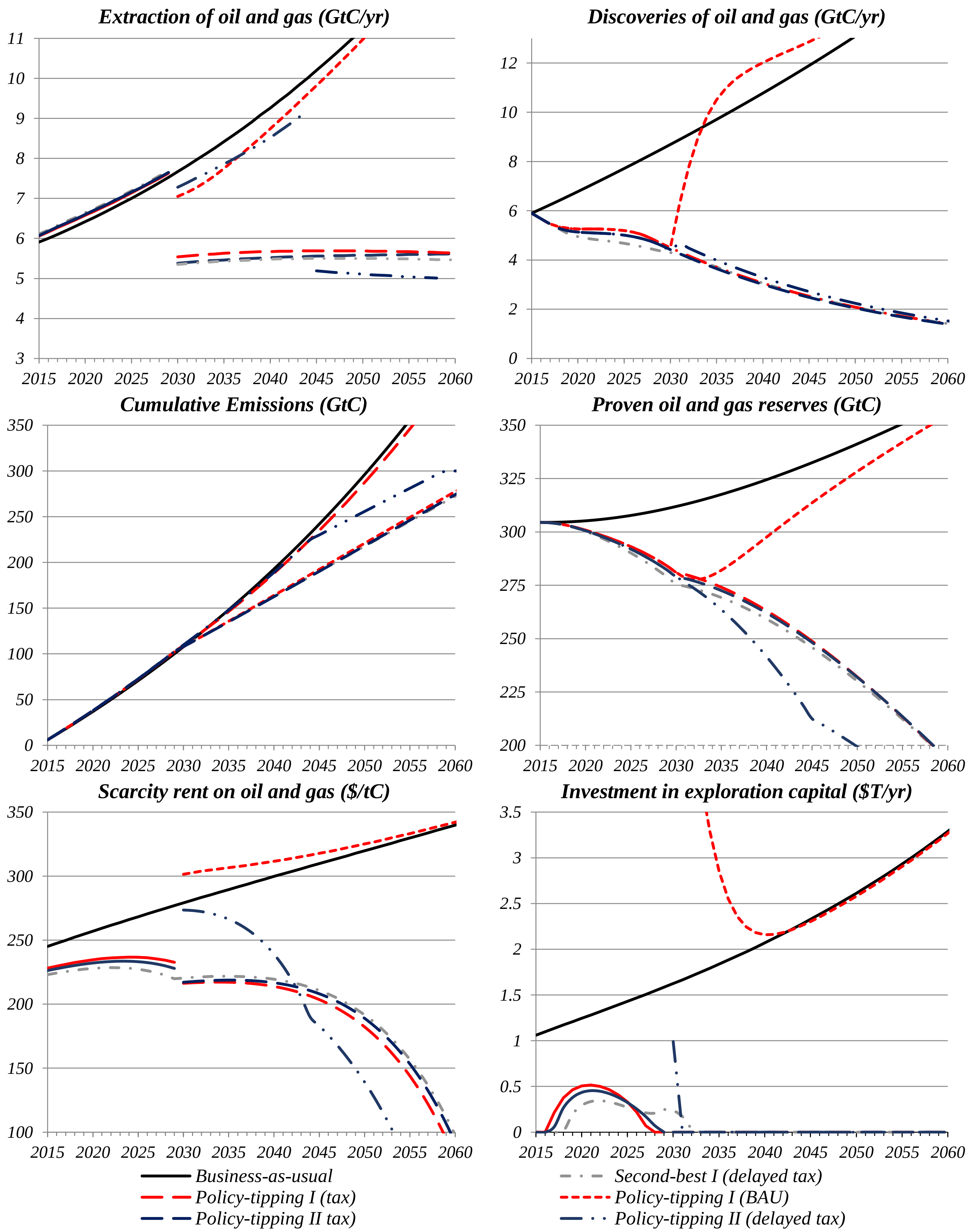
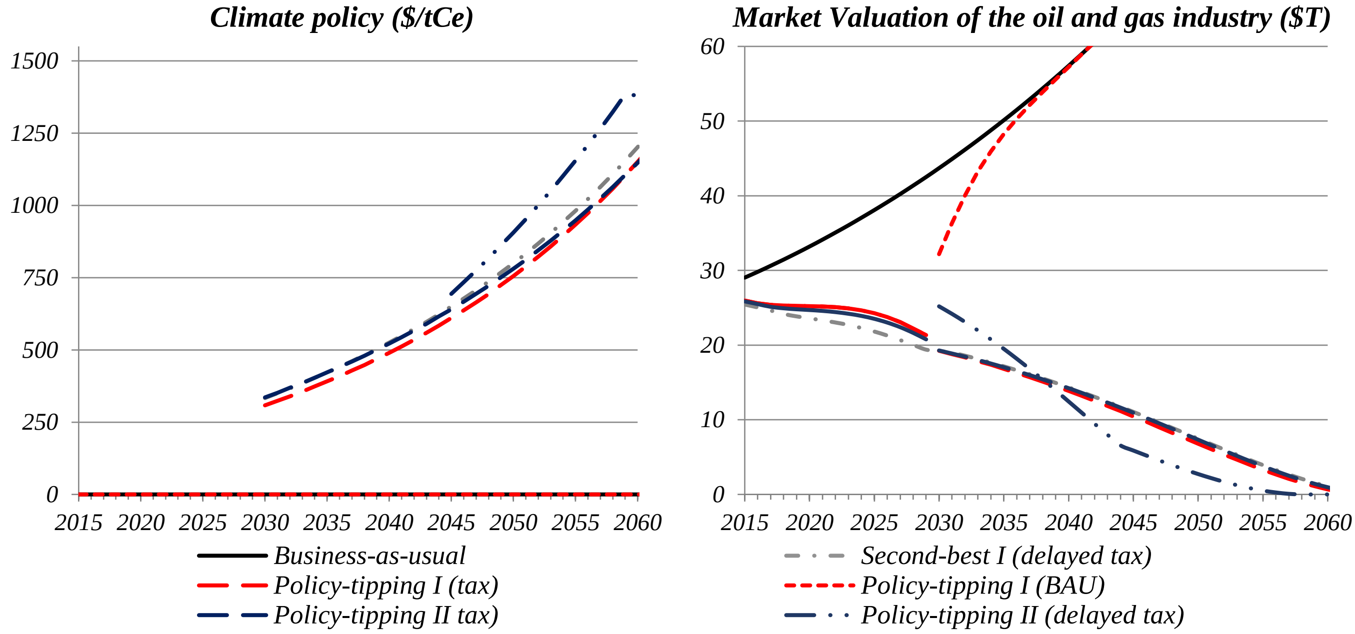


Figure 3 (*con't*): Policy simulations under the risk of policy tipping



business-as-usual growth path. In case the announced carbon tax indeed materializes, extraction drops by 2 GtC per year (due to a carbon tax of $348 per tC) and remains at a depressed level until the carbon budget is fully used up. The scarcity rent drops by nearly $50 to $198.5 per tC (stranded asset effect 4). With no prospect of a recovery in oil and gas demand, the oil and gas industry scraps all investment and runs down existing exploration capital, depleting existing reserves as discoveries fail to keep up with extraction. The prospect of a slow withering of the industry leads to a drop in their market valuation from $23.7 to $17.5 trillion. This discrete jump downward corresponds to bursting of the so-called "carbon bubble". An additional drop in market value occurs previously when agents first become aware of the possibility of carbon pricing (stranded asset effect 3, the difference between the solid black and solid red lines at the beginning in 2015 in Figure 3). In reality this drop is more likely to be a gradual downward adjustment as the probability of policy tipping gradually rises and the carbon budget gets gradually exhausted. In the second policy-tipping scenario "safe or sorry" we show how uncertainty about timing of climate policy (rather than the size of the allowed carbon budget) affects the behaviour of oil and gas firms. There is a 50-50 chance for policy to be implemented either after 15 years (blue, long-dashed) or after 30 years (blue, dot-dot-dashed). Compared to the scenario "second-best II (delayed tax)" where policy is implemented with certainty after 15 years, this cascading of policy introduces weaker green paradox effects as there is a 50 percent chance for fossil fuel demand to continue unfettered for an additional 15 years. The scarcity rent on existing reserves does not drop as much initially but more than in the “safe or none” policy tipping scenario in which there is the 50 percent chance for carbon to remain untaxed forever rather than an additional 15 years.

After 15 years uncertainty about the timing of climate policy is resolved and the agents find themselves in a world of certainty: carbon is taxed either now (the “safe branch” or in 15 years’ time (the “sorry” branch). In case of immediate carbon pricing, fossil fuel demand is depressed by an exponentially growing carbon tax until the carbon budget is used up. All investment ceases and proven reserves are run down as discoveries fail to meet extraction. The tax necessary is lower than along the safe branch of the “safe or none” case as past exploration investment has been lower and current extraction costs are higher. For the same reason, the scarcity rent on existing reserves falls less than in this case. Oil and gas companies might also find themselves in a world where carbon is not taxed for another 15 years. Here, the scarcity rent jumps upward since fossil fuel can be used for longer. With the spectre of climate policy looming large, however, investment remains subdued despite the increase in the scarcity rent. Without these funds for new discoveries, the stock of proven reserves falls rapidly to lower levels than in the case where carbon is taxed immediately. Once the 15-year bonanza is over, however, climate policy is introduced more aggressively, cutting fossil fuel use nearly in half. Since this introduction has been anticipated with certainty, there are no jumps. The market valuation of the oil and gas industry drops from \$29.0 trillion under business-as-usual to \$26.4 trillion with the announcement of uncertain climate policy. After 15 years, the valuation drops from \$22.1 to \$18.4 trillion if carbon is indeed taxed but jumps up by nearly \$3 trillion to \$25.0 trillion if climate policy is kicked down the road yet again. This hiatus is short-lived. Market valuation drops below that of immediate carbon pricing even before the tax is introduced as the period of very low sales is anticipated correctly by shareholders.

9. Robustness to a 1.5°C target, lower demand elasticity, and higher adjustment costs

In our baseline calibration climate policy for 2°C lowers valuations of natural and physical capital in oil and gas industry considerably. The magnitude of these changes depends crucially on the ambition of climate policy, its effect on fossil fuel demand, and the ease with which capital can be adjusted as shown in Tables 5-7 below. Online Appendix B gives further robustness results.

9.1. A 1.5°C target

Lowering the climate ceiling to 1.5°C halves the carbon budget to 150 GtC (plus an additional 50 GtC for coal use). The first-best carbon tax increases from $180 to $434 per tC.[22] As reported in Table 5 this weans the economy from fossil fuel by 2050 and puts the oil and gas industry under severe pressure. The scarcity rent on existing reserves falls to $99 per tC and the stock market valuation drops from $29 to $5.7 trillion. Kicking the can down the road, either in the form of a delayed carbon tax or a renewable energy subsidy mitigates this collapse in shareholder value to $9.7 trillion and $10.1 trillion, respectively, but at the cost of bringing nearer the time of bankruptcy of the oil and gas industry to 2038 and 2033, respectively. In case there is only a 50 percent chance of the carbon budget being kept, the shareholder value increases further to $22.2. The second case of policy tipping (where policy is either implemented in 15 or 30 years) is incompatible with a climate target of 1.5°C. Carbon emissions would have to be taxed after 17 years at the latest to keep cumulative emissions below 150 GtC.

Table 5: Summary results of policy simulations for 1.5°C

	BAU	1st best tax	2nd best tax delayed	2nd best renewable subsidy	Safe or none, tax applied	Safe or none, tax botched
Switch to carbon-free era, T	2200	2050	2038	2033	2043	2200
Locked-up carbon, S(T)	18 GtC	270 GtC	246 GtC	233 GtC	258 GtC	18 GtC
Cumulative discoveries	8600 GtC	116 GtC	92 GtC	78 GtC	103 GtC	8586 GtC
Cumulative emissions, E(T)	8887 GtC	150 GtC	150 GtC	150 GtC	150 GtC	8873 GtC
Final stock of capital, K(T)	272.1 $T	2.0 $T	3.7 $T	4.8 $T	2.9 $T	272.1 $T
Initial stock market value, V(0)	29.0 $T	5.7 $T	9.7 $T	10.1 $T	22.2 $T	22.2 $T
Initial value of capital, q(0)	1.01	0.35	0.39	0.40	0.83	0.83
Initial investment, I(0)	1.1 $T/yr	0 $T/yr	0 $T/yr	0 $T/yr	0 $T/yr	0 $T/yr
Initial scarcity rent, h(0)	245 $/tC	99 $/tC	149 $/tC	152 $/tC	207 $/tC	207 $/tC
Social welfare, diff to first-best	128.0 $T	0.0 $T	-19.8 $T	-316.7 $T	-11.0 $T	126.3 $T

Key: All scenarios except business-as-usual and policy tipping I (tax botched) limit cumulative carbon emissions to 150 GtC.

9.2. A lower price elasticity of energy demand

The impact of climate policy on the stock market valuation of the oil and gas industry is directly linked to the ease with which fossil fuel use can be affected by policy. In a second sensitivity check, we decrease the price elasticity of energy demand ε from 0.8 to 0.3.[23] A lower price

[22] Using the DICE2016R model of Nordhaus (2017), we obtain a very similar price of $420 per tC if we set mitigation prior to 2015 to zero, limit anthropogenic emissions from the start of the fossil era to 750 GtC, and account for annual inflation of 2 percent.

[23] In decreasing the elasticity of demand without adjusting other parameters (e.g. the utility parameter A) some calibration points are not met anymore (e.g. initial extraction decreases from 5.9 GtC to 4.5 GtC).

elasticity implies that extraction is less responsive to reductions in extraction costs and, hence, the oil and gas industry to invest less exploration capital as reported in Table 6.

Cumulative discoveries and emissions fall by roughly 1,200 GtC each compared to the baseline business-as-usual scenario. For the same reason, climate policy must be more aggressive by increasing the first-best carbon tax to \$198 per tC to depress demand for fossil fuel (despite it starting at a lower business-as-usual level, see footnote 23). The impact of the carbon tax is, however, more muted with market valuation of oil and gas companies falling only by \$3.2 trillion to \$20.4 trillion, a drop of 14 percent compared to 24 percent of the baseline case. Second-best policies mitigate this drop as before with stock market values falling to \$21.7 trillion and \$23.3 trillion (by 8 percent and 1 percent) if the introduction of the tax is delayed or a renewable subsidy is used, respectively. The introduction of uncertainty lowers the losses due in climate policy in shareholders' wealth as in the baseline calibration. In the tipping I and II scenarios the market valuation drops to \$22.7 trillion and \$22.3 trillion, respectively. The small (relative) magnitude of changes in prices and valuations in combination with the greater amounts of physical capital abandoned at the end of the fossil era indicates that less elastic energy demand leads to lower immediate losses in wealth but higher losses for oil and gas companies in the future.

Table 6: Summary results of policy simulations for lower price elasticity, ε

	BAU	1st best tax	2nd best tax delayed	2nd best renewable subsidy	Safe or none, tax applied	Safe or none, tax botched	Safe or sorry, tax applied	Safe or sorry, tax delayed
Switch to carbon-free era, T	2200	2066	2065	2060	2065	2200	2065	2063
Locked-up carbon, S(T)	92 GtC	170 GtC	169 GtC	171 GtC	171 GtC	92 GtC	170 GtC	170 GtC
Cumulative discoveries	7405 GtC	166 GtC	165 GtC	166 GtC	166 GtC	7404 GtC	165 GtC	165 GtC
Cumulative emissions, E(T)	7617 GtC	300 GtC	300 GtC	300 GtC	300 GtC	7617 GtC	300 GtC	300 GtC
Final stock of capital, K(T)	247.3 \$T	1.6 \$T	1.6 \$T	2.1 \$T	1.5 \$T	247.3 \$T	1.6 \$T	1.8 \$T
Initial stock market value, V(0)	23.6 \$T	20.4 \$T	21.7 \$T	23.3 \$T	22.7 \$T	22.7 \$T	22.3 \$T	22.3 \$T
Initial value of capital, q(0)	0.97	0.89	0.92	0.95	0.95	0.95	0.93	0.93
Initial investment, I(0)	0.0 \$T/yr	0.0 \$T/yr	0.0 \$T/yr	0.0 \$T/yr	0.0 \$T/yr	0.0 \$T/yr	0.0 \$T/yr	0.0 \$T/yr
Initial scarcity rent, h(0)	205 \$/tC	177 \$/tC	189 \$/tC	200 \$/tC	197 \$/tC	197 \$/tC	193 \$/tC	193 \$/tC
Social welfare, diff to first-best	88.3 \$T	0.0 \$T	-0.9 \$T	-34.8 \$T	-0.8 \$T	88.3 \$T	-0.9 \$T	-2.8 \$T

Key: All scenarios except business as usual and policy tipping I (tax botched) limit cumulative carbon emissions to 300 GtC.

9.3. Higher adjustment costs

We now increase the adjustment cost parameter ϕ from 0.1 to 0.5. If it is costlier to build up exploration capital, the existing capital stock becomes more valuable. The results reported in Table 7 show that most variables are hardly affected by the change in ϕ: investment falls and the scarcity rent increases somewhat relative to the baseline calibration. The amounts of natural and physical assets abandoned at the end of the fossil era change hardly at all. Stock market valuations are affected most. With existing capital becoming more valuable, market capitalization of the oil and gas industry increases by 10 percent to $32.7 trillion under business as usual.

The effect of policy is also more pronounced with the stock market valuation dropping by 32 percent, 21 percent, and 10 percent under the first- and second-best carbon taxes and renewable subsidy, respectively, compared to drops of 24 percent, 12 percent, and 3 percent for the same scenarios in the baseline calibration. Under the tipping I and II scenarios, relative changes in stock market values are also greater with 12 percent and 17 percent compared to the 8 percent and 9 percent under baseline. This indicates that the problem of stranded assets and the risk of policy tipping on market valuations of carbon-based companies are worse if it is costlier to adjust past investments.

Table 7: Summary results of policy simulations for higher adjustment costs, ϕ

	BAU	1st best tax	2nd best tax delayed	2nd best renewable subsidy	Safe or none, tax applied	Safe or none, tax botched	Safe or sorry, tax applied	Safe or sorry, tax delayed
Switch to carbon-free era, *T*	2200	2068	2066	2053	2066	2200	2066	2060
Locked-up carbon, *S*(T)	18 GtC	167 GtC	166 GtC	167 GtC	191 GtC	18 GtC	172 GtC	167 GtC
Cumulative discoveries	8371 GtC	163 GtC	162 GtC	163 GtC	186 GtC	8356 GtC	167 GtC	163 GtC
Cumulative emissions, *E*(T)	8658 GtC	300 GtC	300 GtC	300 GtC	300 GtC	8643 GtC	300 GtC	300 GtC
Final stock of capital, *K*(T)	268.2 $T	1.3 $T	1.3 $T	2.9 $T	1.6 $T	268.2 $T	1.3 $T	1.9 $T
Initial stock market value, *V*(0)	32.7 $T	22.4 $T	25.9 $T	29.4 $T	28.7 $T	28.7 $T	27.2 $T	27.2 $T
Initial value of capital, *q*(0)	1.07	0.94	1.00	1.05	1.03	1.03	1.02	1.02
Initial investment, *I*(0)	0.9 $T/yr	0.0 $T/yr	0.0 $T/yr	0.6 $T/yr	0.3 $T/yr	0.3 $T/yr	0.2 $T/yr	0.0 $T/yr
Initial scarcity rent, *h*(0)	249 $/tC	194 $/tC	224 $/tC	244 $/tC	235 $/tC	235 $/tC	232 $/tC	232 $/tC
Social welfare, diff to first-best	85.3 $T	0.0 $T	-2.3 $T	-114.5 $T	-2.3 $T	84.5 $T	-2.1 $T	-7.1 $T

Key: All scenarios except business-as-usual and policy tipping I curb total emissions to 300 GtC.

10. Conclusion

We have highlighted four aspects of stranded assets that occur if there is market uncertainty about when and if climate policies are implemented to ensure that global warming stays beyond a temperature cap. First, if climate policy is to keep global warming below a cap of 1.5° or 2°C, a substantial proportion of fossil fuel reserves must be abandoned at the end of the fossil era. Second, exploration capital will be stranded at the end of the fossil era too, especially if past investments are difficult to reverse. Third, unanticipated tightening of present or future climate policy causes an immediate drop in the market valuation of fossil fuel and exploration capital. The scarcity rent of fossil fuel and the price of capital drop instantaneously. Fourth, if timing and forcefulness of climate policy is uncertain, as discussed in section 8, additional revaluation of assets occurs once uncertainty is resolved at some future date. As soon as climate policy is unexpectedly stepped up, exploration capital and fossil reserves suffer a sudden loss in value while botching an announced stepping up of climate policy immediately boosts the scarcity rent and market capitalization of fossil fuel companies, leading to an investment boom in exploration and a surge in discoveries. Although the first and possibly the second effect are reasonably well known, we hope to have gained better understanding of the third and four effects.

Whether and to what extent assets become stranded depends on the climate policy instrument used. We allowed policy makers to use carbon taxes or renewable subsidies and to delay either. For society, the first-best instrument is an immediate carbon tax while delaying the tax increases the cost of policy. A renewable subsidy increases this cost further. Fossil-fuel firms, however, have the opposite ranking, when trying to preserve their market valuation. An immediate carbon tax lowers their profits from the start; a renewable subsidy kicks the can down the road, preserving profits and market share. These insights point to the paralysing complex political economy of climate policy. Given that firms and the government are price-takers in our model, we cannot explore strategic interactions between them properly and must leave such inquiries for future research. The same holds for more realistic extensions of our model to various interesting interactions between different types of fossil fuel and capital dynamics in the other sectors of the economy.

Our insights on stranded assets are in line with Carbon Tracker Initiative (2017) who calculate that \$2.3 trillion of upstream projects in the oil and gas industry, roughly a third of business-as-usual projects to 2025, are inconsistent with global commitments to limit climate change to a maximum 2˚C. This report provides a snapshot of the potentially unneeded capex spend for 69 global oil and gas companies, thus highlighting the wide-ranging degree of exposure amongst companies in the sector. However, more work is needed on the implications of global warming on the stock market, paying attention to differences between carbon-based industries and other industries when capital cannot be moved from one sector into another. An interesting first step in this direction has been made by and Karydas and Xepapadeas (2019), who decompose the disaster risks studied by Barro (2009) into those that are temperature related and those that are not and use a CAPM model to illustrate the effects of such risks on asset pricing, asset holdings and the social cost of carbon.[24] Investors and pension funds must take action to limit the systematic risk to their portfolio from global warming (cf. Carbon Tracker Initiative, 2011, 2013; Climate Counts, 2013; Generation Foundation, 2013; ESRB, 2016; Delis et al., 2019). For example, Andersson et al. (2016) show how to use carbon-free trackers to hedge climate risk. Although various Governors

[24] Bansal et al. (2015) and (2017) also analyse the effects of disaster risks on optimal climate policy and of long-run temperature shifts on capital market prices. See also Daniel et al. (2018).

of central banks have warned for the carbon bubble (e.g. Carney, 2015), it is not clear which capital markets regulators are held responsible for the oversight of such systemic risks and which authority ensures that full corporate disclosure of carbon risks takes place.

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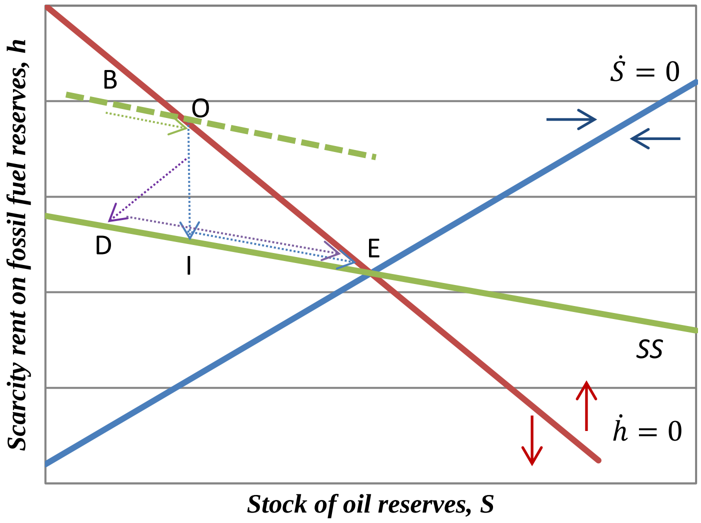
Online Appendix A: Analytic insights from simple model of discoveries and stranded assets

We assume here that there is no carbon-free energy backstop that perfectly substitutes for fossil fuel, so that the transition to the carbon-free era never takes place. Climate policies, however, still can impact fossil fuel use and must thus ensure that enough carbon is locked up, so that (8) is satisfied. We show how reserves and the scarcity rent react to step changes in the carbon tax for given exploration capital and discoveries in section A1. We then illustrate how exploration investment reacts to drops in the scarcity rent in section A2.

A1. Fossil fuel reserves and the scarcity rent

Given the stock of exploration capital, *K*, we solve for the stock of fossil fuel reserves and the scarcity rent from the phase diagram for the state-space system defined by (10a) and (10d) and shown in Figure A1. The locus of points for which $\dot{S}=0$ corresponds to those points for which fossil fuel demand equals exogenous discoveries. Since fossil fuel demand decreases in market price of energy which consists of the extraction cost that decreases in remaining reserves *S*, the scarcity rent *h* and the exogenous carbon tax, it is clear that the $\dot{S}=0$ locus must slope upwards (the slope is $-\mathrm{G}'(S)>0$) and furthermore that this locus must shift down if the carbon tax increases. This also locus shifts up if discoveries fall. This locus corresponds to the points for which the scarcity rent on *in situ* fossil fuel reserves, *h*, equals the present discounted value of future increases in extraction costs, which in equilibrium equals $-\mathrm{G}'(S)R/r$. Since fossil fuel use *R* depends negatively on the market price of fossil fuel, *R* increases in remaining reserves *S* (as it decreases in the extraction cost) and decreases in the scarcity rent *h* and the carbon tax. It follows that along the $\dot{h}=0$ locus *h* is a negative function of *S* (assuming G″ ≥ 0) and the locus shifts up if the carbon tax increases.

Figure A1: Dynamic effects of carbon tax on scarcity rent and reserves given discoveries



Key: The initial equilibrium is at O and the final equilibrium at E. The adjustment paths are indicated by the arrows. The blue dotted lines show what happens with immediate implementation. The purple dotted lines show what happens with a delayed carbon tax. The green dotted lines show what happens with a botched-up carbon tax.

The arrows in the diagrams show the direction of the phase-plane dynamics of this 2-dimensional system. It follows that the stable manifold corresponds to the downward-sloping locus *SS*. Any deviation of this saddle-path can only be sustained for a temporary period as might be the case with temporary or anticipated changes in the carbon tax. Saddle-path stability can also be verified from the determinant of the Jacobian matrix of the dynamic system being negative corresponding to the forward-looking, non-predetermined state variable *h* and the predetermined variable *S*. A sufficient condition for saddle-point behaviour is that the $\dot{h} = 0$ locus slopes downwards.

Before we discuss our two policy experiments, note that the steady-state effects of a carbon tax can be seen from the downward shift in the $\dot{S} = 0$ locus and the upward shift in the $\dot{h} = 0$ locus. As a result, the steady-state equilibrium shifts from O to E in Figure A1. The carbon tax leads in the long run to an unambiguous reduction in the scarcity rent and (provided the shift in the $\dot{S} = 0$ locus dominates the shift in the $\dot{h} = 0$ locus) to more locked-up fossil fuel reserves (higher *S*).

An immediately implemented, unanticipated carbon tax shifts down the $\dot{S} = 0$ locus. On impact markets the scarcity rent falls but by less than the carbon tax rises (see the dotted blue arrow to point I). Fossil fuel demand and the rate of depletion drop instantaneously. As the economy moves along *SS*, the rate of depletion is curbed further as the scarcity rent continues to rise and consequently the stock of *in situ* reserves rises. In the long run the amount of fossil fuel abandoned has fallen which ensures less global warming. Oil and gas companies are adversely affected, since rents have fallen, and reserves are stranded.

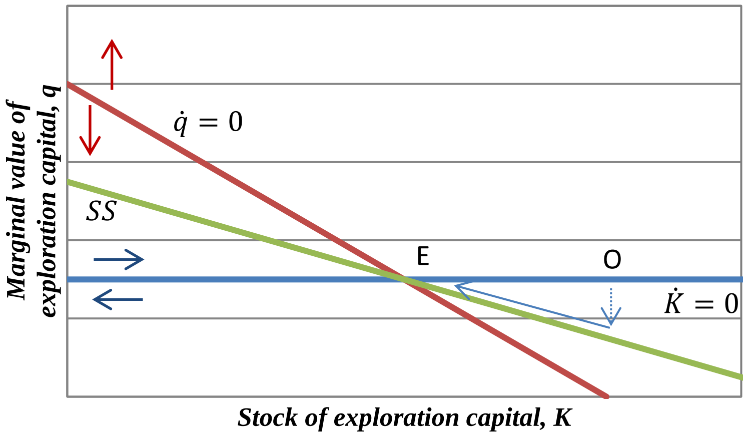
With an unanticipated, credible announcement of a future carbon tax, the scarcity rent falls *ahead of the tax* albeit less so than with immediate implementation (see the purple dotted arrow to point D). On impact fossil fuel demand and depletion jump up instantaneously. During the announcement period the scarcity rent falls and fossil fuel demand and depletion rise. Carbon emissions and global warming thus increase during this announcement period, the green paradox. Once the carbon tax strikes (when the purple dotted arrow hits the stable manifold *SS*), there is no discrete change in the scarcity rent as the news has already been discounted by market participants. However, fossil fuel demand and depletion immediately fall below their initial rates. Afterwards, along the stable arm *SS*¸ the scarcity rent continues to rise, and fossil fuel demand gradually rises back to its initial levels. The long run is as before with more abandoned reserves and less global warming.

If policy makers renege, the scarcity rent immediately jumps up at that future point of time to what it was before the announcement of a future carbon tax and as a result fossil fuel demand and depletion fall below discoveries (see dotted green arrow from point D to point B). Afterwards, the scarcity rent continues to drop thereby driving down fossil fuel demand and depletion to their original values (move along the green-dashed line, the old stable manifold). The stock of *in situ* reserves rises until what it was before the botched-up policy started.

A.2. Dynamics of the share price and the stock of exploration capital

We can see how the fall in the scarcity rent induced by the carbon tax affects exploration and the share price of energy companies by solving (given the time paths of the scarcity rent) for *K* and *q* from (10b) and (10e′) from the phase diagram in Figure A2. The horizontal $\dot{K} = 0$ locus corresponds to points for which exploration capital and discoveries are constant, i.e. $q = 1 + \phi\delta$. The $\dot{q} = 0$ locus slopes downwards due to the diminishing marginal productivity of exploration capital. The stable manifold *SS* slopes downwards. A step reduction in the scarcity rent shifts out the $\dot{q} = 0$ locus. On impact *q* and exploration investment fall instantaneously. As *q* recovers, the investment rate gradually reverses back. Hence, there are lower stocks of exploration capital and discoveries.

Figure A2: Effects of drop in the scarcity rent on capital and its marginal value



Key: The initial equilibrium is O and the final equilibrium is E. On impact *q* jump down along the dotted blue arrow. Afterwards, they recover as the move along the stable manifold SS.

Online Appendix B: More details on policy simulations and sensitivity

In Figures 2 and 3 we only report simulation results for the first 45 years until 2060 to highlight the impact of climate policy for 2°C and 1.5°C on the oil and gas industry. Here we redraw for a longer time horizon Figures 2 and 3 combined in one Figure B1 to provide more details on the simulations conducted in the baseline calibration.

Figure B1: Policy simulations for all policy scenarios over the century

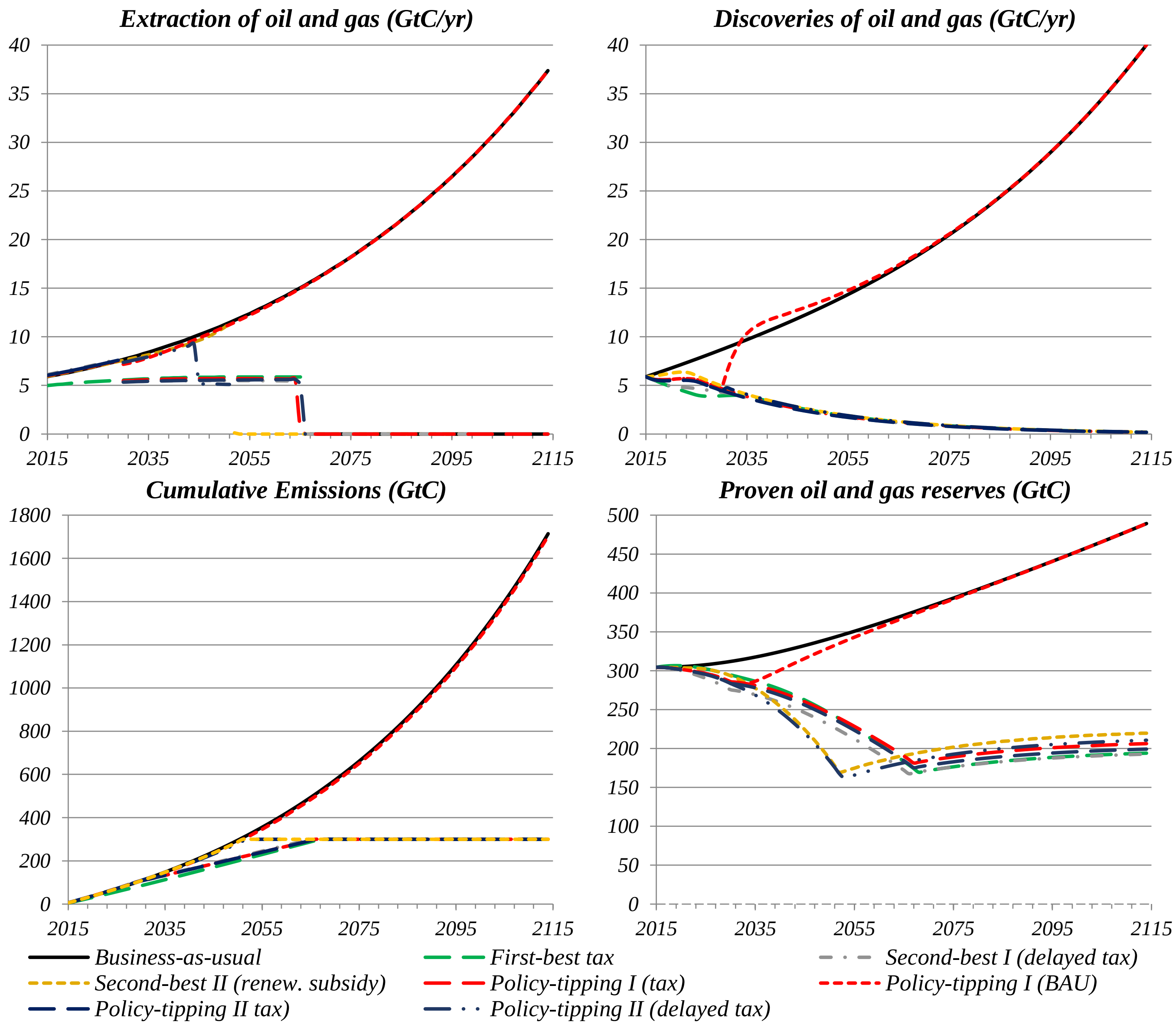
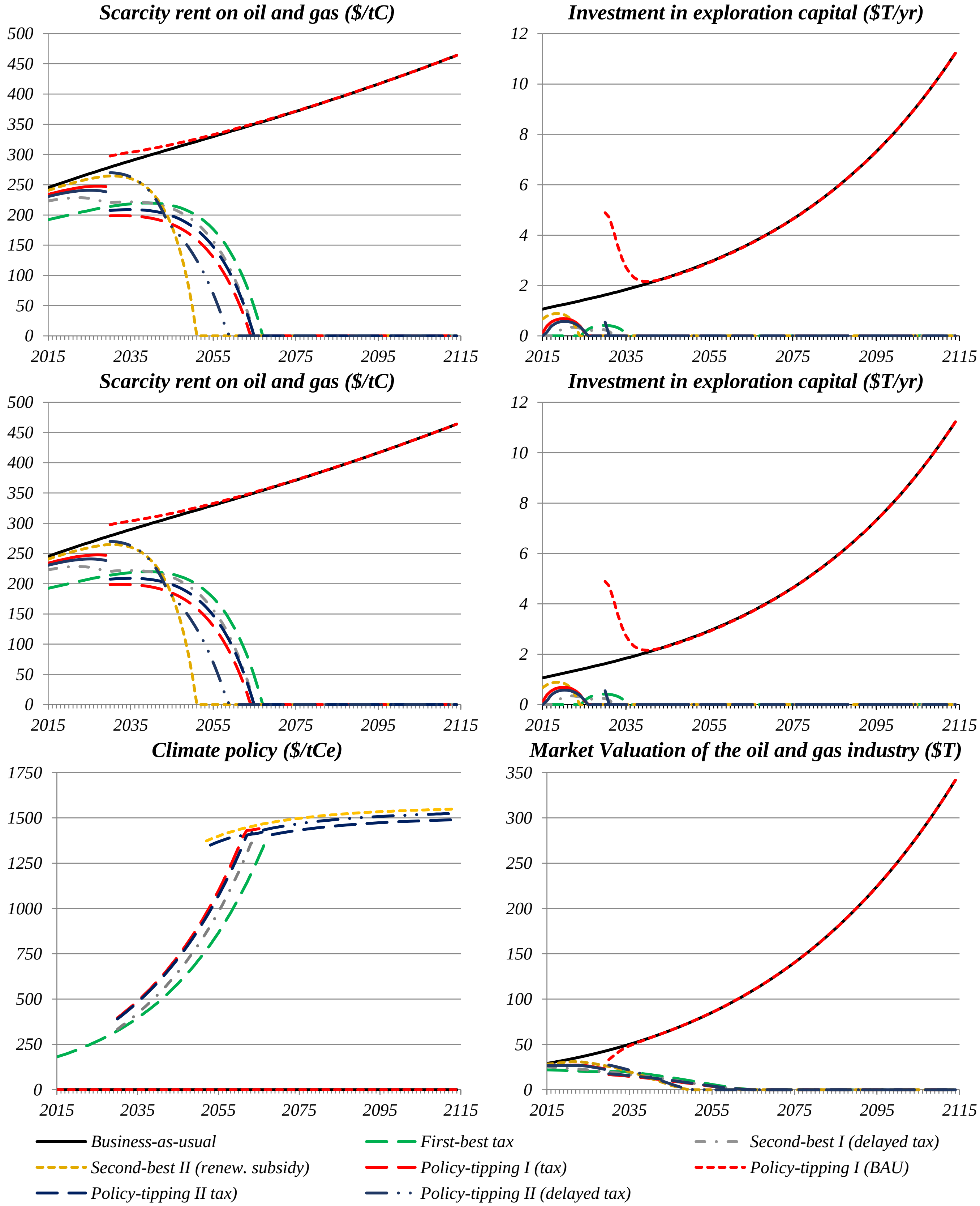


Figure B1 (*con't*): Policy simulations for all policy scenarios over the century



We also report to two additional sensitivity runs in Tables B1 and B2 for a higher probability of tipping into policy in 15 years, π, and a change in technological progress in renewable energy to a declining trend.

Increasing π from 50 to 80 percent makes tipping into policy more likely. (The first four columns are identical to the baseline calibration as these policies do not involve uncertainty.) This lowers the profitability and, hence, prices of natural and physical capital. The scarcity rent, investment, and discoveries fall. With the drop in the scarcity rent slightly larger (by $8 per tC), extraction increases due to the green paradox. Lower investment and higher extraction in the years leading up to the tax imply that the tax necessary to maintain the carbon budget is lower. In this scenario the amounts of carbon discovered during and locked up at the end of the fossil era is lower than in the baseline calibration. If the attempt to institute climate policy is botched, the economy reverts back to business as usual which is not affected by a change in π. The immediate drop in market capitalization is greater as climate policy is more likely. In the second tipping scenario a higher probability for a sooner tax has the same effects as in the first tipping scenario with the tax applied: The scarcity rent drops more and less carbon is discovered and locked up. The drop in market capitalization is greater.

Table B1: Summary results of policy simulations for probability of tipping into policy, π

	BAU	1st best tax	2nd best tax delayed	2nd best renewable subsidy	Safe or none, tax applied	Safe or none, tax botched	Safe or sorry, tax applied	Safe or sorry, tax delayed
Switch to carbon-free era, T	2200	2068	2066	2053	2065	2200	2066	2060
Locked-up carbon, S(T)	18 GtC	170 GtC	168 GtC	171 GtC	172 GtC	18 GtC	169 GtC	169 GtC
Cumulative discoveries	8600 GtC	165 GtC	163 GtC	166 GtC	167 GtC	8588 GtC	165 GtC	164 GtC
Cumulative emissions, E(T)	8887 GtC	300 GtC	300 GtC	300 GtC	300 GtC	8875 GtC	300 GtC	300 GtC
Final stock of capital, K(T)	272.1 $T	1.3 $T	1.3 $T	2.9 $T	1.4 $T	272.1 $T	1.3 $T	2.0 $T
Initial stock market value, V(0)	29.0 $T	21.9 $T	25.4 $T	28.2 $T	26.0 $T	26.0 $T	25.9 $T	25.9 $T
Initial value of capital, q(0)	1.01	0.92	0.99	1.01	1.00	1.00	0.99	0.99
Initial investment, I(0)	1.1 $T/yr	0.0 $T/yr	0.0 $T/yr	0.7 $T/yr	0.0 $T/yr	0.0 $T/yr	0.0 $T/yr	0.0 $T/yr
Initial scarcity rent, h(0)	245 $/tC	192 $/tC	223 $/tC	241 $/tC	228 $/tC	228 $/tC	226 $/tC	226 $/tC
Social welfare, diff to first-best	87.5 $T	0.0 $T	-2.4 $T	-119.7 $T	-2.3 $T	86.7 $T	-2.3 $T	-7.4 $T

Key: All scenarios except business-as-usual and policy tipping I curb total emissions to 300 GtC.

We also allow for continued cost reductions in renewable technology, the cost falls by 1 percent per year: $b(t)=(1-0.01)^t b(0)$. This brings forward the end of the fossil era to 2164 with renewable energy first entering the market in 2127. The declining trend, however, allows for several years of quivering as ongoing discoveries allow fossil fuels to re-enter the market. In a model where fossil and renewable energy are not perfect substitutes, this back-and-forth dynamic would be smoother. With renewable energy cheaper earlier on, investment in exploration capital, cumulative discoveries and cumulative emissions are lower. Market capitalization falls also from $29 trillion to $27.3 trillion. The impact of these changes on the scarcity rent and the level of investment is, however, muted. The first-best tax is lower if renewable energy at the end of the fossil era is lower (see equation (8)). Hence, fossil fuel consumption higher for a shorter period of time. The scarcity rent and the market valuation increase relative to the baseline calibration. The same logic applies to the second-best delayed carbon tax. The results for the second-best renewable subsidy are identical to the baseline calibration, except that the level of the subsidy offered by the government is reduced by the cumulative cost reductions due to the technological progress. The impact of continuously falling *b* on the tipping scenarios follows the same logic as in the first-best tax case. A lower tax enables higher fossil fuel use which is phased out completely earlier on. As in the first-best case, the oil and gas industry is forced to invest more into new discoveries to allow stay competitive compared to the falling cost of renewable energy. This explains why in all policy scenarios (except the one of a second-best subsidy) the stock of stranded capital is larger than in the baseline calibration.

Table B2: Summary results of policy simulations for a declining trend in renewable cost, ***b***

	BAU	1st best tax	2nd best tax delayed	2nd best renewable subsidy	Safe or none, tax applied	Safe or none, tax botched	Safe or sorry, tax applied	Safe or sorry, tax delayed
Switch to carbon-free era, *T*	2164	2061	2060	2053	2060	2163	2060	2057
Locked-up carbon, *S*(T)	118 GtC	170 GtC	169 GtC	171 GtC	182 GtC	136 GtC	174 GtC	169 GtC
Cumulative discoveries	2633 GtC	165 GtC	165 GtC	166 GtC	178 GtC	2625 GtC	170 GtC	165 GtC
Cumulative emissions, *E*(T)	2820 GtC	300 GtC	300 GtC	300 GtC	300 GtC	2794 GtC	300 GtC	300 GtC
Final stock of capital, *K*(T)	9.2 $T	1.9 $T	1.9 $T	2.9 $T	2.1 $T	9.7 $T	1.9 $T	2.2 $T
Initial stock market value, *V*(0)	27.3 $T	24.4 $T	26.2 $T	28.2 $T	26.2 $T	26.2 $T	26.9 $T	26.9 $T
Initial value of capital, *q*(0)	1.01	0.97	1.00	1.01	1.00	1.00	1.00	1.00
Initial investment, *I*(0)	1.1 $T/yr	0.0 $T/yr	0.0 $T/yr	0.7 $T/yr	0.3 $T/yr	0.3 $T/yr	0.1 $T/yr	0.1 $T/yr
Initial scarcity rent, *h*(0)	245 $/tC	212 $/tC	229 $/tC	241 $/tC	236 $/tC	236 $/tC	234 $/tC	234 $/tC
Social welfare, diff to first-best	30.1 $T	0.0 $T	-0.9 $T	-22.7 $T	-0.9 $T	29.7 $T	-0.9 $T	-2.9 $T

Key: All scenarios except business-as-usual and policy tipping I curb total emissions to 300 GtC.