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Climate Policy and Stranded Carbon Assets: a Financial Perspective

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CLIMATE POLICY AND STRANDED CARBON ASSETS:

A FINANCIAL PERSPECTIVE*

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Abstract

Unanticipated climate policy curbs the value of physical capital that is costly to adjust. We illustrate this by showing that climate policy to keep peak global warming below 2°C depresses the share prices of oil and gas majors and their market capitalisation, curbs exploration investment and oil and gas discoveries, boosts proven reserves left abandoned in the crust of the earth, cuts exploitation investment, and induces an earlier onset of the carbon-free era. For a given carbon budget, an immediate carbon tax is the first-best response but delaying the carbon tax or a renewable energy subsidy to meet the same temperature target are preferred by shareholders because they introduce Green Paradox effects and protect the profitability of existing capital.

Keywords: climate policy, fossil fuel, exploration investment, discoveries, exploitation investment, stranded carbon assets, stock prices, irreversible capital, adjustment costs

JEL codes: D20, D53, D92, G11, H32, Q02, Q35, Q38, Q54

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1. Introduction

World leaders have agreed at the Paris International COP21 Conference on Climate Change to limit global warming to 2°C with a goal of eventually lowering that further to 1.5°C above pre-industrial temperatures. Although politicians around the globe seemed happy at the time of the agreement, share prices of oil and gas majors hardly reacted to the news of the agreement.[1] This is hard to square with the need to keep one third of all oil reserves unexploited and half of gas reserves in the ground to meet the 2°C target (McGlade and Ekins, 2015).[2] To limit global warming to 2°C only about 350 Giga-tons of carbon (GtC) or 1283 Giga-tons of CO2 (GtCO2) can still be burnt from 2015 onwards. But private oil, gas and coal reserves have been estimated to be about 3 or 4 (and for probable resources about 10 to 11) times higher than this cumulative carbon budget. Burning all of this fossil fuel induces global warming in excess of 2°C. 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 gets serious. Total proven oil and gas reserves amount to over 200 GtC at current economic conditions and continue to increase (BP, 2017); including coal, this figure would rise to over 1300 GtC. Not only oil-, gas- and coal-rich countries and companies are strongly exposed to carbon risk, but also producers of electricity and final goods that rely heavily on fossil fuel as an input.

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/

Our main objective is to gain analytical understanding of the phenomenon of stranded assets by investigating the effects of unanticipated future changes in climate policy to ensure that peak global warming stays below its target of 2°C or 1.5°C on exploration and exploitation investments,

[1] 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.

[2] 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.

stranded carbon assets more generally, scarcity rents accruing to international oil and gas companies, and the amount of carbon locked up in the ground.[3] We highlight the role of the irreversibility or the costly nature of reversing past investments in capital tied in to the carbon-based economy. If these investments were reversible without any intertemporal adjustment costs, there would be no problem of stranded assets as carbon-polluting capital could be reused as green capital or for general purposes. We first review some empirical evidence on drivers of oil and gas discoveries and then show analytically how unanticipated and anticipated climate policy affects discoveries and the market value of fossil fuel companies.

Policy makers have multiple instruments available to limit peak warming. We compare the effects of immediate implementation of a path of carbon taxes designed to curb cumulative carbon emissions and keep peak global carbon warming below the Paris target of 2°C with (i) a delayed carbon tax that necessarily has to be higher to achieve the same peak global warming target and (ii) a renewable energy subsidy that is designed to keep global warming below 2°C. Both alternatives induce inefficiencies. The delayed carbon tax speeds up fossil fuel extraction as companies try to avoid the burden of taxation. As a result, carbon emissions are brought forward thereby accelerating global warming ahead of the introduction of the delayed carbon tax, which is the Green Paradox effect (Sinn, 2008). To make up for the time wasted and the additional emissions due to the Green Paradox, the delayed carbon tax has to be higher than an immediately implemented carbon tax to meet the same cumulative emissions or temperature target. This second-best climate policy shifts carbon emissions to the near future, but discourages exploitation investment and discoveries, curbs exploitation investment and drilling activities, and locks up more proven reserves in the crust of the earth than under business as usual. This aids the profitability of existing 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). The renewable energy subsidy similarly induces adverse short-run Green Paradox effects, but discourages discoveries and locks up more fossil fuel in the crust of the earth.

To investigate these effects of current and anticipated climate policy on behaviour of international oil and gas majors, we first extend the canonical model of discoveries and depletion developed by Pindyck (1978) where carbon discoveries occur as a result of past investments in exploration to allow for intertemporal adjustment costs for exploration investments. These imply that the exploration and extraction behaviour of an international carbon (oil and gas) company, ICC for

[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.

short, is endogenous and reacts to expectations about future changes in climate policy. Whether and to what extent exploration and exploitation investments, and with them part of the ICC's stock market value, have to be written off, depends on whether these investments are irreversible or costly to adjust for other purposes. Without such intertemporal (or intra-temporal) adjustment costs or some form of irreversibility in exploration investments, the stock market value of ICCs would not be affected by current or future climate policies and one cannot address the issue of stranded natural (hydrocarbon) and physical assets.

We investigate analytically a 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 extraction costs that rise as fewer fossil fuel reserves are left, it does not pay to fully deplete fossil fuel reserves. We use this version of our model of discoveries and exploration investments to show how climate policy affects the investment in and valuation of exploration capital as well as the value of carbon under the ground and value of the ICC on the stock market. We then use the general version of our model where renewable energy is a good enough substitute and can fully drive out fossil fuel in a finite time of years. We study a calibrated version of this more general model of exploration investment, fossil fuel discoveries, climate policy and stranded financial assets with the aid of numerical policy simulations.

Since not all investment in the oil and gas industry is in exploration, we put forward a complementary model of exploitation investments, where for simplicity we keep exploration investment and discoveries as exogenous. So now ICCs have to make large-scale investments in exploitation capital such as rigs to get the fossil fuel out of the ground, offshore or onshore. With an unanticipated change in current or future climate policy, past exploitation investments become stranded and the share prices of ICCs will drop as before. In addition, more fossil fuel will be locked up in the crust of the earth, thus curbing global warming. We again illustrate these results with dynamic policy simulations.

Section 2 reviews empirical evidence on the drivers of discoveries and exploration investments. Section 3 sets up our general analytical model of exploration investments and discoveries of fossil fuel reserves, which we use to study stranded assets. Section 4 investigates a special case to deliver some analytical insights. Section 5 discusses an illustrative calibration of the general model and presents various climate policy simulations to show the effects on stranded assets. This section compares the outcomes in the "laissez-faire" scenario of policy inaction with those of an immediate carbon tax and those of the alternative climate policies of postponed carbon taxes and renewable energy subsidies. Section 6 presents our complementary model of exploration

investments with adjustment costs and uses this to illustrate the issue of stranded carbon assets. Section 7 concludes and discusses stranded assets in other industries and policy implications.

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

The so-called "peak-oil" hypothesis has become virtually irrelevant as globally there is still huge potential for increases in the supply of fossil fuel. First, rapid advances in fracking technology such as horizontal drilling have led to fast growth in the 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 have further potential for the production of large amounts of shale gas. Although technological progress in the production of renewable energy, especially solar energy, has been impressive too, the huge technology-driven boosts to the supply of particularly unconventional fossil fuel have so far been more of a game changer in global energy markets. There is plenty of fossil fuel around and the potential for a lot more. Still, renewable energies are projected to dominate due to sustained technical progress and climate policy, thus leading to the end of the fossil fuel age (Helm, 2017).

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 the emerging market and developing economies. Giant sized discoveries in the developing world have relentlessly increased for decades 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 open up to foreign investment and improve institutions and the rule of law (Arezki et al., 2016).

The coming to the market of new technology and nurturing of an environment that encourages exploration investment reinforce each other and lead to more potential of fossil fuel discoveries and research, especially in developing economies. However, as confirmed by the empirical micro evidence of Bjørnland et al. (2017) for unconventional oil and Arezki et al. (2016) more generally, fossil fuel exploration and the probability of discoveries are driven by the world price of oil too. A crash in the world oil price depresses exploration investments and ultimately leads to less opening up of new oil and gas reserves. Independent of whether a global fall in the oil price is driven by a fall in global energy demand or ambitious climate policy to drive out fossil fuel, oil and gas discoveries will become less frequent and more oil and gas and thus more carbon will be locked up in the crust of the earth. We conclude that any analysis of stranded fossil fuel assets must allow for endogenous exploration (not just exploitation) of oil and gas fields and of reserves. As our main focus is on the risk of stranded assets in the light of anticipated climate policies, we

focus on the effect of unanticipated and anticipated carbon taxation or renewable energy subsidies on the world price of oil and thus on oil discoveries and depletion. In a complementary model of section 6 we shift the focus to exploitation and assume discoveries at a fixed rate.

3. A model of exploration investment, fossil fuel discoveries and depletion

We first describe the behaviour of the representative ICC which engages in exploration investment to enhance discoveries and optimally depletes its fossil fuel reserves under the assumption of competitive international energy and capital markets. Second, we specify a global energy demand function, which gives energy demand as a negative function of the market price of oil plus a specific carbon tax.[4] Third, we specify the supply of an alternative carbon-free source of energy which eventually puts the ICCs out of business. Finally, we put the various parts together to obtain our model for analysing the effects of current and anticipated climate policy on exploration investments, discoveries, depletion rates, global energy demand, global energy prices, stock price and market capitalisation of ICCs, cumulative carbon emissions, peak global warming, and the time at which the world economy switches to carbon-free energies.

3.1. The representative international oil company

The representative ICC operates under perfect competition and takes the world price of energy, p, and the cost of capital, r, as given when it maximises its market capitalisation on the stock market, V. The ICC has access to a stock of fossil fuel reserves, S, which increases due to discoveries at a rate D and is depleted at a rate R. Discoveries are an increasing and concave function of exploration capital, K, so that $D = \mathrm{D}(K)$ with $\mathrm{D}' > 0$ and $\mathrm{D}'' < 0$. Of course, whether any particular exploration activity is successful and leads to a discovery is probabilistic but on average the total number of discoveries will increase with exploration.[5,6] Exploration capital depreciates at the rate $\delta > 0$. The cost of exploration investment, I, increases in the investment rate due to internal adjustment costs. More specifically, the unit cost of exploration investment is $1 + \phi I / 2K$, where $\phi > 0$ is the adjustment cost parameter. Another way of putting this is that only a fraction $1/(1 + \phi I / 2K)$ of total investment outlays translates into additional exploration

[4] 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.

[5] Arrow and Chang (1982) offer an analysis of the stochastic nature of resource discoveries.

6 Discoveries could be a decreasing function of economy-wide cumulative discoveries, C, so that $D = \mathrm{D}(K,C)$ with $\mathrm{D}_C < 0$ and the probability of successful exploration decreasing if already many fields have been discovered. Consistent with the assumption that the firm is a price-taker, the representative ICC would not internalise the adverse impact of cumulative discoveries on current discoveries but take C as given. Since we assume continued exogenous progress in renewable energy, placing an expiry date on the fossil fuel era, we abstract from this effect of cumulative discoveries.

capital. Extraction costs increase as reserves diminish and less accessible fields have to be drilled: $\mathrm{G}(S)R$ with $\mathrm{G}'>0$. We assume that no capital or labour is needed to get the fossil fuel out of the ground, and postpone the analysis of exploration investments until section 6.

The representative ICC takes *p* and *r* as given and solves the optimisation problem:

$$(1)\qquad \underset{R,I}{\mathrm{Max}}\, V(0)=\int_0^{\infty}\left[pR-I-\frac{\phi}{2}\frac{I^2}{K}-\mathrm{G}(S)R\right]e^{-rt}dt \quad \text{subject to}$$
$$\dot{S}=\mathrm{D}(K)-R,\quad S(0)=S_0,\ \text{and}\ \dot{K}=I-\delta K,\quad K(0)=K_0,$$

where the initial stocks of reserves and exploration capital are S_0 and K_0, respectively.[7]

The static efficiency condition for optimal fossil fuel use of the ICC is that the market price of its produce should be set to the scarcity (or Hotelling) rent, *h*, plus the extraction cost, i.e.,

$$(2)\qquad p\le h+\mathrm{G}(S),\quad R\ge 0,\quad c.s.$$

The efficiency condition for the optimal exploration investment rate states that the marginal cost of investment including adjustment costs should equal the marginal value of capital to the ICC, *q*, i.e., $q=1+\phi I/K$. This implies that the investment rate increases in the share price,

$$(3)\qquad I=\frac{1}{\phi}(q-1)K.$$

Here *h* and *q* correspond to the (undiscounted) co-state variables of *S* and *K*, respectively.[8]

There are two dynamic efficiency conditions corresponding to the arbitrage conditions for managing oil reserves and exploration capital. The first is the Hotelling rule which 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) or

$$(4)\qquad \dot{h}=rh+\mathrm{G}'(S)R,\quad h(0)\ \text{free}.$$

Integrating (4) we obtain that the scarcity rent on keeping an additional barrel of oil locked up,

[7] Depletion should not be interpreted as depletion of an individual field which would be governed by Darcy's law for describing the flow of fluid through a porous medium instead of Hotelling rule. Depletion should thus be viewed as the opening up of new fields. Anderson et al. (2018) explain theoretically both the opening up of new fields, which is governed by Hotelling-like rules, and the depletion of existing fields, which is governed by Darcy's law. We use our specification for simplicity and analytical tractability.

[8] If gross investment cannot be negative (as in the numerical simulations discussed in section 6), (3) is replaced by $I\ge(q-1)K/q,\ I\ge 0,$ c.s.

$$(4') \qquad h(t) = \int_t^{\infty} \left[-G'\left(S(s)\right) R(s) \right] e^{-r(s-t)} ds,$$

is the present discounted value of all reductions in future extraction costs if this barrel would be depleted. The second dynamic efficiency condition sets the user cost of exploration capital, which consists of rental plus depreciation charges minus capital gains, $(r+\delta)q - \dot{q}$, to the marginal value of exploration investment, $\mathrm{D}_K(K)h$, plus the reduction in adjustment cost resulting from an additional unit of exploration capital, $\phi(I/K)^2/2$. This gives

$$(5) \qquad \dot{q} = (r+\delta)q - \mathrm{D}'(K)h - \frac{\phi}{2}(I/K)^2, \quad q(0) \text{ free.}$$

Integrating equation (5) we find that the share price of the ICC must equal the present discounted value of all future marginal gains from exploration investments, both in terms of new discoveries and lower future extraction costs. Hence, it is given by

$$(5') \qquad q(t) = \int_t^{\infty} \left[\mathrm{D}'\left(K(s)\right) h(s) + \frac{\phi}{2} \left(\frac{I(s)}{K(s)} \right)^2 \right] e^{-(r+\delta)(s-t)} ds.$$

3.2. Global energy demand, the carbon-free backstop source of energy and climate policy

As long as fossil fuel is competitive and cheaper than renewable energy, global demand decreases in its user cost which equals the world price of fossil fuel (measured in tons of carbon) plus the carbon tax, τ. It is thus given by the global energy demand function $R = \Phi(p+\tau)$ with $\Phi' < 0$. Upon substitution of (2), we can write global fossil fuel demand as

$$(6) \qquad R = \Phi\left(h + \mathrm{G}(S) + \tau\right) \equiv \mathrm{R}(S, h+\tau)$$

with $\mathrm{R}_S = \Phi'\mathrm{G}' > 0$ and $\mathrm{R}_{h+\tau} = \Phi' < 0$. A higher scarcity rent, a higher fossil fuel extraction cost (caused by lower reserves), and a higher carbon tax thus boost the user cost of fossil fuel and curb global demand for fossil fuel.

Global energy consumers also have access to an alternative renewable energy source. This is a perfect substitute for fossil fuel and is infinitely elastically supplied at the cost b. Renewable energy is subsidised at the rate θ, so that the user cost of renewable energy is $b - \theta$. As soon as the price of fossil fuel plus the carbon tax increases beyond the user cost of renewable energy, fossil fuel is substituted and global energy demand becomes $\mathrm{R}(b-\theta)$. This switch, however, is temporary if installed capital leads to continued discovery of new reserves, thus lowering extraction costs and the user cost of fossil fuel. A sufficiently large drop in G could bring fossil fuels back, at least temporarily. If continued technological progress steadily lowers the cost of

renewables (as we assume in the numerical simulations of section 6), fossil fuels will be eventually phased out and no longer used. The ICC is then bankrupt and global energy demand becomes $\mathrm{R}(b-\theta)$ indefinitely. At the end of the carbon era, denoted by time *T*, the scarcity rent has fallen to zero, $h(T)=0,$ and shares in the ICC are worthless, $q(T)=0.$

Climate policy consists of current and expected future values of the carbon tax τ and the renewable energy subsidy θ, where the net revenue of these two policy instruments is rebated in a lump-sum manner. Cumulative carbon emissions, *E*, result from burning fossil fuel and drive peak global warming (e.g., Allen et al., 2009; Millar et al., 2017). Denoting the deviation of peak global warming from pre-industrial temperature in degrees Celsius by *PW*, we have

(7) $$PW=\gamma_0+\gamma_1 E,$$

where *E* is cumulative fossil fuel use (measured in Giga-tons of carbon) and $\gamma_1>0$ denotes the transient climate response to cumulative carbon emissions, calibrated to 2°C per trillion tons of carbon). Cumulative carbon emissions are $E(t)=\int_0^t R(t)ds.$ Note that extraction costs $\mathrm{G}(S)=\mathrm{G}(S_0+C-E)$ increase in cumulative fossil fuel use or emissions, *E*, and fall in the cumulative stock of discoveries, $C(t)\equiv\int_0^t D(s)ds.$

3.4. Climate policies

We analyse the effects of climate policy on fossil fuel exploration and depletion and on carbon emissions as well as on the global demand for energy and price of fossil fuel, the stock price of the ICC and the stock market capitalisation of the ICC. Climate policy is designed to ensure that peak global warming stays below its target value which we set to 2°C. This corresponds a ceiling on cumulative fossil fuel use and carbon emissions of

(7′) $$PW=\gamma_0+\gamma_1 E(T)\leq 2,$$

where *T* indicates the end of the carbon era.

We consider three alternative ways of meeting the climate target (7′):

(I) Immediate implementation of a path of carbon taxes for the whole duration of the fossil fuel era: $\bar{\tau}(t)>0,\ \forall t\geq 0.$ In fact, this carbon tax stays in place once the renewable energy is phased in as the user cost of fossil fuel may still be below that of the carbon-free alternative and the ICC may re-enter the market.

(II) Delayed implementation of a carbon tax: $\tau^D(t)=0, \forall t<T^D$ and $\tau^D(t)>0, \forall t\geq T^D$ with $T^D<T.$ This is in line with the observed procrastination of policy makers who seem more happy to commit to future and more forceful policies than current policies. As a result, τ^D has to exceed τ once positive and the market has to believe that this announcement about future policy is credible.

(III) Credible announcement of a renewable energy subsidy, $\theta.$

We compare these "climate policy" scenarios with a "laissez-faire" scenario which has no climate policies at all ($\tau(t)=0, \forall t\geq 0$ and $\theta=0$).[9] Since cumulative discoveries at the end of the carbon era decrease in the carbon tax (I) and (less so) in the delayed carbon tax (II) and also decrease in the renewable energy subsidy (III), we obtain $C(T)=\mathrm{C}(\bar{\tau},\bar{\tau}^D,\theta)$ with $\bar{\tau}(t), 0\leq t\leq T,$ and $\bar{\tau}^D(t), 0\leq t\leq T^D,$ are the paths of policies under (I) and (II), where all the three partial derivatives are negative. The climate policies can be found from the condition that at the end of the carbon era the user price of fossil fuel has risen (and is about to surpass) the user cost of renewable energy. Hence, given that the scarcity rent must have fallen to zero at the end of the fossil fuel era, $h(T)=0,$ and the carbon budget equals $(2-\gamma_0)/\gamma_1$ from (7′), this implies that

(8) $$\mathrm{G}\left(S_0+\mathrm{C}(\bar{\tau},\bar{\tau}^D,\theta)-(2-\gamma_0)/\gamma_1\right)+\tau(T)=b(T)-\theta$$

must hold. We thus see that each of these policies has to be more aggressive if the initial stock of fossil fuel reserves is large (high S_0), renewable energy is expensive (high b), and the peak warming target is tight, and the transient climate sensitivity is large (high γ_1). Furthermore, the carbon tax has to be higher if its implementation is delayed, $\bar{\tau}^D>\bar{\tau}.$ Given climate policies (I), (II) or (III), we solve (8) for the discovered fossil fuel reserves that must be locked up in the crust of the earth forever,

(8′) $$S(T)=\mathrm{S}\left(\tau(T)+\theta-b(T)\right) \text{ with } \mathrm{S}'=-1/\mathrm{G}'>0,$$

which we assume to be less than $S_0.$ Hence, the stock of stranded reserves or equivalently the stranded *in situ* carbon stock increases in the carbon tax and the renewable energy subsidy and decreases in the market cost of renewable energy at the end of the carbon era. Hence, the stock of stranded carbon reserves is bigger if the target for peak warming is tighter, the transient climate sensitivity for cumulative emissions γ_1 is higher and production renewable energy is cheaper.

[9] An alternative way of modelling climate policy is to model the tipping risk of it being implemented at some future unknown date, which is closely related to the analysis of expropriation risk (e.g., Long, 1975; Bohn and Deacon, 2000; van Benthem and Stroebel, 2013).

3.5. Putting it together

Before putting the bits of the model together, we add from (1) the differential equation

$$(9) \qquad \dot{V} = rV - \left[hR - I - \phi I^2 / 2K \right], \quad V(T) = 0,$$

which is integrated backwards in time from the end of the carbon era when the value is zero to obtain the ICC's stock market capitalisation, *V*. This depends at any time on the value of in situ reserves and on the stock of exploration capital, so $V = \mathrm{V}(S,K)$ with $\mathrm{V}_S = h$ and $\mathrm{V}_K = q$.[10] Upon substituting (6) into the fossil fuel depletion equation, (3) into the accumulation equation for exploration capital, (6) into the Hotelling dynamics (4), (3) into the share price dynamics (5) and (3), and (6) into the dynamics of the market capitalisation of the ICC (9), we obtain six state-space equations for the dynamics of the carbon era from time zero to time *T*:[11]

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

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

$$(10c) \qquad \dot{C} = \mathrm{D}(K), \quad C(0) = 0,$$

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

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

$$(10f) \qquad \dot{V} = rV - h\mathrm{R}(S, h+\tau) - (\tilde{q} - 1)\left[1 - (\tilde{q} - 1)/2\right] K/\phi, \quad V(T) = 0.$$

Here the stocks (S,K) are backward-looking and predetermined state variables and the asset prices and the market capitalisation (h,q) are forward-looking and non-predetermined state variables as can be seen from equations (4′) and (5′). These variables are independent of the stock *C*, which is backward-looking, and the market capitalisation *V*, which is forward-looking. Equations (10a), (10b), (10d), and (10e) thus constitute a saddle-point system with a two-dimensional stable manifold corresponding to the predetermined state variables (S,K). The complete system has seven boundary conditions. Six of these correspond to the initial conditions of the three predetermined state variables and the terminal conditions for the three non-predetermined state variables. The final one is condition (8′), which effectively determines the

[10] Since profits of the ICC are not homogenous of degree one, we do not have $V = hS + qK$ and thus need to evaluate (9) numerically. Abstracting from the cost of extracting reserves, our adjustment costs specification would imply that the marginal "Q" equals the average "Q" (cf. Hayashi, 1982).

[11] Here *q*'s in (10b) and (10f) and the last *q* in (10e) are replaced by $\tilde{q} = \max(q,1)$ the marginal cost of exploration capital adjusted to account for $I \geq 0$.

end of the carbon era *T*. The policy instruments (τ, θ) can take on any value, but we focus at values that ensure that peak warming stays below 2°C and satisfy (7′) or $E = S_0 + C - S \leq (2 - \gamma_0)\gamma_1$.

4. Analytic insights from simplified version of the model of discoveries and stranded assets

Before discussing the simulations of the full model in section 6, we obtain analytical insights to illuminate the underlying mechanisms of our model by making a simplifying assumption: we assume that there is no carbon-free energy backstop that perfectly substitutes for fossil fuel or alternatively that the price of fossil fuel including the carbon tax never rises above the cost of renewable energy. This ensures that the transition to the carbon-free era never takes place or $T \to \infty$. The climate policies τ or θ must thus ensure that sufficient amount of carbon is locked up rather than burnt, i.e., that (8) is satisfied. Armed with this assumption, we investigate how fossil fuel reserves and the scarcity rent react to step changes in the carbon tax taking the stock of exploration capital and discoveries as given. We then illustrate how the price of ICCs and exploration capital react to drops in the scarcity rent. Finally, we comment how the two parts of the model can be put together. Sections 5 and 6 then drop these admittedly somewhat unrealistic assumptions to discuss policy simulations within the full, calibrated model.

4.1. Fossil fuel reserves and the scarcity rent

Given exploration capital, *K*, we solve for fossil fuel reserves and the scarcity rent from

(10a′) $\dot{S} = \mathrm{D}(K) - \mathrm{R}(S, h + \tau), \quad S(0) = S_0,$ and

(10d′) $\dot{h} = rh + \mathrm{G}'(S)\mathrm{R}(S, h + \tau), \quad h(0)$ free.

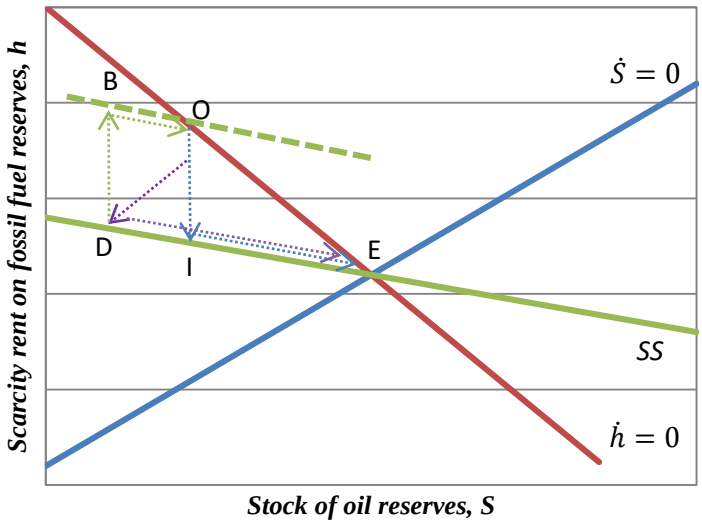
The phase diagram corresponding to this state-space system is displayed in Figure 2. The locus of points for which $\dot{S} = 0$ in (10a′) corresponds to those points for which fossil fuel demand equals the exogenous level of global fossil fuel discoveries. Since fossil fuel demand decreases in the carbon tax and increases in remaining reserves, this locus slopes upwards in Figure 1. Furthermore, this locus shifts up if discoveries fall. The system (10a′) and (10d′) displays saddle-point behaviour and a sufficient condition for this is that the $\dot{h} = 0$ locus slopes downwards.[12] This

[12] Saddle-point stability requires that determinant of the Jacobian $\mathrm{R}_h\left(r + \mathrm{G}'\mathrm{R}_h\right) - \mathrm{R}_S\left(\mathrm{G}'\mathrm{R}_S + \mathrm{G}''R\right)$ is negative. A sufficient condition is that $\mathrm{G}'\mathrm{R}_S + \mathrm{G}''R > 0$ in which case the $\dot{h} = 0$ locus slopes downwards. Section 4 assumes G(*S*) is inversely proportional to *S* so that this condition becomes $\varepsilon G(S)/(p + \tau) < 1$, where ε is the price elasticity of global fossil fuel demand. Since empirically $\varepsilon < 1$ at least for global oil and gas demand, this condition holds.

locus corresponds to those points for which the scarcity rent on *in situ* fossil fuel reserves, *h*, equals the present discounted value of future increases in extraction costs, $-G'(S)R/r$. The stable manifold is portrayed as the downward-sloping locus *SS*.

Introduction of a carbon tax shifts down the $\dot{S}=0$ locus. On impact of the carbon tax, markets anticipate worsening conditions for fossil fuel depletion and thus the scarcity rent falls but by less than the carbon tax rises (see the dotted blue arrow to point I). Hence, fossil fuel demand and the rate of depletion fall instantaneously. Over time, 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 and locked up in the crust of the earth has fallen which ensures that less carbon enters the atmosphere and peak warming has fallen. ICCs are adversely affected by climate policy, since rents on their reserves fall and they have to lock up a bigger part of their reserves in the crust of the earth forever.

Figure 1: Dynamic effects of carbon tax on scarcity rent and reserves given discoveries



Key: A carbon tax shifts the $\dot{S}=0$ locus out, so the initial equilibrium is at O and the final equilibrium is 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 delayed implementation of the carbon tax. The green dotted lines show what happens with a botched-up carbon tax which is not implemented at the promised date.

As soon as it becomes known that there will be a carbon tax installed in the future, the scarcity rent falls *already ahead of the tax* albeit less so than with the immediate implementation of a carbon tax (see the purple dotted arrow to point D). On impact, fossil fuel demand and the rate of depletion jump up instantaneously. During the period when the carbon tax has not been imposed yet, the scarcity rent continues to fall and consequently fossil fuel demand and the rate of depletion

continue to rise. Carbon emissions and global warming thus increase during this announcement period. This is known as the Green Paradox (Sinn, 2008). At the very moment that the carbon tax strikes (i.e., 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 the rate of depletion immediately fall below their initial rates. Afterwards, the economy moves along the stable arm $SS_{\cdot}$ so that the scarcity rent continues to rise and thus fossil fuel demand gradually rises back to its initial levels compatible with the exogenous rate of discoveries. The long run is as before with more reserves abandoned in the crust of the earth and less peak global warming.

If at the moment the carbon tax should have been implemented 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 the depletion rate fall below the rate of discoveries (see dotted green arrow from point D to point B). Afterwards, the scarcity rent continues to drop thereby driving down global fossil fuel demand and the depletion rate to their original values (move along the green-dashed line, the old stable manifold). As a result, the stock of *in situ* carbon reserves rises until what it was before the botched-up policy started.

Summing up, with exogenous discoveries, immediate implementation of a carbon tax leads to gradual falls in the scarcity rent on *in situ* reserves and to more carbon locked up and less peak warming. A delayed implementation induces Green Paradox effects ahead of the rise in the carbon tax, but in the long run ICCs are hit by lower scarcity rents and having to abandon more of their oil and gas reserves. If the carbon tax does not materialise, the scarcity rent jumps up and consequently *in situ* the stock of carbon reserves rises back to its original level.

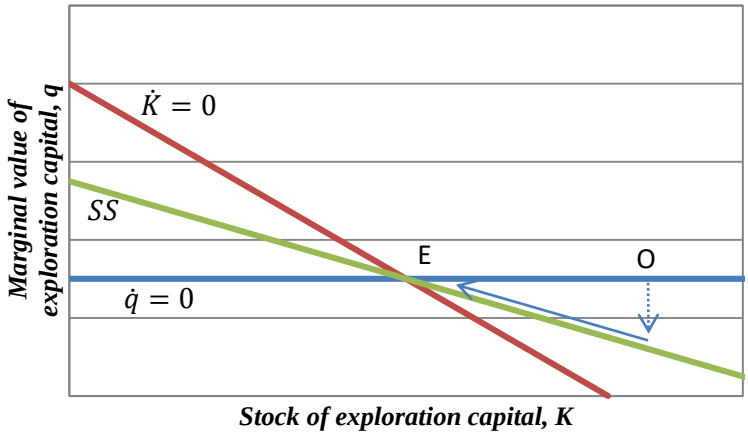
4.2. Dynamics of the share price and the stock of exploration capital

We can now see how the fall in the scarcity rent induced by the carbon tax affects exploration and the share price of the ICC by solving (given the time paths of the scarcity rent) for the stock of exploration capital, *K*, reserves and the stock price of the ICC, *q*, from (10b) and

$$(10e') \quad \dot{q} = (r+\delta)q - \mathrm{D}_K(K)h - \frac{1}{2\phi}(q-1)^2, \quad q(0) \text{ free}, \quad q(T) = 0.$$

The phase diagram for this state-space system is displayed in Figure 2. The $\dot{K} = 0$ locus corresponds to those points for which exploration capital and thus discoveries are constant. Since this is ensured if $q = 1 + \phi\delta,$ this locus is horizontal. The $\dot{q} = 0$ locus slopes downwards due to the diminishing marginal productivity of exploration capital. Hence, the locus corresponding to the stable manifold *SS* slopes downwards.

Figure 2: Effects of drop in the scarcity rent on exploration capital and its marginal value



Key: The phase diagram shows the effects of a step reduction in the scarcity rent on exploration capital and its marginal value. The initial equilibrium is O and the final equilibrium is E. On impact the marginal value of exploration capital and the investment rate jump down along the dotted blue arrow. Afterwards, they recover as the move along the stable manifold SS.

For simplicity, we consider the effects of a step reduction in the scarcity rent on exploration investments and discoveries. This shifts out the $\dot{q}=0$ locus and shifts the equilibrium from O to E. On impact the marginal value of exploration capital and thus the rate of exploration investment fall instantaneously. Over time, as the marginal value of exploration capital recovers, the investment rate gradually reverses back to its initial value. As a result, ICCs end up with lower stocks of exploration capital and lower rates of discoveries. Hence, a step reduction in the scarcity rent of the ICC leads to a temporary fall in exploration investment and the share price of the ICC, and a permanent fall in the stock of exploration capital.

4.3. Solving the general model of exploration investment and stranded carbon assets

Tightening up climate policy thus curbs the scarcity rent and leaves more fossil fuel in the crust of the earth, thereby limiting cumulative carbon emissions and peak global warming. The falls in the scarcity rent erode the share price and market capitalisation of IOCs and curb exploration investment and discoveries. To solve the simple version of our model fully requires second and further iterations. Tracing the second-round effects of the drop in discoveries using Figure 2 and the model of section 4.1, we see that this induces an attenuation of the drop in the scarcity rent and the increase in locked-up reserves. To solve for the two steps in sections 4.1 and 4.2 together needs to be done numerically. To save space, we omit this. Instead, section 5 discusses policy simulations of a calibrated version of the general and more realistic model of section 3. This allows for the phasing in of a renewable energy backstop, finite duration of the carbon era, and setting of the immediate or delayed carbon tax or renewable energy subsidy so that peak warming is limited to 2°C.

5. Policy simulations: discoveries and stranded carbon assets

Here we discuss the calibration of our model of section 3 and present the numerical policy simulations based on the climate policies outlined in section 3.4 and compare them with the "laissez-faire" outcome. In global models of climate change the efficient carbon tax equals the discounted sum of marginal climate damages. Policy in our model abstract from damages and simply limits peak warming to a temperature target and through (7) cumulative emissions where the path of carbon taxes is chosen to minimise cost. This yields a path where carbon taxes follow Hotelling paths to reflect the increasing scarcity of carbon as the carbon budget gets exhausted (e.g., Nordhaus, 1982; Tol, 2013; Bauer et al., 2015; van der Ploeg, 2018).[13]

5.1. Calibration

The calibration of our model of the fossil fuel industry is illustrative and is based on that in Rezai and van der Ploeg (2016). Details are summarised in Table 2. Our definition of fossil fuel includes oil and gas. For our extraction cost of fossil fuel, we specify the function $\mathrm{G}(S)=\chi_0(S_0/S_1)^{\chi_1}$. Since initial energy costs are globally roughly 5-6% of world GDP, we find that the extraction cost are about \$30 per barrel of oil or equivalently \$300 per ton of carbon (using the conversion factor 1 barrel of oil = 0.1 ton of carbon). Hence, we set initial extraction cost to $\mathrm{G}(S)=\chi_0=0.3$. We suppose that extraction cost per unit of energy doubles if a further 125 GtC is extracted.[14] Setting initial reserves to $S_0=200$ GtC, we calibrate $\chi_1=1.5$ We set the initial production cost of renewable energy prohibitively high at b = 2 which falls at 1% per annum. In contrast to the fossil fuel industry, the renewable energies industry has no scarcity rents and does not generate profits. Starting from a Cobb-Douglas production function between energy and an aggregate Y exogenously growing at g, we specify an iso-elastic function for global oil and gas demand, $R=\left((p+\tau)/(\varepsilon Y)\right)^{-\frac{1}{1-\varepsilon}}$, and set the energy share ε to 0.05 (and the price elasticity to 1.05) and g to 2% per annum. Oil and gas contributed two thirds to total fossil use in 2016. With total carbon emissions of 9.1GtC, we obtain emissions of 6 GtC (BP, 2017). Spending on capital in the oil and gas industry was around \$ 0.7 trillion and total spending \$ 1.3 trillion in 2013 (IHS, 2014).

Only 12% of the world economy prices carbon emissions and the average price charged is a mere \$8/tCO2 (Fischer and Pizer, 2017), so we calibrate under the assumption that carbon emissions are not priced at all. We specify discoveries as $\mathrm{D}(K)=\alpha_0 K^{\alpha_1}$, where we set $\alpha_0=1$ and

[13] Mattauch et al. (2018) discuss the equivalent between targets on temperature and cumulative emissions.
[14] The long-term cost curve of the IEA (2008) suggests a doubling or quadrupling of extraction costs if a further 1000 GtC is extracted.

$\alpha_1 = 0.75$. The ICCs operate with a market real rate of interest of 4% per annum (which would be consistent with an elasticity of intertemporal substitution for consumption of ½ and consumption growth of 2% per annum according to the Keynes-Ramsey rule), the depreciation rate of exploration capital δ to 10% per annum, and the adjustment cost parameter ϕ to 0.1 (Hall, 2004). Fossil fuel companies account for 8% of global market capitalisation (Bullard, 2014), we scale the stock of exploration capital to the global stock of $ 150 trillion, $K_0 = 12$. This is slightly above the stock of $ 7.5 trillion for 2017 which results when applying the perpetual inventory method with a depreciation rate of 10% per annum to annual (projected) expenditure (IHS, 2014). Growth in reserves from 2014 to 2015 has been negligible, which implies that initial fossil fuel discoveries are $D(0) = R(0) = 6$ GtC and thus $\alpha_0 \cong 1$. Finally, we calibrate peak warming, $PW = \gamma_0 + \gamma_1 E$, by setting γ_0 to 1.2 °C (implying cumulative past emissions of 600 GTC) and the transient climate sensitivity for cumulative emissions to $\gamma_1 = 2$ K/TtC = 0.002 °C/tC (cf. Alle, 2016).[15] This implies that to keep global warming below 2°C, cumulative emissions must remain below 400 GtC or 1467 GtCO2.[16] Since this carbon budget includes emissions from coal as well, we assume that half of it is available for emissions from coal and the other half for those from oil and gas.[17] The carbon budget, E, used in our policy simulations is then 200 GtC or 733 GtCO2.

Table 2: Calibration of the fossil fuel industry

General and adjustment costs	r = 0.04/year, δ = 0.1/year, and ϕ = 0.1
Exploration: $\mathrm{D}(K,C) = \alpha_0 K^{\alpha_1} \exp(-\alpha_2 C)$	α_0 = 1, 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 = 1.5 and S_0 = 200 GtC
Demand: $R = \left((p+\tau) / (\varepsilon Y (1+g)^t) \right)^{-1/(1-\varepsilon)}$	Y = $ 60 trillion/year, ε = 0.05, and g = 0.02/year
Cost of renewable energy $b = b_0 (1 - g_b)^t$	b_0 = 2 and g_b = 0.01/year
Peak warming: $PW = \gamma_0 + \gamma_1 E$	$\gamma_0 = 1.2$ °C, $\gamma_1 = 0.002$ °C /tCO2 and $PW \leq 2$ °C

[15] Millar et al. (2017) use a transient climate response of 1.6 K.

[16] Carbon budgets are associated with probabilities due to the scientific uncertainty about the climate system. Friedlingstein et al. (2014) find that the cumulative carbon budget from 2015 onwards compatible with a 66% (or 50%) chance of keeping global warming below 2°C is 1200 (or 1500) GtCO2.

[17] McGlade and Ekins (2015) find that 50% of oil and gas in situ and 80% of coal in situ must be abandoned to keep global mean temperature below 2°C. This suggests that our safe budget (using the distribution between reserves of oil and gas from top 200 companies) is 400 GtC x 0.5 x 150.7 GtCO2/(0.5 x 150.7 GtCO2 + 0.2 x 341.7 GtCO2) = 210 GtC which is close to our figure.

We solve the model using the CONOPT of GAMS for 120 periods which is sufficiently long to include the end of the fossil fuel era. Given that after this point, all variables of (11a)-(11f) remain constant, we do not have to allow for continuation values.

5.2. "Laissez-faire" outcome: steadily growing exploration and excessive warming

With no climate policy, fossil fuel remains competitive for an extended period of time and ICCs invest heavily into exploration of new fossil fuel reserves. As depicted in Figure 3 (blue, solid) sustained investment implies continued growth of exploration capital and reserves. Growing reserves makes fossil fuel more abundant and lowers extraction costs. The scarcity rent continues to increase, however, as demand is growing even faster in our simulations. The fossil fuel era continues until 2124 at which point the cost for renewable energy has dropped by two thirds and extraction costs have nearly doubled. At this point the stock of exploration capital and reserves become economically obsolete. As reported in Table 3 a total of 162 GtC and $11 trillion are abandoned since their value has diminished to zero. Since this twilight of the ICCs is still over a century away and exponentially increasing fossil demand bolsters the ICCs' coffers, the ICCs are valued at $29 trillion today. In total, ICCs discover 1606 GtC in new reserves and extract and sell 1735 GtC. This is more than three times the total carbon budget for a 2°C target (including coal) and implies warming in excess of 4°C. This illustrates the size of the policy challenge.

5.3. Immediate implementation of carbon tax to keep global warming below 2°C

To limit global warming and to curb the demand for fossil fuel, the government can impose a carbon tax which limits cumulative emissions to 200 GtC. Cost-efficient policy immediately implements a carbon tax of $146 per tC which grows exponentially until fossil fuel is priced out of the market in 2055. After the end of the fossil era only a maintenance tax is required which falls in tandem with the cost for renewable energy while maintaining a wedge such that fossil fuel remains uncompetitive despite any ongoing discoveries. This forceful pricing of carbon shifts downward the extraction trajectory in Figure 3 (red, long-dashed). As a result, investment in exploration capital grinds to a halt and the stock of exploration capital is slowly wound down. Carbon pricing and its intended consequence of lower cumulative use also bite into the scarcity rent on existing reserves (which falls by 17 percent). This drop (of $61 per ton of carbon) is more than compensated by the carbon tax: no Green Paradox effect emerges. The value of ICCs drops by $7.14 trillion or 25% to $22 trillion with the implementation of climate policy.

5.4. 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 in climate policy, we allow for 15 years of inaction and a

credible, albeit hard commitment to doubled-down policy efforts which still keep cumulative emissions at 200 GtC. Such a delayed policy protects the business model of ICCs initially and depresses fossil fuel demand more than under an immediate policy later on (green, dot-dashed in Figure 3). In anticipation of carbon pricing, however, the scarcity rent on fossil reserves and the price of (and investment in) exploration capital fall already with the announcement. The reduction in the scarcity rent induces a slight (5 percent) increase in fossil fuel use during the announcement phase of the tax. This comparatively small Green Paradox effect is due to the fact that all of existing fossil fuel reserves remain burnable and policy only impacts the scarcity rent indirectly through the evolution of exploration capital and the stock of reserves.

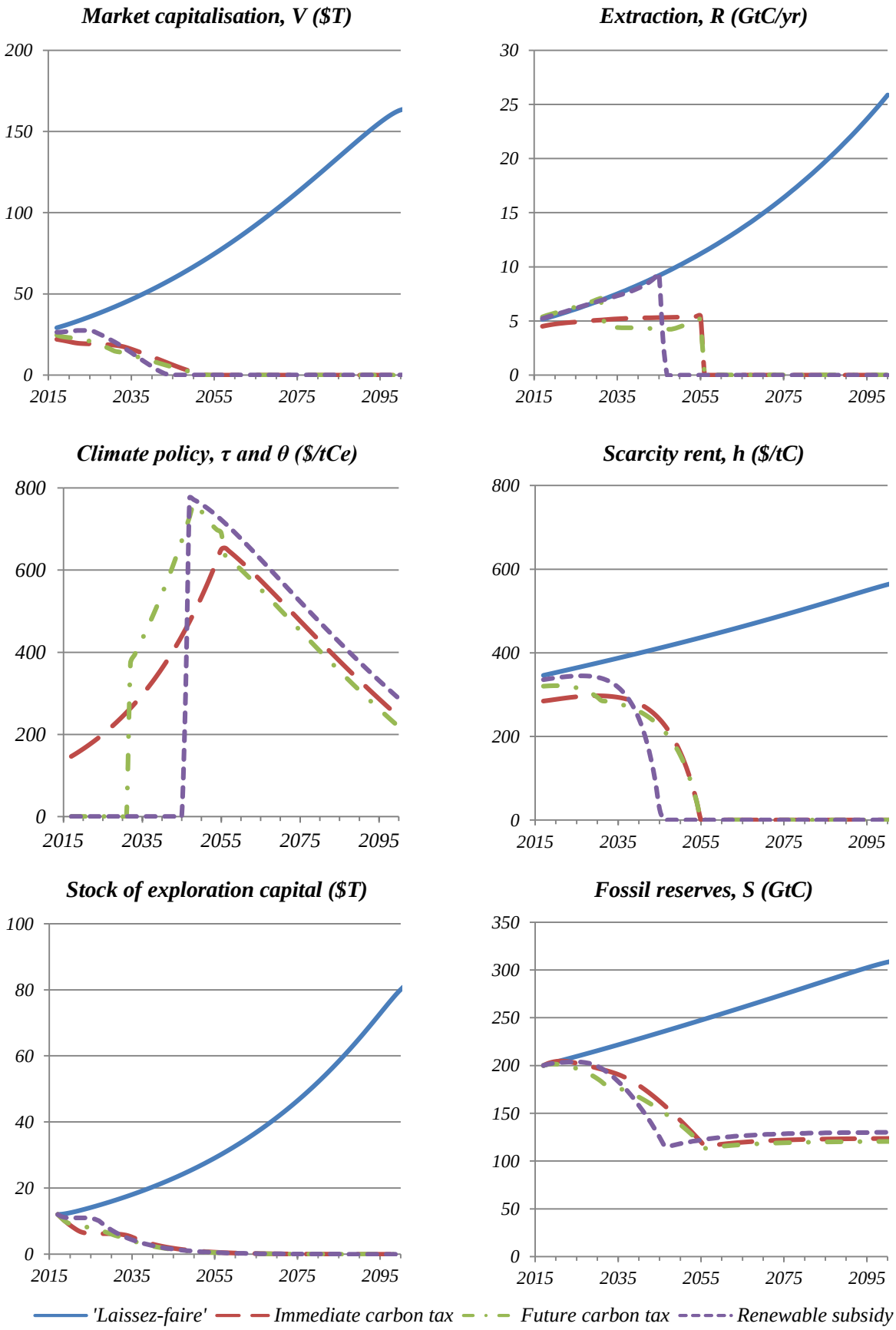
Table 3: Summary results of policy simulations

	"Laissez faire"	Immediate carbon tax	Delayed carbon tax	Renewables subsidy
Switch to carbon-free era, T	2124	2055	2055	2046
Locked up carbon, $S(T)$ (GtC)	162 GtC	115 GtC	114 GtC	115 GtC
Cumulative discoveries (GtC)	1606 GtC	115 GtC	114 GtC	120 GtC
Cumulative carbon emissions, $E(T)$ (GtC)	1735 GtC	200 GtC	200 GtC	205 GtC
Final stock of exploration capital, $K(T)$ ($T)	10.96 $T	0.63 $T	0.45 $T	1.23 $T
Initial stock market valuation, $V(0)$ ($T)	29.12 $T	21.98 $T	24.58 $T	26.35 $T
Initial marginal value of exploration capital, $q(0)$	1.011	0.946	0.993	1.005
Initial avg. value of exploration capital, $V(0)/K(0)$	2.43	1.83	2.05	2.20
Initial investment, $I(0)$ ($T/year)	1.29 $T/year	0.00 $T/year	0.00 $T/year	0.55 $T/year
Initial scarcity rent, $h(0)$ ($/tC)	346 $/tC	285 $/tC	320 $/tC	335 $/tC

Key: All scenarios except "laissez faire" limit cumulative carbon emissions to 200 GtC.

As depicted in Figure 3, reserves begin to diverge relatively quickly as the capital stock for new explorations is wound down. The delay in policy allows a front-loading to profits relative to immediate policy which mitigates the reduction in market capitalisation from $7.1 trillion to $4.5 trillion but the value of the firm still drops to $24.6 trillion (by 16% from its "laissez-faire" value). The delay also reduces the amount of stranded natural and physical assets (114 GtC and $0.45 trillion) while leaving the terminal period unchanged at 2055. This suggest that it is in shareholders' interest to seek a deferral of climate policy as it preserves their stock market wealth.

Figure 3: Policy simulations: discoveries and stranded carbon assets



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

Policy makers have two instruments available: the carbon tax and the renewable subsidy. While the former is the efficient instrument to curb fossil fuel use in light of climate change, the carrot might be more appealing than the stick. Here, we study the effect of such a cost-efficient second-best subsidy on ICCs. If the announcement of a subsidy is deemed credible, it only leads to a slight drop in the scarcity rent (of $11 per tC) and a small increase in extraction which increases by less than 2% relative to "laissez faire" in the next three decades (the Green Paradox effect). Value and level of investment in exploration capital are, however, impacted early on and due to the unavailability of new discoveries, the valuation of ICCs starts to diverge further from its "laissez-faire" value. The initial market capitalisation is curbed by $2.8 trillion (a 10% reduction). Unhampered growth in fossil fuel demand combined with an abrupt shift to carbon-free renewables leaves a high amount of physical assets stranded ($1.23 trillion). In terms of policy design, a second-best policy which delays a reduction in fossil fuel demand as long as possible is the preferred option for shareholders as this minimises the reduction in their wealth. Such an abrupt change in relative energy prices in turn leaves more capital stranded while the amount of in situ reserves (115 GtC) is hardly affected by policy design.

6. Exploitation capital in the fossil fuel industry and stranded carbon assets

To highlight the effect of unanticipated and anticipated climate policies on exploitation capital and the issue of stranded assets, we put forward a complementary model to the one discussed in section 3. To have a clear focus, we assume here that exploitation investments and discoveries are exogenous, $D = \bar{D}$. Now I and K denote *exploitation* (instead of exploration) investment and capital, and δ denotes the depreciation rate and ϕ the adjustment cost parameter of exploitation capital. Since capital is needed to get the fossil fuel out of the ground, we specify the production function of the ICCs as $\mathrm{H}(R,K)$. This production function is concave, has constant returns to scale and satisfies the Inada conditions. The ICCs take the cost of exploitation capital, r, and the market price of oil, p, as given when maximising the discounted value of its profits, and solves

$$(11)\qquad \max_{R,L,I} V(0) = \int_0^{\infty} \left[p\mathrm{H}(R,K) - I - \frac{\phi}{2}\frac{I^2}{K} - \mathrm{G}(S)R \right] e^{-rt} dt \quad \text{subject to}$$
$$\dot{S} = \bar{D} - R, \quad S(0) = S_0, \text{ and } \dot{K} = I - \delta K, \quad I \geq 0, \; K(0) = K_0,$$

where $V(0)$ indicates the market capitalisation of the ICC as before. The static efficiency condition sets the marginal revenue product of fossil fuel taken out of the ground to the extraction cost, $\mathrm{G}(S)$, plus scarcity rent, h, respectively, so that

(12) $p\mathrm{H}_R(R,K) = \mathrm{G}(S) + h.$

Equation (12) can be solved to give the ratio of fossil fuel use to the stock of exploitation capital as a function of the real cost of *in situ* fossil fuel, (G(*S*)+*h*)/*p*. Hence, we write depletion of in situ fossil fuel and production of fossil fuel as

(12′) $R = \hat{\mathrm{R}}\big(G(S)+h, p\big)K \quad \text{and} \quad H = \hat{\Phi}\big(G(S)+h, p\big)K.$

Note that the first partial derivatives of the functions $\hat{\mathrm{R}}(.)$ and $\hat{\Phi}(.)$ are negative and the second ones are positive and that, given extraction cost and prices for the resource above and under the ground, exploitation capital and extraction are substitutes.

Like exploration investment, the rate of exploitation investment reacts positively to the marginal value of exploitation capital, denoted by *q*, and more strongly if adjustment costs are low, i.e., $I/K = (q-1)/\phi.$ The dynamic efficiency condition for exploitation capital follows from the usual co-state equation and is given by

(13) $\dot{q} = (r+\delta)q - p\mathrm{H}_K(R,K) - \frac{1}{2}\phi\left(\frac{I}{K}\right)^2.$

Equation (13) is an arbitrage equation, which states that the marginal revenue product plus the marginal reduction in intertemporal adjustment costs must be set to the user cost (i.e., rental plus depreciation charges plus capital gains or minus capital losses on exploitation capital) of an additional unit of exploration capital. As before, the dynamic efficiency condition for in situ fossil fuel reserves is given by $\dot{h} = rh + \mathrm{G}'(S)R.$

To complete the model, we require equilibrium in the world market for tradable fossil fuel,

(14) $\Psi(p+\tau) = \Phi\big(\mathrm{G}(S)+h, p\big)K, \quad \Psi' < 0, \quad \Phi_{\mathrm{G}(S)+h} < 0, \quad \Phi_p > 0,$

where Ψ(.) is the global fossil fuel demand function and τ the carbon tax, as before. Equation (14) gives the equilibrium world market price of traded fossil fuel as

(14′) $p = \mathrm{p}\big(K, S, h, \tau\big), \quad \mathrm{p}_K < 0, \quad p_S < 0, \quad p_h > 0, \quad \mathrm{p}_\tau < 0.$

Fossil fuel is thus cheaper on world markets if there is more exploitation capital, more in situ fossil fuel reserves (driving down extraction costs), the scarcity rent on fossil fuel is high (driving costs up), and the carbon tax is high (especially if the price elasticity of fossil fuel demand is large and of fossil fuel supply is small. Upon substitution of (14′) into (12′), we get

$$(15)\quad \begin{array}{c} R = \mathrm{R}(K,S,h,\tau) \text{ and } H = \Phi(K,S,h,\tau) \text{ with } \mathrm{R}_K = \hat{\mathrm{R}} + \hat{\mathrm{R}}_p \mathrm{p}_K (>0),\ \ \Phi_K = \hat{\Phi} + \hat{\Phi}_p \mathrm{p}_K (>0), \\ \mathrm{R}_j = \hat{\mathrm{R}}_j + \hat{\mathrm{R}}_p \mathrm{p}_j,\quad \Phi_j = \hat{\Phi}_j + \hat{\Phi}_p \mathrm{p}_j,\quad j = S,h,\quad \mathrm{R}_\tau = \hat{\mathrm{R}}_p \mathrm{p}_\tau < 0,\quad \Phi_\tau = \hat{\Phi}_p \mathrm{p}_\tau < 0. \end{array}$$

Reduced-form depletion of *in situ* fossil fuel and production of fossil fuel thus increase in the stock of exploitation capital, but fall with the size of the carbon tax. The effects of the stock of *in situ* reserves and the scarcity rents on these variables are ambiguous. However, if the direct cost effects in (12′) dominate the indirect effects, more in situ reserves or a lower scarcity rent imply lower extraction costs and thus depletion and production of fossil fuel increase.

We can thus summarise the complete model for policy simulation purposes by

$$(16a)\quad \dot{S} = \bar{D} - \mathrm{R}(K,S,h,\tau),\quad S(0) = S_0,\quad S(T) = \mathrm{S}\big(\tau(T) + \theta - b(T)\big) < S_0,$$

$$(16b)\quad \dot{K} = \left[\frac{1}{\phi}(\tilde{q} - 1) - \delta\right]K,\quad K(0) = K_0,$$

$$(16c)\quad \dot{h} = rh + \mathrm{G}'(S)\mathrm{R}(K,S,h,\tau),\quad h(0) \text{ free},\quad h(T) = 0,$$

$$(16d)\quad \dot{q} = (r+\delta)q - \Theta(K,R,h,\tau) - \frac{1}{2\phi}(\tilde{q} - 1)^2,\quad q(0) \text{ free},\quad q(T) = 0,$$

$$(16e)\quad \dot{V} = rV - h\mathrm{R}(K,S,h,\tau) - \Theta(K,S,h,\tau)K - (\tilde{q} - 1)\big[1 - 0.5(\tilde{q} - 1)\big]K/\phi,\quad V(T) = 0.$$

with $\tilde{q} = \max(q,1)$ the marginal cost of exploitation capital adjusted to account for $I \geq 0$, $\Theta(K,S,h,\tau) \equiv \mathrm{p}(K,S,h,\tau)\mathrm{H}_K\big(\mathrm{R}(K,S,h,\tau),K,\mathrm{L}(K,S,h,\tau)\big)$ the marginal revenue product of exploitation capital. The initial and terminal conditions are as in section 3. The extra terminal condition in (16a) gives the end of the carbon era and how much fossil fuel is locked up forever and, as before, comes from the condition that extraction costs just before the end of the carbon era has to equal production cost of renewable energy net of subsidy just after the carbon era.

6.1. Calibration

The calibration of our model of exploitation capital follows mostly the calibration of section 5.1 and is summarised in Table 4. An important difference to the previous model is that now new discoveries are exogenous and fixed at 5 GtC per annum. Interest rate, depreciation rate and adjustment costs are as before. The initial stock and cost of extracting fossil fuel also remains at 200 GtC and \$300 per ton of carbon, while the extraction costs exponent is lowered to 1.5 to account for the limited supply in fossil fuel as time evolves. The extraction function is specified as Cobb Douglas, $\mathrm{H} = \alpha_0 K^{\alpha_1} R^{1-\alpha_1}$ with α_0 = 20 and α_1 = 0.1, so that initial extraction under

"laissez faire" is 4 GtC per annum. Global demand, the initial cost of renewables, and the peak warming relationship remains as before with the cost of renewable energies remaining constant.

Table 4: Calibration of the fossil fuel industry

General, adjustment costs, and exploration	r = 0.04/year, δ = 0.1/year, ϕ = 0.1, and $\bar{D}$ = 5 GtC/year
Extraction: $G(S) = \chi_0 (S_0 / S)^{\chi_1}$ and $H = \alpha_0 K^{\alpha_1} R^{1-\alpha_1}$	χ_0 = 0.3, χ_1 = 2 and S_0 = 200 GtC α_0 = 20, α_1 = 0.1, and K_0 = \$2 trillion
Demand: $H = \left((p+\tau) / (\varepsilon Y (1+g)^t) \right)^{-1/(1-\varepsilon)}$	Y = \$ 60 trillion/year, ε = 0.05, and g = 0.02/year
Cost of renewable energy $b = b_0$	b_0 = 2
Peak warming: $PW = \gamma_0 + \gamma_1 E$	$\gamma_0 = 1.2$ °C, $\gamma_1 = 0.002$ °C /tCO2 and $PW \leq 2$ °C

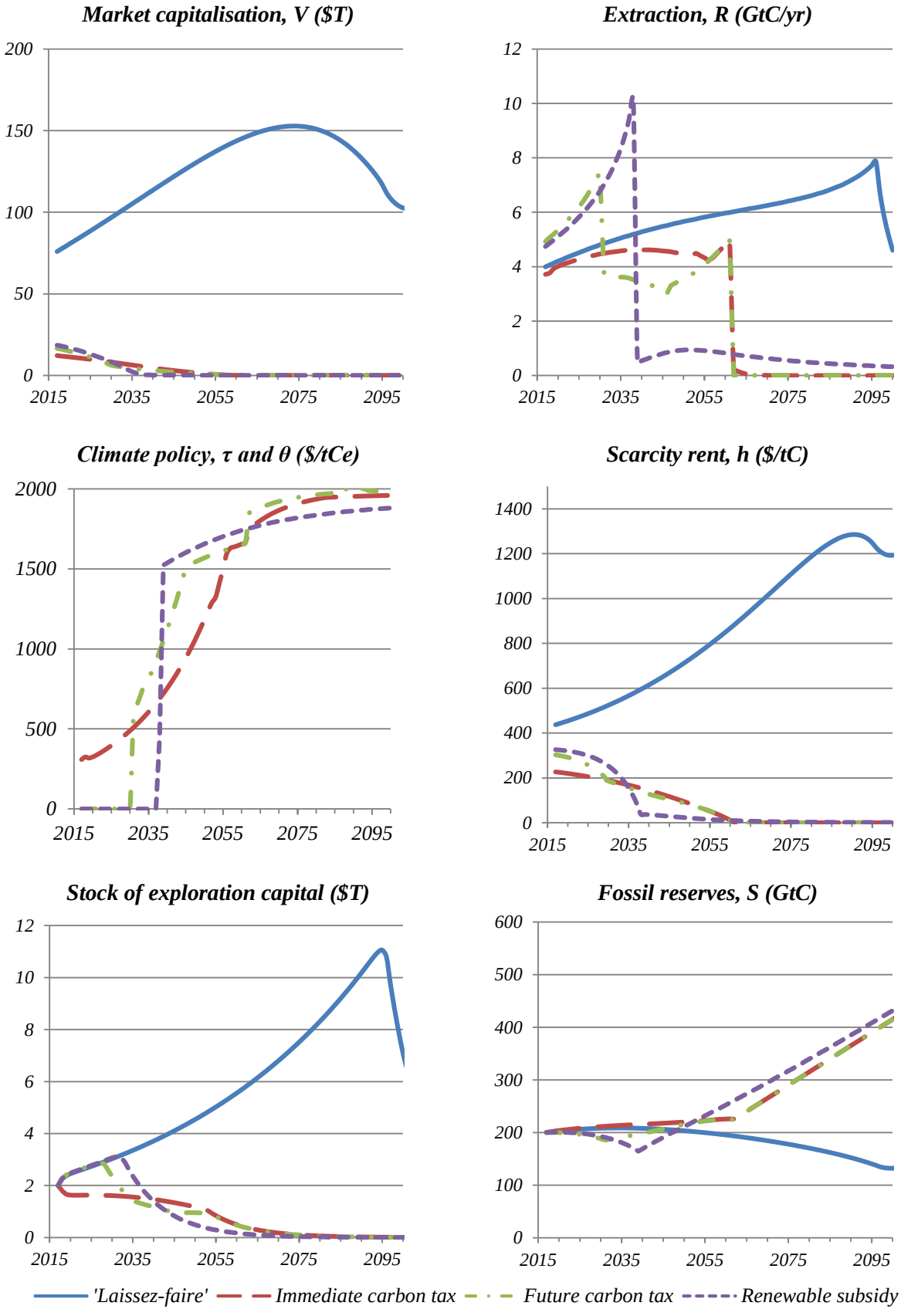
As before, we solve the model using the CONOPT of GAMS but extend the period as fossil fuel is now competitive forever in the "laissez-faire" and renewable-energy-subsidy scenarios. We choose the horizon long enough to ensure that additional periods do not affect initial variables.

6.2. Policy simulations

The introduction of constant discoveries in combination with investment in exploitation changes the dynamics of investment and extraction considerably. Unlike in section 5, here the ICCs never completely abandon fossil fuel and never go out of business, as we assume constant costs for renewable energy. As shown in Figure 4, continued extraction slowly runs down the stock of fossil fuel reserves, aided by increasing amounts of capital, until extraction costs approach the cost of renewable energy. From that point on, both types of energy are used despite being perfect substitutes. After using up the initial resource abundance, the company shifts to a regime of low but stable extraction in line with new discoveries and a lower stock of capital sufficient to support extraction. For our calibration this shift occurs toward the end of this century and is partially depicted in Figure 4. Remaining energy demand is covered from renewable energy sources. Cumulative extraction and peak warming grow as long as new resource discoveries continue. The ICCs are valued initially at \$75.9 trillion.

An immediate carbon tax, starting at \$309 per tC and growing rapidly, can limit cumulative use to 200 GtC. Unlike in the previous model, the carbon tax is not a perfect instrument here in the sense that profitability of extraction depends on the stock of capital (see the discussion around equation (12′)). As a result, the extraction path under the immediate carbon tax (red, dashed in Figure 5) does not budge as much as in the model of section 5 while investment, the capital stock, the amount produced by ICCs fall rapidly. A collapse of productive capacity implies lower output

Figure 4: Policy simulations: exploitation and stranded carbon assets



and profits and the value of the firm drops to $12.1 trillion (16% compared to under “laissez faire”). Once extraction ends, the resource stock recovers due to continued exogenous discoveries.

A policy involving a delayed carbon tax (green, dot-dashed in Figure 4) has the same effects as in section 5. Initial demand for the ICCs produce and extraction increases due to the Green Paradox, helping to protect shareholder value. The anticipation of future carbon pricing also lowers investment into exploitation capital, while initial investment remains almost the same. Market capitalisation falls only to $16.5 trillion (22% compared to under “laissez faire”).

A subsidy for renewable energy to limit cumulative emissions (purple, short-dashed in Figure 5) forces the lowest loss on owners of the ICCs with the value falling to $18.5 trillion (24% compared to under “laissez faire”). While this is desirable from a private perspective, the policy is socially highly inefficient. The subsidy induces strong Green Paradox effects, especially shortly before the imposition of the subsidy. This sharp increase in extraction compensates for the decline in capital and investment which ceases a decade earlier. Unlike in section 5, the subsidy cannot price fossil fuels out of the market (again, see the discussion around equation (12′)). As long as the capital stock has not decayed completely, its marginal product becomes infinite as extraction goes to zero. As a consequence, fossil fuels will be used alongside renewable energy for an extended period of time.

7. Conclusion

Climate policy, whether unanticipated or anticipated, leads to stranded carbon assets if investments in such assets are costly to reverse. Exploration and exploitation investments by international oil and gas companies are the first ones to be affected. There will be a gradual running down of exploration and exploitation capital, and thus proven reserves fall and more carbon is locked up in the crust of the earth. As a consequence, share prices of international carbon companies will slide. We set the cumulative carbon budget for oil and gas emissions to stay within the 2˚C target to 200 GtC or 733 GtC. Carbon Tracker Initiative (2011) argue that the total global carbon budget for 2010-50 is even less, only 154 GtC or 565 GtCO2 if the risk of exceeding 2˚C target should be not greater than 20%, in which case share prices will slide even further. Listed reserves held by the top 100 coal and top 100 oil and gas companies represent 204 GtC, which represents already the global carbon budget for oil and gas and this does not account for the reserves non-listed oil and gas any majors or any further discoveries. Counting in reserves held by sovereign states, 80% of declared reserves owned by the world’s largest fossil fuel companies and their investors might become stranded (Carbon Tracker Initiative, 2011). This study also suggests that 20-30% of market capitalisation of the stock exchanges of London, San Paolo,

Moscow, Australia and Toronto is connected to fossil fuels.[18] About one third of the total value of the FTSE was accounted for by mining and resource companies, so the risk of stranded assets jeopardises London's role as global financial centre.

Our analysis has been limited to how anticipated climate policy cuts the value of irreversible or difficult-to-revert fossil fuel producer assets, i.e., the stock of exploration and exploitation capital needed for locating and producing oil, gas and coal, but other industries that rely on fossil fuel may suffer from the problem of stranded assets too. The most important one is coal-fired electricity generation. Pfeiffer et al. (2016) calculate that the 2˚C capital stock for electricity will have been reached by 2017 on current trends.[19] Hence, no new emitting infrastructure can be built after 2017 for this target to be met (with 50% probability), unless other electricity infrastructure is scrapped. Baldwin et al. (2018) show that an anticipated carbon tax induces less irreversible investments in dirty capital that require fossil fuels (e.g., in coal-fired power stations). This stems from a desire to avoid stranded dirty assets and thus curbs short-run carbon emissions, in contrast to the usual Green Paradox effects (Sinn, 2008).

Besides coal-fired electricity generation, other carbon-based industries such as the steel industry, the aluminium industry, and greenhouse horticulture will suffer too from a tightening of climate policy. Bansal et al. (2017) uses real market data in the US and around the world to identify the intensity of the negative impact of long-run shifts in temperature on financial asset prices. Daniel et al. (2017) and Bansal et al. (2015) show that future macroeconomic catastrophes whose risks rise with temperature have a big impact on the SCC.[20] Andersson et al. (2016) argue that hedging against carbon exposure is nowadays almost costless when carbon-free trackers are used.

Since it is unavoidable that global policy makers have to take action to combat global warming and the risk of all kinds of climate catastrophes, the state of financial markets can be characterised as a "carbon bubble". Such a bubble poses a serious risk for investors and pension funds in particular if they are heavily exposed to carbon-based industries. Hence, it is important to improve oversight and control of the implied systemic carbon risks in financial markets. Against the risks of a deflating carbon bubble risk, there will be the gains in productivity, output and share prices of renewable energy industries and other industries and services that thrive without fossil fuel.

[18] Carbon Tracker Initiative (2013), Climate Counts (2013), Lewis (2014) and Bettis et al. (2017) offer similar arguments, and Manley et al. (2016) and Malova and van der Ploeg (2017) discuss the issue of stranded assets for sovereign states.

[19] Also, see Knoch and Bassen (2013) for a study of carbon risk exposure of European utilities.

[20] Barro (2009) first studies the economic impact of rare disasters and long-run risks; see also Gollier (2012), Hansen and Scheinkman (2012) and Gabaix (2012).

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. Investors and pension funds must take action to limit the systematic risk to their portfolio from global warming. Although various Governors 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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