Title

Divestment prevails over the green paradox when anticipating strong future climate policies

Authors

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Summary

Fossil fuel market dynamics will have a significant impact on the effectiveness of climate policies.[1] Both fossil fuel owners and investors in fossil fuel infrastructure are sensitive to climate policies that threaten their natural resource endowments and production capacities[2–4], which will consequently affect their near-term behaviour. Although weak in near-term policy commitments[5,6], the Paris climate agreement[7] signalled strong ambitions in climate change stabilisation. Many studies emphasise that the 2°C target can still be achieved even if strong climate policies are delayed until 2030.[8–10] However, sudden implementation will have severe consequences for fossil fuel markets and beyond and these studies ignore the anticipation effects of owners and investors. Here we use two energy-economy models to study the collective influence of the two central but opposing anticipation arguments, the Green Paradox[11] and the Divestment effect[12], which have to date only been discussed separately. For a wide range of future climate policies we find that anticipation effects, on balance, reduce CO_2 emissions during the implementation lag. This is because of strong divestment in coal power plants starting ten years ahead of policy implementation. The Green Paradox effect is identified, but is small under reasonable assumptions.

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Main Text

Since the 18th century fossil fuel use – and resulting CO_2 emissions – has increased steadily. Yet the remaining endowment of coal, oil and gas is abundant, which, if combusted using conventional technologies, will lead to dangerous climate change in the future. The Paris Agreement aims to limit the global mean temperature increase “well below” 2°C. This implies a very tight global carbon budget for the 21st century and, consequently, that policies to reduce CO_2 emissions would leave a considerable share of fossil fuels underground.[1,3,4]

Previous studies have shown that cost-effective emission reduction policies tend to begin as soon as possible and progressively tighten over time, thus allocating the CO_2 budget most efficiently over the remainder of the century. The Paris Agreement, however, is weak in near term policy ambition. The sum of the nationally determined contributions (NDCs), made as part of the Paris Agreement, are around 12-14 $GtCO_2$-eq higher in 2030 than the global cost-effective Greenhouse Gas (GHG) emission pathways commensurate with the 2°C target.[9] Previous studies assessed that it is possible to delay the implementation of strong climate policies until 2030 and still achieve the 2°C target. But this significantly increases the challenge of complying with the 2°C target because of: (i) higher necessary CO_2 prices,[13] (ii) a strong drop in fossil fuel prices because of the rapid reduction in demand,[1] (iii) stranded assets of fossil fuel-based infrastructure,[14] and (iv) a strong acceleration in the required ramp-up of low-carbon technologies.[10]

These studies made the simplifying assumption that emitting sectors are forced to follow prescribed emission trajectories until 2030. Some of these baselines include weak climate policies such as NDCs[6,10], while others do not,[8] but a key limitation is that relevant actors are unable to react to policies that are brought into force post-2030 before they are actually implemented. If actors were given knowledge of future climate policy, it has been argued that they would choose to deviate from these prescribed trajectories, which could therefore lead to large deviations in CO_2 emissions.

Two arguments, the Green Paradox and the Divestment effect, are central in the debate. Both are responses to a climate policy that has a lag between announcement and implementation. The Green Paradox[15] argument hypothesises that near-term CO_2 emissions would rise *above* the baseline. Fossil fuel owners frontload supply from their endowments to evade the negative consequences of future drops in fossil fuel prices due to future climate policies. The argument relies on resource owners' seeking to maximise rents received from their resources: they seek to avoid, or reduce, the devaluation of fossil fuels that are rendered ‘unburnable’ because of future climate policies. In the near-term this increases fossil fuel supply at lower prices and thus boosts CO_2 emissions.[11,15–17] Conversely, the Divestment effect argues that near-term CO_2 emissions would decrease *below* the baseline. Investors avoid building fossil fuel based infrastructure whose operation would become uneconomic by the future climate policy. They divest away from infrastructure with high emission intensities, high capital costs and long technical life times that could become stranded and search for alternative investment opportunities. The Divestment effect intensifies as climate policy ambition increases and the policy implementation date comes closer. The Green Paradox effect materialises directly after the policy announcement, since fossil fuel owners frontload extraction as long as climate policies are weak or even absent during an implementation lag.

The growing literature on the Green Paradox relies on highly idealised theoretical models that agree that near-term emissions tend to exceed baseline levels because of future climate policies.[11,16,17] Yet these studies ignore the Divestment argument since infrastructure inertia is difficult to treat analytically. Conversely, while a few numerical studies have investigated the Divestment argument,[12] the methods employed were unable to take into account the maximisation of intertemporal resource rents that are essential for the Green Paradox effect.[18,19]

In this paper we explore the balance of these counteracting effects on near-term aggregate CO_2 emissions and fossil fuel markets using two multi-regional global models: TIAM-UCL[3] and REMIND[4] (see **Methods**). TIAM-UCL is a technology-rich, partial-equilibrium model of the energy sector, while REMIND is a general equilibrium model that additionally includes interactions with the wider economy. Both models are harmonised in the fundamental drivers of energy demand (population and GDP) resulting in similar baseline emissions (Figure 1(a)). However, the models differ in their characterisation and parameterisations of the energy system, which leads to different responses to climate policies (**Supplementary Table 1)**. The use of two models improves the reliability of core findings. Generally, the REMIND model is more responsive than TIAM-UCL. The relationship between both IAMs and the Green Paradox literature is discussed in the **Methods Section**.

To model announcement effects, scenarios are constructed with CO_2 taxes reaching specific levels in 2050 but with the introduction of these taxes subject to varying delays. Scenarios within the IPCC's 5th Assessment Report database that have varying likelihoods of keeping below 2 °C increase are used to motivate our choice of taxes (see **Methods** and **Supplementary Figures 9, 10**).[20] The medium case has a CO_2 tax that reaches US\$100/tCO_2 in 2050, while the low and high cases reach US\$25/tCO_2 and US\$300/tCO_2, respectively. In all cases taxes rise at 5%/yr and are introduced in 2030 or 2040. Since they are introduced at different times, but reach the specified level in 2050, initial tax levels therefore vary depending on the period of delay (**Supplementary Figure 8(a)**). To examine the pure announcement effects we exclude the NDCs in our baseline scenario and so no climate policies are incorporated prior to the introduction of the CO_2 tax.

Without any explicit CO_2 taxes (the 'baseline'), global CO_2 emissions from fossil fuel combustion and industry grow from 32Gt/yr in 2010 to around 60Gt/yr in 2050 (**Figure 1(A)**). When CO_2 taxes are announced, the Divestment effect dominates the Green Paradox effect in both models in all tax cases regardless of the implementation delay (**Figure1(B)**). The Green Paradox occurs in the period immediately following announcement of the CO_2 tax, and is largest for the low tax case when the implementation lag is extended to 2040. However, even at its maximum level, it never exceeds 1GtCO_2/year, and its cumulative impact during the implementation lag remains smaller than that of the Divestment effect. The Divestment effect increases with the tax level: in the low tax cases cumulative emission reductions during the implementation lag are 5% below the baseline. For the medium tax this increases to 5-10% and to 10-20% in the high tax case. When the tax is actually introduced annual emissions are well below the baseline. For example, with the medium tax introduced in 2030, emissions are 8-9GtCO_2/yr lower than the baseline (and within the range of NDC estimates **Figure 1(A)**).

These impacts on total CO_2 emissions can be understood by examining the balance of the counteracting effects on the individual fossil fuel markets (**Figure 2(A))**. For all tax cases, both models display a strong Divestment effect in coal use while the Green Paradox is generally observed in oil markets (**Figure 2(B))**. A Green Paradox effect does occur in coal markets in the period immediately following announcement of a CO_2 tax but only if the tax implementation is delayed to 2040. The increase in coal consumption is marginal: it is largest in the low tax case, but consumption is no more than 4% above the baseline. As the implementation date approaches, while coal prices are much lower than in the baseline, the Divestment Effect outweighs the Green Paradox and coal consumption drops below the baseline. In the oil market the strongest Green Paradox effect occurs in REMIND for the high tax case starting in 2040: oil output in 2030 is 21EJ/yr (9%) greater than the baseline, but since coal use is more than 77EJ/yr below the baseline in that period, CO_2 emissions are lower than the baseline. Gas markets react very differently in both models. In TIAM-UCL gas demand grows to substitute coal, which increases gas prices. This substitution partly neutralises the Divestment effect in the coal market. In REMIND a small Green Paradox effect in 2020 is followed by a notable Divestment effect in latter periods.

With high capital cost and long-lived assets, the electricity sector (**Figure 3)** is particularly susceptible to the Divestment effect. In the medium and high tax cases, during the implementation lag, there is a noticeable decrease in the installation of new coal power capacities. This shortfall in electricity supply drives prices upwards (see **Supplementary Figure 15**), incentivising investments into low carbon alternatives that are less vulnerable to future CO_2 taxes. The investment into alternatives is stronger in REMIND and electricity prices are moderated to a greater extent.

The Divestment effect is triggered by the expectation that future CO_2 taxes make the operation of CO_2 emitting power plants uncompetitive. If a climate policy credibly threatens economic operation of a power plant, it must recover its capital costs in a shorter time, which increases the production costs of electricity. The Divestment effect is strongest for coal-fired power plants because of their high capital cost and high level of CO_2 emissions per kWh generated. For example, if the economic life-time of a coal-fired power plant is reduced from 40 years to 10 years, its effective capital cost increases by 120% (assuming a 5% discount rate). The prospect of the future climate policy has the same effect as a present CO_2 tax of around US\$20/tCO_2 (see **Supplement**). If low carbon alternatives are competitive and can be ramped up sufficiently they substitute for coal power plants and limit electricity price inflation (**Figure 3**).

There are three key reasons why the Green Paradox effect in oil markets is not larger. First, oil demand is price inelastic[21,22], which effectively limits the flexibility of producers to frontload supply as prices drop steeply. Second, rigidities in expanding hydrocarbon production capacities[21,22] and natural decline constraints[4,23], arising from falls in reservoir pressure, limit the ability of oil producers to expand oil supply beyond baseline levels. Finally, the sensitivity of oil prices to a CO_2 tax is relatively small, particularly in comparison to coal. For example, while a US\$/20tCO_2 carbon tax nearly doubles the cost of consuming coal, the mark-up for oil is only 15%, because the oil price is larger and because combustion emissions are 25% lower than those of coal (per unit of energy supplied; see **Supplement**). After the tax is introduced, the impact on oil demand is therefore muted.

Under few specific conditions the cumulative Green Paradox effect can exceed the Divestment effect. If the implementation lag is longer than considered in any of the cases above (i.e. with the tax introduced only in 2050) and the tax starts low, the Green Paradox dominates (**Supplementary Figure 12&13**). The reason is that with a longer implementation lag and a smaller initial tax the fossil fuel owners increase frontloading of extraction over a longer period before the Divestment effect starts to become the dominant effect. Further, if the discount rate or the cumulative fossil fuel availability is lowered, the Green Paradox effect increases as the net present value of future fossil fuel rents threatened by the future CO_2 tax are higher.[4] In these cases the Green Paradox can exceed the Divestment effect, but again only in the low tax case (**Supplementary Figure 16**).

Our results hinge on four crucial assumptions. First, the international community can credibly commit to CO_2 taxes (or equivalent climate policy) several years ahead.[21,22] Second, all investors fully anticipate the climate policy with certainty and re-evaluate their decisions accordingly.[2,24,25] Third, the CO_2 tax is uniform across regions, which precludes adverse effects from international carbon leakage.[1,26] Finally, the lifetimes of existing power plants cannot be extended—allowing this would tend to reduce the Divestment effect.

The results of this study suggest that the original literature on delayed-action climate policies[8–10] is likely to be overly pessimistic. If policymakers provide clear signals that strong climate policies will be imposed in the future, then divestment will reduce carbon lock-in and the low-carbon technology phase-in will ramp up earlier. Divestment from coal power plants reduces the risk that these will become stranded assets. However, these results also carry a warning for policymakers. The Green Paradox effect is most prominent if the implementation lag is longer than ten years and if the policy starting thereafter is weak: strong and timely signals from climate policymakers are therefore necessary.

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Figure 1: Global CO_2 emission dynamics. (A) global CO_2 emissions for fossil fuel combustion and industry historically[29], in the no-policy baseline scenarios and the medium tax case starting in 2030. Cumulative emissions in the baseline scenario of TIAM-UCL and REMIND for the period 2016-2030 are 620 and 580 $GtCO_2$, respectively, and 1180 $GtCO_2$ and 1110 $GtCO_2$ respectively up to 2040. The data for the IPCC AR5 scenarios is taken from https://secure.iiasa.ac.at/web-apps/ene/AR5DB; NDC estimates from literature[5,6,30] **(B)** global cumulative gross emission changes compared to the baseline during the implementation lag period with Green Paradox effects on the positive side and Divestment effects on the negative side. Markers indicate the net effect.

Figure 2: Fossil fuel market dynamics. (A) categorisation of fossil fuel market effects due to policy announcement differentiated by price and quantity changes. The Method section details the method applied to derive these deviations. The upper left quadrant is not relevant for the results in this study. **(B)** the quantitative fossil fuel market effects derived with both models. The figure depicts for the three tax levels that start in year 2030 and 2040 reporting relative deviations from baseline levels of global quantities of primary energy and the corresponding prices in the US for the period 2015-40. Baselines for quantities and prices, and absolute differences over time are shown in **Supplementary Figure 6 and 14**.

Figure 3| Differences in global annual capacity additions to baseline for key electricity technologies. For comparison global wind power capacity grew by 52 GW in 2015 and solar by 63 GW.[31] Note that renewable power capacities have lower 'capacity factors' (the number of full load hours per year) than the fossil and nuclear technologies. The vertical dashed lines indicate the implementation date.

Supplementary Information is available in the online version of the paper.

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Methods

A. Definition of Green Paradox and Divestment effect

The Green Paradox and the Divestment effects are derived by comparing scenarios that do not include any climate policies (the 'baseline') and scenarios with climate policies. The baseline and the policy scenarios are derived with the models, introduced in Section B, using various CO_2 taxes. Model parameters, such as the discount rate or fossil fuel resource availability, are also varied, which induce changes in the baseline. This baseline effect is considered in the sensitivity analysis in the **Supplementary Material**.

For CO_2 emissions, the Green Paradox occurs when CO2 emissions from fossil fuels and industry in any period prior to introduction of the CO_2 tax are **greater** than in the baseline scenario, while the Divestment effect occurs when total CO_2 emissions from fossil fuels and industry are **lower** than the baseline. To assess the balance of the two effects, we consider the cumulative change in emissions up to the introduction of the CO_2 tax. If cumulative CO_2 emissions are **greater** than in the baseline scenario, then the Green Paradox is dominant, while if cumulative CO2 emissions are **lower** than the baseline, the Divestment effect is dominant (see **Supplementary Figure 1)**.

For changes in fossil fuel production, an additional condition is also necessary when considering the two effects. The Green Paradox occurs if production of the fossil fuel in a policy case is **greater** than the baseline and its price is **lower** than in the baseline scenario. The Divestment effect occurs if production of the fossil fuel in a policy case is **lower** than the baseline and its price is also **lower** than in the baseline scenario.

This additional criterion is necessary because cumulative changes in fossil fuel markets only distinguish between gross negative and gross positive deviations from baseline. The negative deviations are not, however, necessarily Green Paradox effects, since they could also result from ordinary inter-fuel substitution (as is observed, for example, in gas markets in TIAM-UCL). Further, while the gross cumulative effects may appear large within individual fossil fuel markets, the CO_2 emissions from fossil fuels and industry can appear relatively small. This is because negative effects in one fossil fuel (e.g. oil) can be neutralised by positive effects in another (e.g. coal). The Green Paradox and the Divestment effect for CO_2 emissions are therefore the result of heterogeneous combinations of various changes across the three fossil fuel markets. .

B. Methodology for quantification and model description

A general overview on key features relevant for this study REMIND and TIAM-UCL are given in **Supplementary Table 1**. Both models compute equilibrium solutions for energy markets with perfect foresight, and fossil fuel demand and the supply are both price responsive. On the supply side, both models differentiate fossil fuel supply by fuel type, extraction costs, and supply expansion inertia. The cumulative availabilities and region-specific extraction costs imply, in combination with perfect foresight, that fossil fuel owners chose extraction paths rationally and, therefore, intertemporal scarcity rents are determined endogenously. These endogenous rents are crucial for the analysis of the Green Paradox. The trade of fossil fuels as well as uranium and biomass including trading costs is also fully represented in both models.

On the demand side, final energy demands, e.g. electricity and transportation fuel, are also price responsive. TIAM-UCL represents final energy demand with a set of energy-service demand functions, while REMIND contains a macroeconomic production function with various final energy carriers as inputs to a nested tree of constant elasticity of substitution functions. The main drivers of final energy demand are socio-economic changes like population growth and GDP growth. The final energy carriers are produced from primary energy carriers such as fossil fuels or renewables given available conversion capacities (e.g. coal power plants). The capacity stocks are not malleable between different uses and are represented as vintages with exogenously specified technical life-times. This representation of conversion capacities is crucial for the analysis of the Divestment effect since investments in each period are evaluated against future price changes including carbon taxes. However, in both models capacities have flexible (and endogenous) utilisation rates. For example, if variable costs were to increase sufficiently, but final energy prices stagnate, the utilisation of existing capacity would decrease to avoid operational losses and (eventually) the capacity turned off. Because CO_2 prices in this study increase steadily, once fossil-fuelled capacity is turned off, it is unlikely ever to be ever turned on and, thus, is considered to be an economically-motivated early retirement. Nevertheless, both models allow the build-up of CCS-ready capacities, which could therefore be converted to avoid such a situation.

Both models apply optimisation methods to compute equilibrium solutions. This approach is well established in both theoretical and computation economics[32,33], and has been employed in many applied economics fields.[34] Theoretical research has shown that if perfect competition and price taking behaviour are assumed, the properties of a decentralised economy, in which demand and supply are equilibrated by market prices, are fully replicated by the optimal solution of an associated problem. The shadow prices (or dual variables) of balance equations in the optimisation problem replicate the market prices of the decentralised economy.

The dynamic Hotelling model for resource markets, on which the Green Paradox is based, can be solved by applying optimisation methods. Indeed such optimisation methods (assuming a centralised planner) were used to derive and characterise equilibrium pathways for resource markets under various climate policy assumptions in the seminal paper on the Green Paradox.[15] The aggregation of various actors to a sector that represents the sum of individual behaviour is common practice in the theoretical literature on the Green Paradox.[11]

Both models are well-established in the scientific literature of climate change economics and energy economics, have been utilised widely for policy-relevant assessments, and have been reviewed extensively (see references below).

Full model documentations, introduction of baseline assumptions and scenarios as well as more detailed results from the policy runs and sensitivity analysis is included in the **Supplementary Material** to the manuscript.

The Green Paradox literature and Integrated Assessment Models

This review examines the Green Paradox (GP) effect and its connection to the IAMs used in this study. We do not aim to be exhaustive in this, but rather provide an overview to elucidate how the most salient points discussed in the GP literature are covered within the modelling frameworks used. We focus here on the so called “weak” GP, which arises when CO_2 emissions exceed a baseline level in the near-term due to delayed CO_2 taxes.[34] We also focus only on global effects and do not review the literature on fragmented climate policies or spatial carbon leakage effects.

The literature on the GP has grown rapidly since the publication of the seminal paper by Hans-Werner Sinn in 2008.[15] The standard Hotelling model served as the starting point for Sinn’s model of the GP. This model rests on a number of simplifying assumptions:

1. There is a single non-renewable resource with a given quantity and zero extraction costs;
2. The resource owners choose an extraction path to maximise their net welfare subject to a given market interest rate;
3. Profits can be invested into financial assets at the market interest rate;
4. The demand function for the resource is given exogenously and is constant over time;
5. There is a competitive market. This includes well-defined ownership of assets, all agents are price takers, and full information is available to all agents); and
6. If additional policies are implemented, this is carried out by a government that is not influenced by market participants.

The assumptions listed above lead, in a case without any climate policies, to the well-known Hotelling rule. This states that the market price of the non-renewable resource grows over time at the same rate as the interest rate. The resource becomes completely exhausted, with extraction of the resource highest at the beginning and monotonically decreasing over time. This has been discussed in a large number of papers and has recently been used to exemplify the GP at the most basic level.[11]

From the perspective of applied energy systems modelling, it is critical to derive reasonable "baseline" scenarios that (i) match insofar as possible the situation in energy markets in a given base year as described in energy statistics publications (for example the level of oil, gas and coal consumption in 2010) and (ii) provide a reasonable trajectory for how energy markets would evolve in the future in the absence of any climate policies. On both of these issues, the pure Hotelling model is insufficient. For example, the extraction path of the pure Hotelling model (that is in a baseline scenario, without any policies controlling CO_2 emissions) implies that global CO_2 emissions would decrease over time due to decreasing fossil fuel extraction and consumption. This has not been observed historically and is not expected in the near to mid-term future. It is also not possible to generate a reasonable calibration to energy statistics in the base year given the assessments of fossil fuel reserves and resources. This is because one of the two following problems necessarily appears. If resource figures as given by current resource assessments are taken as a starting assumption then the rates of resource extraction in the base year, which are determined endogenously by the Hotelling model, are much higher than what we observe currently. Alternatively, if resource levels calibrated in the model to ensure that emissions level in the base year is correct, then cumulative extraction is much smaller than current resource assessments. A reasonable base year calibration must match both (i) current energy and emission statistics and (ii) assumptions about fossil fuel availability based on current resource estimates. Integrated Assessment Models therefore do not rely on the pure Hotelling model because it does not meet the requirements of achieving a reasonable base year calibration or deriving a reasonable baseline emissions scenario with CO_2 emissions increasing in the near to mid-term.[36]

For this reason IAMs deviate from the pure Hotelling model. While the models REMIND and TIAM-UCL both maintain the basic logic of the Hotelling model, which gives rise to the GP, they integrate a number of additional features: (i) they aim to represent techno-economic and institutional realities (such as the existence of renewable energy technologies), (ii) they incorporate empirical data to help parameterise relevant functions (such as how the cost of extraction will evolve over time), and (iii) they aim to generate baseline projections that respect base year calibration and known trends in energy markets.

Some of these additional features (for example extraction costs that depend on the proportion of the resource that has been produced) that are included in REMIND and TIAM-UCL not only impact the baseline scenario, but also impact the strength of the GP in scenarios that introduce delayed climate policies. A significant portion of the theoretical literature on the GP effect has examined these features and discussed how they may affect the GP. **Supplementary Table 2** provides an overview of the most crucial features discussed in the GP literature and how these are connected to the two IAMs used in this study. This overview, partly drawn from existing review articles,[11,17] examines how the features affect the baseline scenario, the GP effect, and whether or not they are included in REMIND and TIAM-UCL.

One general conclusion from **Supplementary Table 2** is that extending the Hotelling Model to include these features reduces the strength of the Green Paradox. Only two of the features make the GP effect stronger if added to the pure Hotelling model. The first is that increasing energy demand over time is likely to increase the GP effect (#8). Surprisingly, this has not received much attention in the theoretical literature and we cannot provide any. The argument for how this would lead to a stronger GP effect is relatively straightforward. Since growing energy demand increases the Hotelling rent of the fossil fuel, one could expect that incorporating increasing energy demand to the Hotelling model would imply a stronger GP. This logic could, however, be reversed if there are constraints on the expansion of fossil fuel supply, for example due to short-term supply rigidities and adjustment costs. If the growth of fossil fuel supply needs to accelerate due to faster demand growth it could become very difficult for fossil fuel owners to frontload extraction (#6 and #7). Hence, near term supply rigidities could undermine the stronger GP effect due to higher demand growth. Energy demand growth is of great concern in quantitative IAMs since it is a crucial factor for the future of fossil energy markets and CO_2 emissions.[36] The second model feature likely to increase the strength of the GP is the inclusion of the technology option to add CCS to the use of fossil fuels (#5).[37] This modelling feature, however, has no impact on the Baseline scenario.

The theoretical analysis in the GP literature tends to consider each of the features listed in **Supplementary Table 2** individually or in isolation as the combination of more than one can soon become analytically intractable. In contrast, IAMs include most of these features within a single modelling framework to improve the representation of energy market developments in various dimensions. Nevertheless, not all modelling features discussed in the theoretical GP literature have been included in the versions of REMIND and TIAM-UCL used in this paper. Most notable is the issue of market structure and oligopolistic behaviour of supply cartels like OPEC (#10) or a monopolist. The main reason for not considering this issue in this paper is that econometric analysis has repeatedly rejected the hypothesis that cartels are systematically influencing fossil fuel markets.[38-40]

In our perspective the most notable model feature that acts to decrease the strength of the Green Paradox is the fact that marginal extraction costs increase as a function of cumulative extraction (#2). This common techno-economic phenomenon is empirically well-founded and is crucial for deriving reasonable Baseline projections. It has important implications for the Green Paradox, because any CO_2 tax will reduce long-term cumulative fossil fuel extraction, which means the occurrence of a “strong” Green Paradox (when the net present value of damages from climate change is higher as a result of the introduction of climate policies) is unlikely.[35] This result is confirmed by other IAMs and it is found to be significant for future global warming (see **Supplementary Figure 9 and 10**). Moreover, increasing extraction costs tend to reduce the likelihood of a near-term increase in emissions beyond the Baseline level (the “weak” Green Paradox).

The modelling feature of natural decline rates (#6) limits the expansion of production from low-cost deposits because the maximum extraction flow is effectively limited. In baseline scenarios this modelling feature gives rise to producer rents, since low-cost and high-cost deposits of the same fuel (for example conventional oil and oil sands) are produced simultaneously. This constraint tends to reduce the ability of producers to act flexibly and thus constrains their ability to frontload supply and so reduces the GP effect.[41] The need to explore and develop in preparation for fossil fuel extraction (#7) also reduce the strength of the GP.[42] Exploration and development activities are not explicitly included in both IAMs, but the associated costs are a component in the marginal extraction costs.[43] REMIND also includes adjustment costs that increase non-linearly for rapid acceleration of extraction (which is similar to an upward sloping supply function for exploration and development). These factors limit the strength of the GP because they reduce the flexibility of producers to adjust extraction plans.

Finally, to the best of our knowledge, the GP literature does not consider that announcing a future CO_2 tax could also reduce emissions below the baseline level during the implementation lag – the Divestment effect. This is most likely because it relies on an explicit representation of capacity vintages, which can be difficult to include within theoretical models. The explicit consideration of capital vintages, especially in the power sector, is crucial in IAMs to derive meaningful baseline scenarios and representation of infrastructure inertia, investment dynamics and capital turnover.

C. Data Availability

The data that support the findings of this study are available from the corresponding author upon request.

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