Carbon Divestment as a Rational Climate Protection Measure?

Abstract

Fossil fuel divestment is intended to help reducing our dependency on fossil fuels and to mitigate climate change. We consider whether there is really a carbon bubble as asserted within the divestment movement, and consider economic and financial effects of partial divestment for the divestors and for the remainder of the market. Naturally, a large part of divested funds tend to be offset by inflowing funds from indifferent investors. Nevertheless, the financially relevant trade-off between expected return and risk limitation means the offsetting is not 100 %, and at least small divestment levels could achieve overall investment reductions at limited costs. A more close look with a dynamic stochastic financial-economic resource market and demand model reveals, however, that even if the invested funds are overall reduced to some extent, the bulk of this already limited reduction likely reduces the valuation of fuel deposits as financial assets, but, as the price elasticity of fuel demand is limited, the effect on the amount of fuels extracted can be expected to be very small. Divestment could play a role in a second best world where alternative, unilateral policies are also subject to large leakage effects. If they can influence the efforts of fuel owners to align political agendas, it could however be advisable for conscious shareholders to remain invested in the sector to prevent an increase of anti-climate protection lobbying – divestment could backfire. Even if climate protection is seen as a moral duty independent of cost benefit analysis, (dis)investors have to ask themselves whether efforts should be channelled into more effective means of emission reductions.

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Part I

Introduction

Carbon Divestment refers to the active withdrawal (or withholding) of funds from assets directly related to fossil fuel extraction, mainly motivated by the aim to reduce the financial incentives for fuel extraction, and to reduce the influence of firms on the the political climate change agenda. It is also seen as a contribution to awareness raising for the climate change problem. The fundamental motivation of the carbon divestment movement seems to stem from the recognition that the vastness of fossil fuel reserves existing and valued on the stock exchanges are many times larger than the carbon budget to be respected if we want a decent chance of limiting global warming to 2 degrees.

Much has been said – and already quite a bit done – about carbon divestment. Yet, empirical or theoretical evidence about financial and economic effects from fossil fuel divestment is scant at best. This may be due to the often highly ideologized or financially influenced nature of the topical debates, with environmentalists on one side and, for example, investors with shareholder value at stake on the other. Economists for their part, tend to reject the idea as addressing the problem from the wrong side; much more efficient than via divestment – likely to be offset by additional funds from indifferent investors –, would be to tackle the root of the problem of free carbon dumping into the atmosphere, namely via carbon taxes. However well funded this scepticism, the extraordinary political difficulty of implementing a stringent pricing scheme may well warrant other, *per se* less efficient, solutions, among which carbon divestment could be a candidate. This paper uses financial and economic non-renewable resource theory, to investigate potential equilibrium effects from carbon divestment, considering also possible geopolitical repercussions, and also considers the potential moral case for divestment beyond cost-benefit analysis.

A question of crucial importance for the analysis throughout the paper, is to which degree carbon divestment could ever lead to a worldwide, systematic retraction of funds from the fossil fuel markets. Most of the analysis relies on the assumption that divestment would remain partial, that is, that even if it could potentially grow to a sizeable share of currently invested fuels, overall the funds divested for climate's sake would constitue a limited share of the sums originally invested.

A report by the Oxford University Smith School (Ansar et al., 2013) contains an overview of other divestment campaigns in the 20th century, and focuses notably on the case of the South Africa divestment campaign in the 1980s targetting the Apartheid establishment. While some parallels between that divestment case and the one from fossil fuels could be encouraging for today's campaign, there is an important difference between that arguably successful divestment program targetting an inhumane regime and one targetting fossil fuel investments. Fossil fuels are a commodity which, though relatively widely considered to be overconsumed, is still largely agreed to also be an essential input to developed and developing modern economies and hence not only an evil to be eliminated but also a blessing for humanity that most would not currently want to see vanish fully. And societies that the campaign tries to convince of the divestment are largely *themselves* the direct consumers of the fuels, making divestment less clearly the obvious option as a response to the climate problem compared to the direct control of fossil fuel use that the consumers can simply excert through their fuel consumption decisions as a much more immediate measure. This was different in the case of the Apartheid, as a geographically and economically relatively remote entity with which an interference via financial markets was a more obvious substitute for the impossible direct control of the Apartheid's deeds. This difference casts some doubt on whether the motivation and powers from earlier divestment compaigns unleashed e.g. against the Apartheid regime, or currently to some limited degree also against Russia related to the Ukraine crisis, can be counted upon in the case of the fossil fuel divestment campaign. Given the reluctance of broad masses to reduce their fuel consumptions despite many years of abundant warnings about climate change (and of the geopolitical undesirability of a fossil fuel dependency), and the lack of willingness or capability of governments to politically address the problem with decisive steps, the odds strongly point to a situation where also the fossil fuel divestment campaign would have difficulties to gain enough momentum for fuel investors to largely divest their funds from fuels beyond a degree warranted simply from an optimal protfolio strategy given a certain risk of future political climate measures. It appears thus appropriate to analyse the effects of mainly a – though potentially significant – limited 'unilateral' divestment by a limited fraction of financial actors. This view is further warranted considering experiences from divestment campaigns from the past more broadly. Of the nine divestment cases Ansar et al. (2013) were able to identify, the South African is arguably the most successful story. Nevertheless, even in this case, the financial impact was limited overall. This is at least the judgment in the study about the case by Teoh et al. (1999) who argue targeted companies experienced no discernible pressure. Instead the authors found simply a reallocation of shares from divestors to indifferent investors, concluding that *"Despite the prominence and publicity of the boycott and the multitude of divesting companies, the financial markets' valuations of targeted companies or even the South African financial markets themselves were not easily visibly affected [...] it appears that financial markets managed to avoid the brunt of the sanctions.*" – a threat that risks to undermine also the effect of divestment in the present case.

Climate protection is clearly the main motivation of the most ardent divestment campaigners protesting in Harvard (FT, 2014a), Oxford (BBC News, 2014) et al. But mixed into the arguments of the decentralized campaign are explicit concerns about financial turmoil when emission restrictions hit the stock market: the value of stranded fuels must sooner or later crash and fall to zero; the carbon bubble is bound to burst. In section II we ask the question to which degree the notion of a 'carbon bubble', that is, the assertion that unjustifiably many fossil fuels would be valued on the stock markets, and that their financial values would be excessive when the climate policy risk for fossil fuel returns is taken into account, has a point. Given that even an arbitrarily small probability of extraction at any future point in time can per se justify that fossil fuels have currently some financial value, and that moreover there exist non-zero probabilities that some novative solutions or developments mean that more fossil fuels than currently anticipated could be used relatively savely for the climate, the claim that 'too *many*' fuel resources are valued on stock exchanges, seems unsubstantiated. Further, whether the listed reserves would be overvalued appears an extremely difficult question and two very simple examples based on key numbers of major fossil fuel companies suggests that the valuations might easily be reconcilable with even relatively good prospects for stringent climate policies. We also develop a theoretical framework in which the risk of climate policy for fossil fuel valuations could result in an asymmetric risk problem that would lead to an excessive risk taking by investing agents. But climate policy, especially relevant *global* agreements, tends to evolve very slowly over time, in which case we find it much less likely that a distinctive limited liability problem leads to an incentive incompatibility with excessive risk taking.

Divestment begs the question to which degree a unilateral (or to any degree limited) withdrawal of funds from the fossil fuel sector can be expected to impact a fund's expected financial payoff, as well as the total amount of funds invested into the sector globally. The analysis in section III (and the extension in the Annex A.1) employs a financial investment/divestment model based on Markovitz financial theory capturing the key tradeoff between expected return and diversification as a means to reduce risk. We find that individual agents can withdraw limited fractions of their funds from the fuel sector at marginal-only costs per unit of fund divested. The costs rise, however, for full divestment by individual market participants. Further, the other participants who do not divest react to the partial divestment by increasing their fund allocations to the fuel sector, offsetting a potentially large fraction, though not 100 %, of the withdrawals by the divesting agent(s). Both, the cost for the divestor, as well as the limited offsetting by other market participants depend on the fact that besides the expectancy of the investment return levels, also their riskiness is a key determinant of fossil fuel asset investments. If this riskiness issue, which disincentivizes investors to accumulate too large shares from an individual economic sector, is less relevant, then not only the net effect of unilateral divestment on the global amount of fuels invested, but also the costs for the divestor, become small. Despite the large financial leakage effects that partial carbon divestment may be subject to, there can be a case for partial unilateral divestment as a second best policy complementing unilateral carbon taxes in the case where efficient global policies are politically infeasible.

In what is arguably the foundation stone for the fuel divestment movement, McKibben (2012) has described a key aim of divestment as breaking the political influence the financially powerful fuel sector excerts on climate policy. Section IV asks whether divestment is an appropriate strategy to achieve this aim of reducing the influence fossil fuel owners have on the political agenda in terms of climate change, with their vested interests meaning that climate policy developments could be slowed down. Several reasons point into the direction that divestment from fuels might at least as likely, if not even more likely, lead to stronger and more effective overall opposition by fossil fuel owners than without divestment. The effect could be exacerbated when one takes into account in which geopolitical regions divestment seems to gain most of its traction, and which other regions of the world might most likely be the profiteers from the cheaper access to fossil resources. It might thus be more useful to consciously remain invested in the fossil fuel companies and to use the shareholder voice to counterbalance companies' tendency to try to align political agendas with ones' own prefered outcomes.

Section V refines the analysis from section III to distinguish several types of fossil fuel divestments, taking into account how fossil fuel prices affect fuel demand; section A.2 provides the mathematical framework with a dynamic stochastic economic and financial fossil fuel investment and consumption model. Key findings include that the low elasticity of demand implies that the offsetting of funds divested from extraction projects is likely to be very large, and hence only a very limited effect on fuel extraction can be expected. Divestment of funds invested into purely financial resource holdings for deposits to be extracted only in the future, may be less strongly offset by indifferent parties' investment reactions, but the therefore entailed overall reduction in funds invested in these not yet to be developed reserves primarily entails a devaluation of the fields rather than a reduction of the amount of fields invested into; after all, the amount of fields available is physically given, and relevant fields will always be worth at least a penny. Moreover, plausibly the small real effect the divestment in such fuel holdings may have, is to accelerate extraction, as it makes holdings of fossil fuels for the future more costly relative to direct fuel extraction.

Section VI considers a moral argument for the case for fossil fuel divestment. In historic cases the divestment may have represented the single most effective means available to discourage some undesirable behavior. Regarding carbon divestment, more effective ways to reduce emissions seem available, so that carbon divestment can be difficult to justify even when climate protection is seen as an ethical imperative beyond cost-benefit analysis.

Part II

Is there a carbon bubble?

A central component of the fuel divestment concept is the idea that there exists a carbon bubble that implies the fossil fuel markets are overcapitalised. Two very distinct fears related to the alleged carbon bubble are expressed within the debate. One relates directly to the risk for the climate posed by carbon contained in the fuel (e.g., McKibben, 2012), and the other emphasizes the financial risk associated to the overvalued assets of the assets (e.g., Carbon Tracker, 2011; Carbon Tracker and Grantham, 2013), depicting the possibilities of a financial crisis caused by the sudden recognition that climate policy means vast amounts of assets become stranded, with invested pension funds to be come illiquid and the upheavals that could come along with it. This discinction tends to not be made explicitly, and the risk of confoundedness between the arguments is large. The main focus here lies on the direct risk for the climate; after all,

The carbon divestment movement is mainly motivated by climate protection and within the divestment movement, the financial risk argument seems mainly a supporting tool to emphasize the urgency of taking action. This section reconsiders the reflections related to the carbon bubble. From a financial perspective, the uncertainty about future climate change and energy markiet developments suggests that the valuation of the fossil fuels say little, if anything, about the climate change problem. In the evidence brought forward by the fuel divestment movement, we did not find any good indicators that too many fuel reserves would be valued, and the data did not contain any direct evidence for fuel firms to be overvalued. On the contrary, we find that it is extraordinarily difficult to judge to which degree a fossil fuel firm could be overvalued even if climate policy would pose a major threat to fuel sales profits. We also find little support for the idea that climate policy uncertainty could be distinctive, major cause for a too-big-to-fail like principle-agent problem where investors would have incentives to exploit the uncertainty about climate policy and benefit from excessive risk-taking; the gradual evolution of climate policy observed in the past, suggests climate policy risk may stand out less strongly from other structural risks to which many sectors see themselves exposed, than the carbon bubble concept as discussed within the divestment movement suggests.

Evidence for overvaluation and fyring plans?

The precise magnitude of the effect of further increases of greenhouse gas emissions and along with it of their accumulation in the atmosphere is far from being set in stone, and scientific measures and assessment models regularly bring up smaller or larger surprises on how the climate may react to a doubling or more of the warming potential of all accumulated greenhoues gases in the atmosphere. Nonetheless, research, notably by the UN Intergovernmental Panel on Climate Change (IPCC, 2013), strongly suggests that the release of the amount of carbon dioxide contained in the fuel deposits that geological evidence on energy content and economic recoverability allows to classify as proven reserves, would very likely lead to a warming well beyond the 2 degrees to which countries have officially pleged to contain climate change within the UN Framework Convention on Climate Change. Only about a sixth of the worldwide fuel reserves could be used if we wanted a high chance of containing global warming to below 2 °C, and even a warming of 3 °C would not change that picture dramatically (see Figs. 1 and 2). This seeming discrepancy is the underlying fundament on which the carbon divestment movement is ultimately built: there are so much fuels in the earth's crust, that it would be disastrous for the climate if all were burned and the carbon contained released. And apparently some are consider burning these fuels, as else the reserves it would be hard to explain why the reserves would listed on the stock exchanges at all. Hence, urgent action seems needed. The insight that fuel reserves seem large enough to propose a major threat to the climate is of course nothing new, as estimates of both, the sizes of fossil fuel deposits, and of the sensitivity of the climate to accumulated emissions, have existed since decades. After all, if it wasn't for fossil fuel deposits as the major source for anthropogenic carbon emissions to represent a major threat for the climate, that is, if there weren't enough fuels to pollute the atmosphere, we would we talk about reducing fuel use at all – why would anybody talk about climate change at all? In this sense, the name of the "new math" McKibben (2012) – which can arguably be seen as the founding document for the divestment movement – proposes seems misleading.

While divestment proponents tend to emphasize that the fossil fuel *reserves* are too large, Fig. 3 shows that in reality, the issue is in some sense even much bigger than generally acknowledged: fuel *reserves* are only the tip of the iceberg; the estimated total carbon content of the less well assessed fossil fuel *resources* dwarfs the fuel reserves that constitute the more well known deposits of fossil fuels by such a large factor that comparing the amount of carbon in resources to a 2 or 3 °C budget seems to become meaningless.

The comparison to a 2 °C carbon budget is, of course, to be put into perspective by the fact that sticking to this target seems already today rather illusive, given not only the current unattenuated growth of fuel consumption, but also the investments into long-term fuel consuming assets such as coal power plants in the emerging world (cf., e.g., UNEP, 2013).

Itself, the fact that a fuel is valued on the stock exchange is not telling about the likelyhood for its carbon to reach the atmosphere in the near future, and to conclude about a 'carbon bubble' how it is done within the divestment movement may be premature. Forwardlooking investors value a fuel deposit depending not only on the most likely future outcomes, but as a weighted average of different possible future returns it may yield. Risk aversion may limit, but should not nullify, the weight of less likely outcomes in asset valuations. Even absent political influences by fossil fuel related, vested interests, the odds are less than 100 % that society will decide on enforcing stringent climate protection. This already means that rational fuel asset investors would place at least some limited value on the fossil fuels that we currently observe to be traded. Moreover, even if we (or investors) irrationally restrict attention to scenarios of a world where we could count on net damages from climate change being limited, there are numerous possible developments that

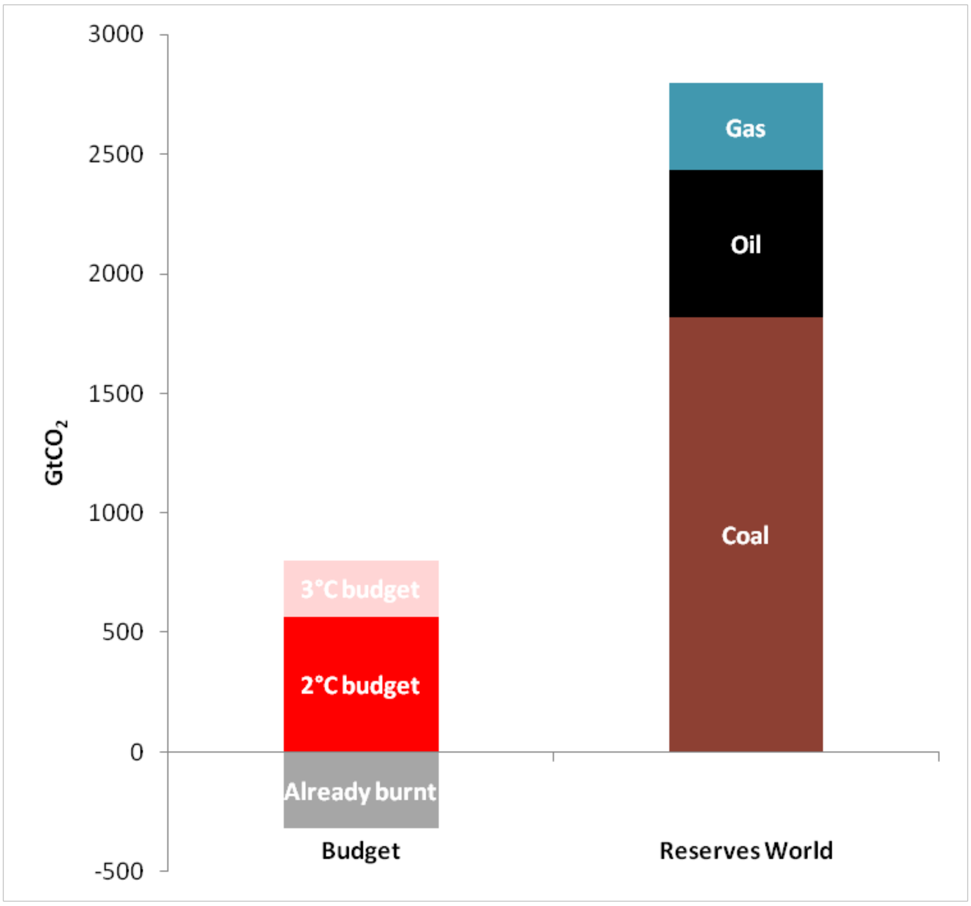

Figure 1: Fossil fuel reserves and carbon budget
Data: Carbon budgets for 80 % chance to remain below warming limits. Sources: Meinshausen et al. (2009), Carbon Tracker (2011), Carbon Tracker & Grantham (2013)

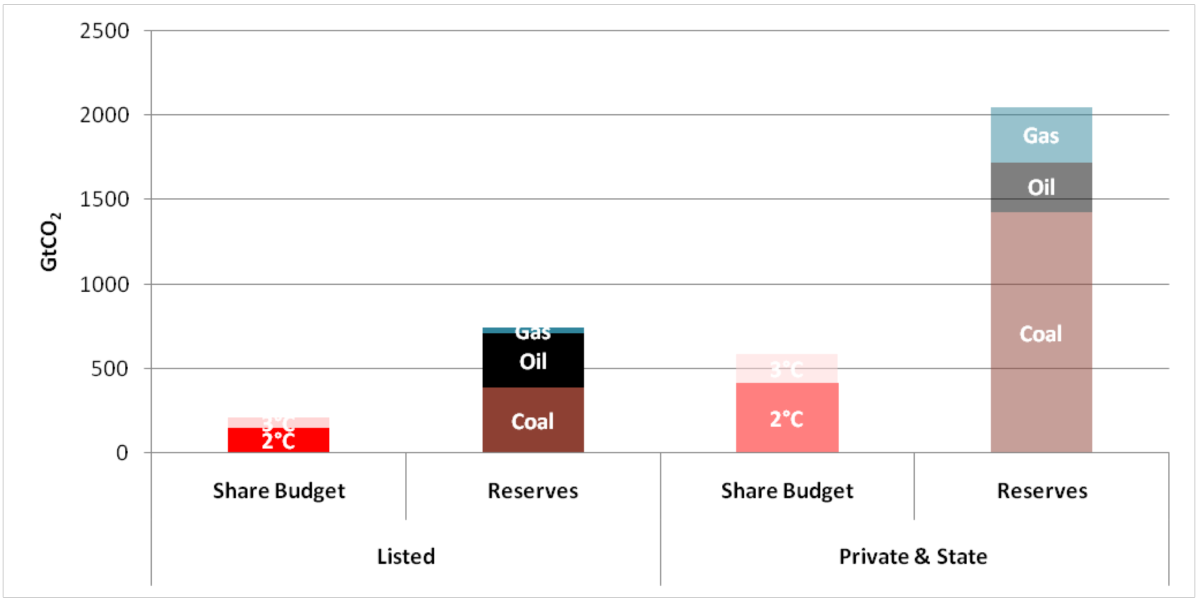

Figure 2: Share of reserves and carbon budget for large listed companies
Data: Own calculation, BGR (2012) and Carbon Tracker (2011). Carbon budgets split proportionally according to reserves' carbon contents.

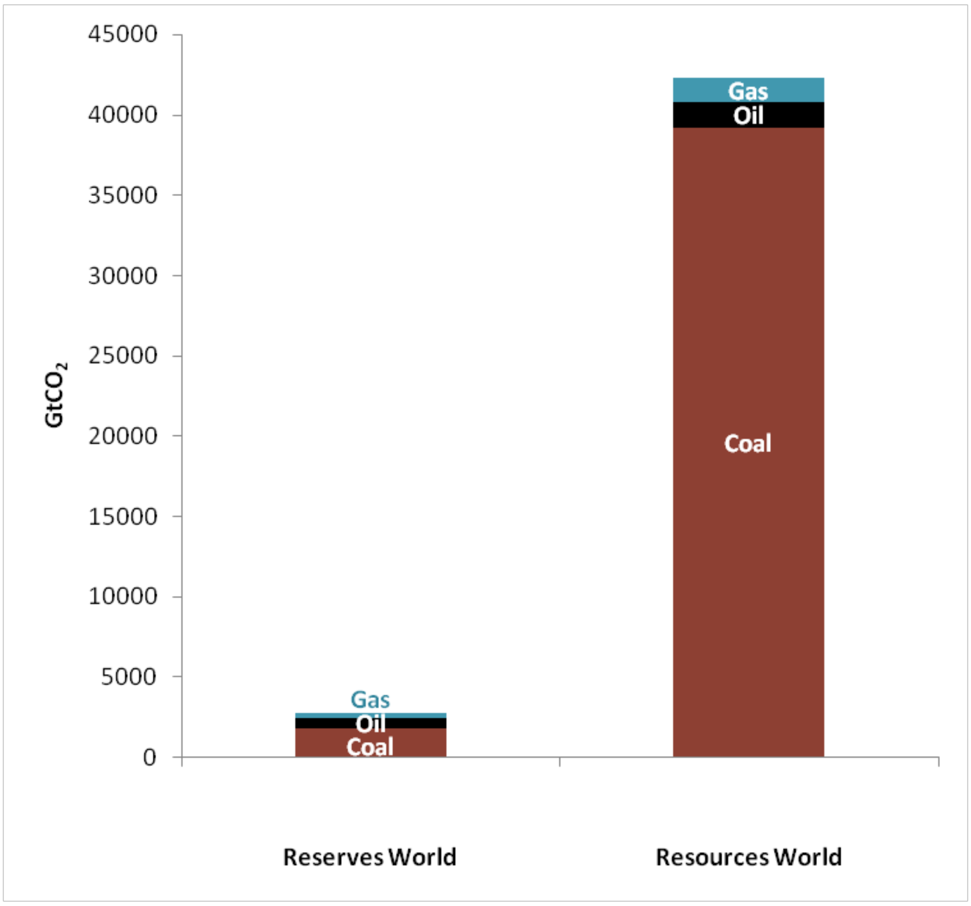

Figure 3: Resources vs. Reserves

Data: Own calculations, BGR (2012) and Carbon Tracker (2011) mean very large parts of the fossil fuels should keep at least *some* value. For example, carbon capture and storing could become widely applicable and economic; geoengineering could effectively contain the effects from increased greenhouse gas concentrations in the atmosphere (or absorb the gases); the natural climate sensitivity could turn out smaller than anticipated and warming thus contained; the effects of warming could prove more benign than anticipated and adaptation even in poor regions more effective than expected. Individually, none of these possibilities currently seems very likely – indeed, one might rightfully argue that each of them seems quite unlikely to become a silver bullet for climate protection in the near future –, and it would be much too dangerous to consider the urgency of finding a proven solution to the climate problem as being strongly reduced because of them. But overall, there is a non-zero chance of solutions of some sort to allow further use of fossil fuels. After all, there are reasons why thousands of scientists all around the world work on a vast range of possible projects that could at some point help to substantially reduce the climate risks even if large amounts of fuels are being used for energy purposes in future. Hence, in addition to the possibility of society failing to tackle the climate problem at all, also the non-zero probability of finding solutions that allow the use of fossil energies without an unjustifiable burden on the climate warrants for fossil fuels to be valued at least to some degree.

This may be better understood with an analogy to a lottery game. Even if the chance of a gain is small, lottery tickets do have a strictly positive value, with the level related to both the possible gains both in terms of probability of gaining, as well of the amount to be gained. It is true that a rationally calculating investor would in general not use his funds to play lotteries as financially the odds do not justify the participation fee, but it is undeniable that a rational financial investor would pay *some* money to be allowed to take part, if he could buy them lottery tickets at a low enough price. If valid tickets for a lottery even with the lowest strictly positive odds of winning were auctioned at the stock exchange, they would clearly yield a positive price (assuming transaction costs away), and similarly rational is the case for significant fuel deposits to be valued by investors.

Carbon Tracker Intiative (2011) looks at the amount of carbon reserves valued on stock exchanges and claims, mainly based on their total carbon content exceeding the carbon allowance for a hypothetical 2 °C warming world, to show that fossil fuels are 'overcapitalised'. As we just showed, and as is nothing but natural even in a world with a rationally anticipated possibility for climate policy, basically all reserves and theoretically even unproven resources, could be valued on the stock exchange; the question simply being *how much* they are valued, and whether that valuation is in discrepancy to a justified valuation that would take into account that climate policy might hamper investment returns by reducing fuel demand. This is a much more complicated question than the Carbon Tracker Intiative report acknowledges. The question is extraordinarily difficult to answer due to several highly critical and inherently uncertain developments on the fuel market that can easily rival, potentially dwarf, the uncertainty for the sector posed by climate policies: first, the development of the global economy, especially of demand in the rapidly growing emerging markets, are crucial to the prices future fuel sales may achieve. Similarly, the global supply of fuels, dependent not only on only very imperfectly assessed geophysical characteristics of deposits as well as hard to anticipate technological progress and financial funds available, but also on many global and more regional geopolitical developments. Because fuel demand exhibits such a strongly price-inelastic nature in the short- and medium-term, prices the fuels achieve on the markets are thus extraordinarily difficult to predict and can vary by very high two-digit percentage changes even from one year to another for different fuel types, as regularly observed in the past. Many other factors, such as the possibility for additional resource findings, but also of implicit or explicit expopriations from fuel deposit ownerships, have their influence on the fuel scarcity rents as well. Such factors have since long had an impact on the acknowledged riskiness of fuel reserve investments, which is well taken into account by investors into the sector. Correspondingly, the answer to the question how large exactly the financial valuation of fuel reserves should be, is in practice of a very subjective nature, and at least very difficult, if not possible, to answer in a generally valid way. It definitely requires a probabilistic quantitive analysis of plausible developments of fossil fuel prices and sales, which the Carbon Tracker Report (2011), does not even attempt to provide,[1] a shortcoming that the update of the report, Carbon Tracker & Grantham Institute LSE (2013) essentially shares. Two basic examples with BP PLC and Royal Dutch Shell PLC show that the numbers in the Carbon Tracker (2011) report's valuation can by no means be enough to conclude fossil fuel companies would be overvalued. The companies' values during the time the report was written were ranging somewhere around \$190 bn each (FT, 2010). The report lists the two companies' fuel reserves as being in the order of 76 Gbbl (BP) and 33 Gbbl (Shell) of oil, and 35 tcf (BP) and 38 tcf (Shell) of gas respectively. Debt ratios are relatively limited,[2] so that debt may to a large degree be offset by already undertaken investments into current extraction projects, and by assets other than the physical oil and gas reserves themselves. Evaluated at prices that many would probably deem rather conservative for today and especially for future sales, \$80/bbl and \$6/MMBTU for oil and gas respectively, the reserves would imply prospective fuel market revenues of around 6.1 (BP) and 2.6 (Shell) trillion dollars according to the reserves figures the Carbon Tracker report lists, and ignoring potential additional revenues from possible future reserve additions and unproven resource access the companies might get access to through their expertise in the field. Assuming half of the fuel sales revenues would be direct project

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[1] In fact, the 2011 report does not even provide market capitalisation numbers for the fossil fuel companies it lists.

[2] Total debt to equity of the companies is roughly 20 % to 30 %. This is in line with the industry wide average of around 25 % in 2012 (Stock Analysis on Net, 2014a; 2014b).

costs and, maybe rather conservatively as well, that the delay in cashflows – fuel deposits are not all developed and exploited today but over substnatial periods of time – reduces their value by a factor three, would leave room for a current valuation of around \$1050 bn (BP) and \$477 bn (Shell) for the two companies. These values sum up to more than 4 times the market capitalisations the two companies together had in the considered period (individually it is almost 6 times for BP and almost 3 times for Shell). With other words, even if climate action was expected to reduce the value of fuel reserves by more than a factor of 4, it could not *a priori* be excluded that the valuation of such companies could theoretically be justified economically, even if we take into account substantial extraction costs for the fuels and reduce the value of expected cash-flows by a factor three because extraction is spread over time rather than taking place today, and even if we consider fuel prices that are lower than today's worldwide average prices and if they are assumed to not increase over time. When comparing the prospective fuel sales revenues to the market capitalisations without taking into account the unknown extraction costs and the time discounting, one would even achieve a ratio of more than 24 between the total sum of prospective sales revenues – even at non-increasing fuel prices – and the market capitalisation. These examples illustrate the impossibility to conclude about a misallocation of capital without a very detailed knowledge about the structure of companies' fuel reserves and prospective revenue and expenditure streams, as well as about how various investors prioritise revenue streams according to their time and risk structures. Of course, the calculations above are too rough for a precise estimation of a justified valuation of a fuel company, but they show how easily it is possible that not only the amount of reserves valued on the stock exchanges be rationally explicable, but also the companies' market capitalisations that are criticized along with the carbon bubble theory. Even more, based on these numbers that account for those provided by the Carbon Tracker report, it would seem equally legitimate to conclude that fossil fuel companies could be substantially undervalued and that investors might overvalue the expropriation risk posed by prospective climate policy.

Climate policy as asymmetric risk for financial markets?

But the claim that notably socially relevant investments such as by public pension funds would be under threat by an at some point necessarily bursting carbon bubble is also put into perspective considering fuels' shares in the institutional investments. Research by Oxford's Smith School shows the fraction of university endowments and public pension funds invested into oil and gas equity assets,[3] making up the bulk of their investments into that sector, to be limited to a range of 2-5 %, namely maximally \$600 bn of the endowment of \$14 tn.

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[3] Coal mining companies tend to be much more fragmented and smaller, with much smaller market capitalisations than the oil and gas companies (Ansar et al., 2013).

Nevertheless, even if the direct, overall financial exposure of vulnerable parts of society to climate policy risk is therefore limited, the question whether there is an excessive risk taking given the possibility that stringent climate policy could ultimately reduce the value of large parts of fossil fuel assets, deserves some investigation: Investments into risky assets can be subject to an asymmetric risk problem, when the investing agent has a limited liability in outcomes where the investments has very low returns (such as could be the case for fossil fuels when climate change suddenly makes them redundant). As the agent is not held fully responsible for such downward risk, but may well fully participate in all large returns, he can have a distorted incentive to seek investments with unjustifiably high risks. This could be imagined personally by individual investing agents which are employees with necessarily limited liabilities, or, with a too-big-to-fail problem also institutionally in case enterprises would be so important that they know they would be saved in case they were to be found in financial trouble. We model this situation and find that with a large risk for the sudden emergence of stringent climate policies, unjustifiable investments into therefore risky fossil fuel deposits could occur. But, in reality stringent climate measures that make the bulk of fossil fuel investments redundant quasi overnight, seem implausible for many countrywide and global political reasons; all evidence on global climate policy developments so far suggest that a gradual resolving of uncertainty related to climate policy is much more likely. In this case, it seems much more difficult to plausibly find a relevant asymmetric risk problem specifically for the fuel sector due to climate policy that would be fundamentally different from risk in other sectors.

To see this, consider the following principal-agent investment model with a theoretical possibility for an asymmetric risk related to climate policy.

(a) Quasi-static case: sudden emergence of climate policy. Invested fund x. Gross return rate in fuel sector r, hence gross payoff, 'return', from fuel investment rx. The gross return rate r is distributed with finite densities $f(r)$ and cumulative distribution $F(r) \equiv \int_{-\infty}^{r} f(r)\mathrm{d}r$. Without loss of generality and to simplify exposition, we assume risk neutrality, that is, the expected utility $\underline{u}$ from an invsetment with a stochastic return r equals that of a save investment with save return equal to the expectancy of the stochastic return, $E[u(r)] = u(E[r])$. Instead one could consider the here used stochastic return r as being scaled such to adjust it for any specific degree of risk aversion. Besides the risky fuel investment, be there an alternative, safe, asset with return R. Say investor, the 'agent', participates in revenue according to deviation of return from target return r^*, $a(r - r^*)x$, $0 < a \ll 1$, though limited instiutional (bankruptcy) or personal liability (outside option) means payoff π effectively bounded at a finite lower level $-\infty < \underline{\pi} < 0$, $\pi \equiv \max[\underline{\pi}, a(r - r^*)x]$, or, equivalently but more conveniently expressed with a minimum payoff-equivalent minimal return rate, $\underline{r} \equiv r^* + \frac{\underline{\pi}}{ax}$, so that we can redefine $\pi \equiv a(\max[\underline{r}, r] - r^*)x$, where thus $\underline{r}$ is the rate of return below which the agent does not get further losses from stronger underperformance. For notational simplicity we normalize the returns so that the target return becomes unity, $r^* \equiv 1$, and we assume that the remuneration is based on strictly positive (gross) returns, with a positive lower bound $\underline{r}$, $0 < \underline{r} < 1$. Say without potentially extraordinarily high losses in the fuel sector arising from climate policy, relevant return distribution bounded within $r \in [r_0, r_u]$ with $r_0 > \underline{r}$, which means nothing else than that in normal times, when investing into the fuels, the pension fund has no relevant risk of getting bankrupt, or the investing agent a has no relevant risk of getting such a low return for him to get the minimal possible remuneration (and reputation) or for him to be better off leaving the mess behind and start a new life. In this case, the payoff scheme is incentive compatible in the sense that the agent has an incentive to invest into the risky fund exactly when the expected payoff exceeds that from the possible alternative investment into the risky asset, i.e. only if $E(r) \geq R$, which is simple to see as the expected payoff from fuel investment, $E[\pi] = aE[r]x - ax$ exceeds that of the alternative investment, $\pi = aRx - ax$, if and only if $E(r) > R$. As stringent climate policy can make large parts of the existing fossil fuels redundant so that deposits loose all their value, one could, however, argue that climate policy makes extremely large losses plausible, decreasing the lower bound of the return distribution to r_c to a low value, $0 < r_c < \underline{r} < r_o$, that is, to such a low value that the agent's outside option can become relevant in some states of the world, as $\pi(r_c) = a(r_c - 1)x < \underline{\pi}$. In this case, it is easy to see that the incentive compatibility is violated and the agent has an incentive for excessive investment into the risky fuel asset instead of into the save asset. The agent derives an expected revenue $E(\pi_f) \equiv \int_{r_c}^{r_u} \pi(r)\mathrm{d}r = \int_{r_c}^{\underline{r}} \underline{\pi}\mathrm{d}r + \int_{\underline{r}}^{r_u} a(r-1)x\mathrm{d}r$ from fuel investment, with $\underline{r} \equiv \frac{\underline{\pi}}{ax} + 1 > r_c$. It dominates the return from the save investment $\pi_s = a(R-1)x$ whenever $F(\underline{r})\left(\frac{\underline{\pi}}{ax} + 1\right) + (1 - F(\underline{r}))E[r|r \geq \underline{r}] > R$. For the total expected investment revenue, however, the save invetmen yields a higher expected payoff whenever $R > E(r)$ or whenever $R > F(\underline{r})E[r|r < \underline{r}] + (1 - F(\underline{r}))E[r|r \geq \underline{r}]$. As the definition of $\underline{r}$ directly implies $\frac{\underline{\pi}}{ax} + 1 < E[r|r < \underline{r}]$, the limited exposure of the agent to the risk his investment choice implies on the return, thus creates an incentive to invest into the risky fossil asset even if the possible high returns do not compensate for the overall downward risk from low returns and from a theoretically possible total loss of the entire investment. The overinvestment in fuel assets when the save asset would yield a higher expected total payoff even in the present case without risk aversion materializes whenever

$$\frac{\underline{\pi}}{ax} + 1 < \frac{R - (1 - F(\underline{r}))E[r|r \geq \underline{r}]}{F(\underline{r})} < E[r|r < \underline{r}].$$

This modeled discrepancy between the incentive of the agent and of the socially optimal investment is nothing but the analogy to the simple standard explanation of the too-big-to-fail problem as discussed in depth in the literature related to the governance of the financial sector especially since the financial crisis in 2007 (Biais et al., 2010; Sappington 1983). It can in general destroy large amounts of financial value by both, reducing the expected revenue from investments, and by leading to an excessive riskiness of the investments beyond a level justified by the tradeoff between risk and expected return. In the lead up to the financial crisis such induced excessive risk appetite has been at the core of the problem that has resulted in a major recession affecting at least the western world and strongly affected the faith in the capitalistic financial and economic system by large masses. On first sight, it could seem that climate policies, threatening to dramatically reduce the value of major parts of the fossil fuel reserves, would present a formidable example for such an asymmetric risk problem: investors into fuel assets may benefit from their lucrativity, until at a certain point, stringent climate policies render the fuels redundant and hence *de facto* expropriate the asset holders, while until that time, their investment agents enjoyed their commissions that went along with the healty pre-policy returns, and with their limited personal liability move on to other projects. Fuel investments representing a significant share of global private and institutional funds invested, this could be a major risk to the portfolio of particular private and institutional investors, potentially to entire sectors or economic systems.

(b) Dynamic case: gradual policy evolution: But for a distinct, major incentive failure to exist in the fossil fuel sector, specifically due to the risks posed by climate policies, one condition is central: the asset stranding due to the emerging climate policy has to hold up fuel investors at a sudden stroke. Experience with global and regional climate policy progress throughout the past decades suggests such a sudden emergence of a stringent policy is very unlikely. On the contrary, a worrisome slowness characterises the efforts at various levels of climate policy, as witnessed throughout the preparation phase and now already the third phase of implementation with very doubtful sucess in terms of global emission reductions induced. That the last century's geopolitical macro structure with a relatively clearly dominating hemisphere is steadily giving way to a much more multipolar world, with highly heterogenous national and regional interests of many powerful players to be taken into account, could make stringent global accords even more difficult to achieve. In this point, the situation differs from the possibility suggested in the quasi-static case above, and it strongly limits the scope for the asymmetric-risk problem related to climate policy to pose a main threat for the security of large shares of global investments in the fuel sector. To see this, consider an extension of the quasi-static model from (a) to multiple periods. For simplicity but without loss of generality of the argument, we ascribe the variability of fuel asset returns in (a) solely to uncertainty related to climate policy. Be the time horizon split into n periods and consider for simplicity a case where the uncertainty from each period corresponds to a stochastic multiplicative return rate, $r_i \, \forall i \in [1, n]$, with identical bounded distributions so that the cumulative maximal variability after n periods equals the variability from framework (a), $r_i \in [\sqrt[n]{r_0}, \sqrt[n]{r_u}]$, which yields the bounds from (a) for the overall return to be calculated as the product of the per-period (e.g. annual) returns, $R_n \equiv \prod_{i=1}^{n} r_i$, yielding $R_n \in [r_c, r_u]$. The investment being purely financial, each period the investors can reconsider the investment, choosing between the two alternatives independently of the choices in other periods. We assume that theoretically the same source of incentive incompatibility in terms of limited liability exists, with each period the corresponding agent's payoff being proportional to the period's return except for the liability to be bounded, $\pi_i \equiv a(\max[\underline{r}, r_i] - 1)x$. It is easy to see that as the number of periods grows large, that is, when the uncertainty about climate policy is resolved gradually rather than abruptly, the excess risk from the limited liability becomes arbitrarily small and even vanishes for a large enough but finite number of periods,

$$\exists k < \infty \, \text{s.t.} \, \forall n \geq k \, P(r_i < \underline{r}) = 0,$$

as for any given $\underline{r} < 1$, for a large enough n we necessarily have $r_c^{1/n} > \underline{r}$. Naturally, this means in terms of incentive compatibility we are again in a similar situation as in the quasi-static world without climate policy, where – here in each period – the agent's incentive to invest into the fuel asset goes hand in hand with the maximization of the expected profit for the asset owner: $E(\pi_i) \equiv a[\underbrace{P(r_i < \underline{r})}_{0}\underline{r} + P(r_i \geq \underline{r})E(r_i | r_i > \underline{r}) - 1]x = a(E(r_i) - 1)x$, so $E(\pi_i) \geq a(R-1)x \Leftrightarrow E(r_i) \geq R$, and the investing agent has thus an incentive to invest into fuels if and only if the expected total return from such investment exceeds that from the alternative investment.

That there is no clear reason for climate policy to imply a large incentive incompatibility problem related to limited liabilities by the investing agents, does not mean investments into fossil fuels are unproblematic. Adding a political economy component in the investment model would in general reveal that along with sizeable investments into fossil fuels tends to come an incentive for the investors to lobby against stringent climate policies.[4] This seems also confirmed by current political developments, such as with the example of Australia where the resource extractive sector has a sizeable share in GDP and the power of lobbying, on behalf of vested interests, to influence the political climate policy agenda, to the detriment of stringent unilateral climate policy, is apparant (e.g., FT, 2014b), so that one could hardly deny that vested money plays an important role in determining climate policies. Section 10 discusses this effect, and shows that, contrary to what one might think on first sight, carbon divestment may be more likely to exacerbate rather

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[4] This incentive is not as unambiguous as it may seem on first sight. The life-cycle carbon intensity varies strongly across fuel types and specific deposits. Given the inelasticity of energy demand but the good substitutability of fossil fuels between themselves in many applications, low-carbon fossil fuel deposits can well increase in value when favoured against more carbon intensive fuels by carbon emission constraints. This can currently be observed in power markets where natural gas suppliers and gas power station owners can benefit a lot from higher carbon taxes that make coal power plants – much more carbon intensive than gas power plants – less competitive.

than to alleviate the burden vested interests in the fossil fuel sector may represent to a successfull political combatting of climate pollution.

Concerning the economics of non-renewable resources, there is one further question that carbon divestment proponents have to ask themselves regarding the concept of a carbon bubble with the alleged resource overvaluation. From a dynamic non-renewable resource economics point of view, a high scarcity value of fuels is often seen as the best protection for the climate, absent any stringent current climate measures: the only force that prevents fossil fuel owners from extracting all their fuels as soon as possible, is the expectation that the resources could be at least as profitable when extracted in the future instead (Hotelling 1931; Herfindahl 1967), and a threat to these future revenues tends to increase the rate at which fossil fuels are extracted, rather than reduce the amount of fuels consumed (e.g., Sinclair 1982; Sinn, 2008). From that perspective, securing property rights in order to limit the discount rate the fuel owners take into account when comparing future to current revenues, and ensuring that climate protection measures do not threaten the future value of fossil fuels as much as the current values. Targetting the value of fossil fuel reserves in general, and presumably with more sucess in the future than currently as the divestment campaign is likely to progressively gain traction over time, the movement could risk to exactly create a situation where fossil fuel sales are accelerated rather than stopped; a divestment Green Paradox (Sinn, 2008) seems not implausible.

Part III

Financial divestment model

Divestment begs the question to which degree a unilateral (or to any degree limited) withdrawal of funds from the fossil fuel sector can be expected to impact a fund's expected financial payoff, as well as the total amount of fuels invested into the sector globally. The analysis employs a financial investment/divestment model based on Markovitz financial theory capturing the key tradeoff between expected return and diversification as a means to reduce risk. An extension of the model accounting for to be expected general equilibrium effects allows to account for effects of investment decisions by individual actors on returns and fund allocation of other participants.

The results suggest that asset holders can reduce their investments in the sector at marginal-only per-unit costs, and achieve with it a non-marginal reduction of global investments in the market even after other participants had time to adjust their investments to the divestors' action. This seems good news for carbon divesters, and at least puts into perspective the argument that whatever is divested by one party would necessarily be compensated by increased investments by third parties. That unilateral divestments are not fully offset by third party investment increases stems from the incresed lumpiness of the risk when individual investors increase the funds allocated into a single economic sector. The large shares of fossil fuel firms in traded stocks – Carbon Tracker (2011) suggests 20-30 % of the market capitalisation in London and in various other major stock exchanges is linked to fossil-fuel extraction –, as well as the high correlation among the high within-sector correlations of returns suggested by the comovements of global fossil fuel prices, mean that the effect could indeed be non-negligible, even though the offsetting by optimizing, non-divesting parties might be very substantial. Given the apparent, strong reluctance by many to consider it likely that financial risk effects, that is, the variability of a sector's returns when an investor's sectoral exposure is significant, may really be relevant in the fossil fuel divestment case, and that therefore it cannot a priory be excluded that partial-only divestment can have non-marginal effects, an additional point stressing the factors may be in order. In 2013, Harvard University found itself under increasing pressure, by organized students and fossil fuel campaigners, to withdraw its large funds from fossil fuel assets.[5] Despite some stated sympathy for the cause *per se*, the university leadership decided against it, based notably upon the substantial financial cost and risk divestment would entail, as witnessed, for example, with the speech by the university's president Faust (2013). Basic financial analysis, however, suggests that the cost (to divesters) from divestment and the cost (to non-divesters) in terms of increased sectoral risk exposure when fully offsetting the divested sums, go hand in hand: if spread risk from financial exposure to the fossil fuel sector was entirely irrelevant, it is hardly conceivable that Harvard saw a non-negligible financial value in remaining invested. Without risk concerns, competing investors would offer Harvard enough for the sectoral shares for Harvard to be equally well off by diverting its funds. In line with the main theories of financial analysis, and the major role diversification plays throughout financial markets, Harvard's response does show, however, that sectoral reallocation of funds from some sectors to others, tends to come at non-negligible financial costs. Our analysis suggets that these risk-related costs also mean that the offsetting of divestment by third parties, is, at least financially, not complete.

To which degree the results in this section really qualify divestment as a promising avenue for effective climate protection, appears, however, less clear than the *per se* positive result may suggests on first sight. The applications of the results from this section in section IV considering plausible geopolitical implications of carbon divestment, and in section V considering specifically shorter- and longer-run implications taking into account fuel exhaustibility and specifics of fuel demand, shows that the unilateral investment reductions

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[5] Cf., e.g., Reuters (2013) and Hendey (2014). The pressure has since been upheld until today. In spring 2014, Harvard students blocked university offices, and a letter by faculty members compared investment linked carbon investments morally to investments in slavery before the abolition (FT, 2014a). The 92 original signatories of the letter represent less than 4 % of Harvard's 2400 faculty members.

may mainly yield a reduction in the *value* of fuels rather than in amounts consumed, and that dynamic exhaustion and geopolitical effects could make divestment counterproductive in environmental terms.

1 Setup

To ease the discussion, this section analyses the repercussions of divestment in a simplified framework. Appendix A.1 extends the analysis to a substantially more general case, confirming the generality of the results. Section V further discusses a more dynamic case, tracking the interaction of fuel demand in multiple periods and divestments from several different types of fuel assets, with an analytical supplement in Annex A.2.

Number N of investors $i = \{1..N\}$. One of them is the divestor called d; there are $N-1$ standard investors. Size of each investor $s = \frac{1}{N}$. We assume only a single 'clean' (i.e. non-fuel) asset. We adopt the standard Markovitz framework for the analysis of portfolio choices, with the key trade-off between expected return from the portfolio investment and the volatility of that return, governed by the individual volatilities and correlation of the assets returns, and extend it to catch the relevant general equilibrium effects. While we allow for a large number of investors, we here restrict ourselves to investments into assets from three sectors: current consumption (which equivalently can be considered as an investment into a save asset with fixed return), and a fuel and a non-fuel ('*o*ther') sector. Markovitz-type investment analysis focuses an individual actor's payoff within a specific framework (considering him as a purely self-interested price taker). In contrast, for our divstment question, we concern ourselves with effects of that actor's investment on global investment volumes. Hence, the general equilibrium effects of the actor's investment choices must be taken into account. Hence, the fact that the economic sectors exhibit decreasing returns on investments is modelled explicitly. Fuels gross return, in expectation, r_f and clean return r_o, with, for simplicity of the exposition, only the former here decreasing in global fuel investment F; in the model extension in Annex A.1 we explicitly model also the non-fuel sector's returns to decrease in investments. The clean investment return is thus here assumed constant independent of the clean ('other') investment o,

$$\begin{aligned} r_f &= R_f - \phi F \\ r_o &\{= R_o\} \end{aligned} \tag{1}$$

Be correlation between the two asset types' returns $-1 < \gamma < 1$, here typically assumed positive, $\gamma > 0$. Returns within a sector are considered perfectly correlated, and for simplicity but without any more specific qualitative impacts, in the simplified version we assume in both sectors the same volatilities, with variances $\sigma_f^2 = \sigma_o^2 = \sigma^2$ – relaxed in Appendix A.1.

Be i the index for the parties, and $c_{i,t} = \frac{C_{i,t}}{s}$ party i's per capita consumption in period t. All parties have convex utilities and exhibit thus risk averse behavior. Rather than directly specifying a CARA or CRRA utility, we simply directly assume the utility to be of the form

$$u_{i,t} = s \cdot (E[c_{i,t}] - \delta V[c_{i,t}]),$$

where $E[\cdot]$ and $V[\cdot]$ are the expected values and the variances,[6] respectively.

Each party i's welfare is the sum $W_i = u_{i,1} + u_{i,2}$; for simplicity but again without any major impact on the main results, we disregard the discounting β here in the simplified version; Appendix A.1 relaxes this.

Assume unitary 'per-capita' endowments s (per-capita here means per size of the party; in reality it rather corresponds to the share of the parties in the world's investments rather than in a genuine head-count). Let F_i and O_i be region i's investment in the fuel and clean assets, and $f_i \equiv \frac{F_i}{s}$ and $o_i \equiv \frac{O_i}{s}$ the corresponding per-capita investments. Per-capita consumption becomes (for any state with a certain materialized returns r) $c_{i,1} = 1 - (f_i + o_i)$ and $c_{i,2} = r_f f_i + r_o o_i$. The global sectoral investments sum to

$$\begin{aligned} F &= \textstyle\sum_{i=1}^N F_i = \sum_{i=1}^N s f_i, \\ O &= \textstyle\sum_{i=1}^N o_i = \sum_{i=1}^N s o_i, \end{aligned}$$

and we note $Ns = 1$. The variances of per-capita consumption, zero in the first period, in the second period become

$$V(c_{i,2}) = \sigma^2 \left(f_i^2 + o_i^2 + 2\gamma f_i o_i \right).$$

2 Unconstrained Solution

Part (a) Investment rule (portfolio choice) as fct. of some expected returns $\hat{r}_f$ and $\hat{r}_o$

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[6] This linear tradeoff between expected return and variance is consistent with a CARA utility function if utility is held constant. This is here only approximatively the case for the divesting party. As the number of parties gets large, for all the other parties, this is, however, asymptotically valid and hence does not affect our analysis of their investment responses: the direction of the derivative at the optimum is the right one (note, assuming normal returns, the mean and variance fully specify the distribution of the revenues). It is going to be easy to see that the remainder of the qualitative findings about the cost-benefit calculation for the divestment would not be impaired by changing to a different analysis; for marginal divestments the utility approximation used here is compatible even for the divestor, and for larger unilateral divestments, the divestment costs would remain finite with any other well-behaved utility function as well, and it is easy to see that this ultimately implies that all the qualitative findings derived here remain valid also for other standard utility functions.

$$W_i \quad = \quad u_{i,1} + u_{i,2} = s \cdot \Big\{ (1 - (f_i + o_i)) + \Big(r_f f_i + r_o o_i - \delta\sigma^2 \left[f_i^2 + o_i^2 + 2\gamma f_i o_i \right] \Big) \Big\}$$

Assuming individual investors to be small relative to the market, so that they consider themselves as price-takers, the FOCs (we assume parameters such that interior solution; this requires notably that both returns are high enough for a strictly positive investment to be warranted):

$$\tfrac{\partial W_i}{\partial f_i} = 0 : \quad 1 = r_f - 2\delta\sigma^2 \left(f_i + \gamma o_i \right) \quad , \quad \tfrac{\partial W_i}{\partial o_i} = 0 : \quad 1 = r_o - 2\delta\sigma^2 \left(o_i + \gamma f_i \right) \tag{2}$$

Solving for f_i and o_i yields

$$\begin{aligned} f_i &= \tfrac{r_f - 1 - \gamma(r_o - 1)}{2(1-\gamma^2)\delta\sigma^2}, \\ o_i &= \tfrac{r_o - 1 - \gamma(r_f - 1)}{2(1-\gamma^2)\delta\sigma^2}. \end{aligned} \tag{3}$$

Part (b) Equilibrium: investments f_i and o_i and equilibrium returns r_f and r_o

From (3) we know that the investments of all parties are the same, so we can write *global* investments $F = Nsf_i = f_i$ and $O = Nso_i = o_i$, hence

$$\begin{aligned} F &= \tfrac{r_f - 1 - \gamma(r_o - 1)}{2(1-\gamma^2)\delta\sigma^2}, \\ O &= \tfrac{r_o - 1 - \gamma(r_f - 1)}{2(1-\gamma^2)\delta\sigma^2}. \end{aligned} \tag{4}$$

Using (1) in (4) yields

$$\begin{aligned} F &= \tfrac{(R_f - \phi F) - 1 - \gamma(r_o - 1)}{2(1-\gamma^2)\delta\sigma^2}, \\ O &= \tfrac{r_o - 1 - \gamma((R_f - \phi F) - 1)}{2(1-\gamma^2)\delta\sigma^2}, \end{aligned}$$

and solving for F and O and thus also f_i and o_i yields:

$$F^* = f_i^* \quad = \quad \frac{R_f - 1 - \gamma(r_o - 1)}{2\left(1 - \gamma^2\right)\delta\sigma^2 + \phi}, \tag{5}$$

$$O^* = o_i* \quad = \quad \frac{2\left(r_o - 1 - \gamma(R_f - 1)\right)\delta\sigma^2 + (r_o - 1)\phi}{4\left(1 - \gamma^2\right)\delta^2\sigma^4 + 2\delta\sigma^2\phi}. \tag{6}$$

The per-capita investments, and the global investments are thus independent of the size of the individual investing parties, s, that is, they are independent of the number of investing parties N that constitute the totality of global investors.

An interior solution with strictly positive investments f_i^* and o_i^* obtains when $R_f > 1+\gamma(r_o-1)$,[7] and when $r_o > 1+\gamma(R_f-1)/(1+\frac{\phi}{2\delta\sigma^2})$. These are weak conditions[8] and in the following we assume them to be met.

Equilibrium fuel interest rate r_f^*:

$$\begin{aligned} r_f^* &= R_f - \phi F^* \\ &= R_f - \phi\frac{R_f - 1 - \gamma(r_o-1)}{2\left(1-\gamma^2\right)\delta\sigma^2+\phi}. \end{aligned}$$

Utilities:

$$\begin{aligned} u_{i,1}^* &= s\left[1-(f_i^*+o_i^*)\right] \\ &= s\frac{2(-1+\gamma)\delta\sigma^2\left(R_f+r_o-2-2(1+\gamma)\delta\sigma^2\right)-\left(r_o-1-2\delta\sigma^2\right)\phi}{4\left(1-\gamma^2\right)\delta^2\sigma^4+2\delta\sigma^2\phi}. \end{aligned}$$

$$\begin{aligned} u_{i,2}^* &= \frac{s}{4\delta\left(2\left(1-\gamma^2\right)\delta\sigma^3+\sigma\phi\right)^2}[4\left(R_f^2+r_o^2-2+2\gamma-2R_f r_o\gamma\right)\left(1-\gamma^2\right)\delta^2\sigma^4 \\ &\quad +4(1-\gamma)\left(R_f+r_o^2-2+\left(r_o-1\right)r_o\gamma\right)\delta\sigma^2\phi+\left(r_o^2-1\right)\phi^2]. \end{aligned}$$

$$\begin{aligned} W_i^* &= u_{i,1}^*+u_{i,2}^* \\ &= \frac{s}{4\delta\left(2\left(1-\gamma^2\right)\delta\sigma^3+\sigma\phi\right)^2}[16\left(1-\gamma^2\right)^2\delta^3\sigma^6+\left(r_o-1\right)^2\phi^2+4\delta\sigma^2\phi\left(\left(r_o-1\right)^2\left(1-\gamma^2\right)+\phi\right) \\ &\quad +4\left(1-\gamma^2\right)\delta^2\sigma^4\left(2+R_f^2-2\gamma+r_o\left(r_o-2+2\gamma\right)-2R_f\left(1+\left(r_o-1\right)\gamma\right)+4\phi\right)] \end{aligned}$$

3 Divestment Solution

One among the N investors, the 'divestor', indexed d, decides freely on an investment level f_d; with a partial or full divestment being expressed as $f_d < f_i^*$. The FOC from (2) for party d now implies

$$o_d = \frac{r_o-1}{2\delta\sigma^2} - \gamma f_d. \tag{7}$$

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[7] This condition for a positive fuel-investment can be interpreted as follows: Marginal investment into fuel brings expected return R_f in period 2 and must exceed the period 1 consumption value. For marginal-only fuel investments, the fuel return variance is itself not central, but positive correlation $\gamma > 0$ with other investments reduces the value of the fuel investments, and more so the larger investments into the other investments are, i.e. this disincentive to invest in fuels increases not only in γ but also in $r_o - 1$ whose value is the primary driver of non-fuel investments. The condition for positive non-fuel investment is very similar, except for a slight complication introduced by the effect of the fuel-investments on the fuel asset returns.

[8] E.g. , for any pair of gross returns $R_f = r_o > 1$ the conditions would necessarily hold in any case.

The other investors are indexed $n = \{i | i \neq d\}$. Their investments f_n and o_n are still guided by the optimal investment reaction rules (3).

The equilibrium for investments $F = sf_d + \sum_{i \neq d} sf_n = sf_d + (1-s)f_n$ and $O = so_d + (1-s)o_n$, and the fuel return rate according to (1) solves to

$$\begin{aligned}
f &= \frac{(1-s)\left(R_f - 1 - \gamma(r_o - 1)\right) + 2f_d s\left(1-\gamma^2\right)\delta\sigma^2}{2\left(1-\gamma^2\right)\delta\sigma^2 + (1-s)\phi}, \\
o &= \frac{2\delta\sigma^2\left(r_o - 1 - r_o s\gamma^2 + \gamma\left(1 - R_f(1-s) - s\left(1 - \gamma + 2f_d\left(1-\gamma^2\right)\delta\sigma^2\right)\right)\right) + (r_o - 1)(1-s)\phi}{2\delta\sigma^2\left(2\left(1-\gamma^2\right)\delta\sigma^2 + (1-s)\phi\right)} \\
r_f &= R_f - \phi\frac{(1-s)\left(R_f - 1 - \gamma(r_o - 1)\right) + 2f_d s\left(1-\gamma^2\right)\delta\sigma^2}{2\left(1-\gamma^2\right)\delta\sigma^2 + (1-s)\phi},
\end{aligned}$$

and while d's non-fuel investment was already fully known from (7), independent of r_f but dependent on the directly chosen f_d, having pinned down the equilibrium interest rate, the investments in the rest of the world from (3) can be written out explicitly:

$$\begin{aligned}
f_n &= \frac{R_f - 1 - \gamma(r_o - 1) - f_d s\phi}{2(1-\gamma^2)\delta\sigma^2 + (1-s)\phi}, \\
o_n &= \frac{(1-s)(r_o - 1)\phi + 2\delta\sigma^2\left(r_o - 1 - \gamma(R_f - 1) + f_d s\gamma\phi\right)}{2\delta\sigma^2(2(1-\gamma^2)\delta\sigma^2 + (1-s)\phi)}.
\end{aligned}$$

Utilities and welfare as their sum, of the divesting party are

$$\begin{aligned}
u_{d,1} &= s\left(1 - (f_d + o_d)\right) = s\left(1 - f_d(1-\gamma) - \frac{r_o - 1}{2\delta\sigma^2}\right), \\
u_{d,2} &= s\left(r_f f_d + r_o o_d - \delta\sigma^2\left(f_d^2 + o_d^2 + 2\gamma f_d o_d\right)\right) \\
&= \frac{s}{4\delta\sigma^2\left(2\left(1-\gamma^2\right)\delta\sigma^2 + (1-s)\phi\right)} \\
&\quad \cdot\Big[\left(r_o^2 - 1\right)(1-s)\phi + 2(1-\gamma)\delta\sigma^2\left(\left(r_o^2 - 1\right)(1+\gamma) + 2f_d(1-s)\phi\right) \\
&\quad + 4f_d\left(1-\gamma^2\right)\delta^2\sigma^4\left(2R_f - 2r_o\gamma - f_d(1+s)\phi\right) - 8f_d^2\left(1-\gamma^2\right)^2\delta^3\sigma^6\Big], \\
W_d &= u_{d,1} + u_{d,2} \\
&= \frac{s}{4\delta\sigma^2\left(2\left(1-\gamma^2\right)\delta\sigma^2 + (1-s)\phi\right)} \\
&\quad \cdot\Big[8f_d^2\left(1-\gamma^2\right)^2\delta^3\sigma^6 + (r_o - 1)^2(1-s)\phi + 2\delta\sigma^2\left((r_o - 1)^2\left(1-\gamma^2\right) + 2(1-s)\phi\right) \\
&\quad + 4\left(1-\gamma^2\right)\delta^2\sigma^4\left(2 + f_d\left(2\left(R_f - 1 - \gamma\left(r_o - 1\right)\right) - f_d(1+s)\phi\right)\right)\Big],
\end{aligned}$$

with $\xi \equiv R_f - 1 - \gamma(r_o - 1)$ and $\theta \equiv 2\left(1-\gamma^2\right)\delta\sigma^2 + (1+d)\phi$.

The reaction of global fuel investment F to divestor's per-capita fuel investment choice f_d is

$$\frac{\partial F}{\partial f_d} = s\frac{1}{1 + \frac{(1-s)\phi}{2(1-\gamma^2)\delta\sigma^2}} \in (0,1).$$

It is a constant ratio independent of the divestment choice f_d itself. Per unit of absolute amount of fuel investment $F_d = \frac{f_d}{s}$, the ratio becomes also largely independent of the size of the divestor, s, and it is non-marginally larger than zero,

$$\frac{\partial F}{\partial F_d} = \frac{\partial F}{\partial f_d} / \frac{\partial F_d}{\partial f_d} = \frac{\partial F}{\partial f_d} / s = \frac{1}{1 + \frac{(1-s)\phi}{2(1-\gamma^2)\delta\sigma^2}} \in (0,1). \tag{8}$$

Clearly, there is an effect that one might coin 'divestment leakage': If a party divests unilaterally, the economy tends to a point where other parties partly offset the reduction by increasing their own investments, hence $\frac{\partial F}{\partial F_d} < 1$. But, the 'leakage' the unilateral divestment is subject to, is clearly smaller than 100 %, and the share of non-offset investment reductions remains stable even when the size of the divesting region converges to zero. Some interesting economic implications of the form of the leakage effects implied by (8) are discussed in section V.

Welfare reacts to the fuel divestment or investment at the rate

$$\frac{\partial W_d}{\partial f_d} = s \frac{2\left(1-\gamma^2\right)\delta\sigma^2\left(R_f - 1 - 2f_d\delta\sigma^2 - \gamma\left(r_o - 1 - 2f_d\gamma\delta\sigma^2\right) - f_d(1+s)\phi\right)}{2\left(1-\gamma^2\right)\delta\sigma^2 + (1-s)\phi}.$$

Expressed per absolute unit of divestment or investment, the ratio becomes

$$\frac{\partial W_d}{\partial F_d} = \frac{\partial W_d}{\partial f_d} / s = \frac{2\left(1-\gamma^2\right)\delta\sigma^2\left(R_f - 1 - 2f_d\delta\sigma^2 - \gamma\left(r_o - 1 - 2f_d\gamma\delta\sigma^2\right) - f_d(1+s)\phi\right)}{2\left(1-\gamma^2\right)\delta\sigma^2 + (1-s)\phi}.$$

We are concerned about unilateral divestments of one party among a large number of investors, $\lim N \to \infty$. Focusing on this case is harmless in the sense that the key qualitative findings all extend to the case of fewer investors (and divestors), with thus a significant market share by each. The present focues makes the analysis conservative in the sense that larger divestment 'leakage' is naturally more plausible for a relatively small party, where there is a relatively large remainder of the world that could compensate the unilateral fuel investment reductions. Practically, the focus on relatively small divestors or investors implies that market-power considerations on behalf of the divestor become negligible. This facilitates the analysis.[9]

We are now ready to perform the cost-benefit analysis in terms of unilateral cost of the divestment, per unit of reduction in *global* fuel investments that the unilateral divestment implies. For a marginal change in investment or divestment this is

$$\frac{\partial W_d}{\partial F} = R_f - 1 - \gamma(r_o - 1) - f_d\left[2\delta\sigma^2(1-\gamma^2) + \phi(1+s)\right]. \tag{9}$$

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[9] Whilst our non-divestment scenario considers the standard Nash solution for optimal investment, a large player could theoretically deviate from this standard equilibrium investment and, as a Stackelberg leader, chose his his investments optimally in the sense that he'd know how the other players will adapt their investments in reaction. Such considerations are in practice unlikely to play a role for investors, and it would be unclear why one specific investor would be able to behave as a Stackelberg leader while others would not.

For the considered case of a large number of investors, (9) implies for marginal divestment around the unconstrained investment level f_i^* from (5), level initial divestment has marginal-costs

$$\lim_{f_d \to f_i^*} \frac{\partial W_d}{\partial F} = 0, \tag{10}$$

and

$$\frac{\partial W_d}{\partial F} < R_f - 1 - \gamma(r_o - 1) \, \forall f_d \in [0, f_i^*].$$

This means, a marginal, unilateral divestment by the divesting fuel investor reduces the total of global fuel investments at marginal-only costs to the divestor. This turns upside down the initial hypothesis that whenever one divests funds away from fuel assets, one would incur losses without achieving any reduction in global investments; the divestment cost-benefit analysis suggests contrary the case: one can achieve some reduction in global fuel investments at marginal-only costs, at least for the first units of funds divested (i.e. when the fuel investment is still kept at a level close to the unconstrained optimal level f_d^*, but slightly below). The second result means that for larger, and even for full unilateral divestment, the cost-benefit ratio is in no sense a trivial one; such larger divestments cannot be achieved at zero cost per global divestment achieved, but they can be achieved at finite such costs per unit globally divested.

Appendix A.1 shows that the results extend to the case with a substantially relaxed model structure, where the equilibrium return on the non-fuel assets varies with the investment as well and where the return volatilities vary across sectors, and returns from the future are time-discounted.

4 Interpretation/Discussion

Though this result, especially the first part of it, may surprise on first sight, and even if the model in which it is derived is a realtively simple one, the underlying mechanism leading to the result is straightforward and extends to substantially more complicated frameworks. Institutional investors devote substantial efforts to diversify their portfolios; given the volatily of any single sector's returns, it would be unresponsible of large public investors to put all their eggs in one basket, and instead it is of first-order importance to structure portfolios according to return volatilities of assets and the interdependencies among them. This is here taken into account by considering not only differences in expected returns of assets but also differences in the uncertainty structures for these returns, with non-unity cross-correlation of the different assets' returns. This means that as a reaction to an increased residual offer of assets of a certain type at a certain price when one market player restructures its investments, the remaining market participants will increase their holdings of that asset type, but there is a non-negligible satiation effect that tends to make *them absorb less than the total amount by which the divesting player reduces his holdings.*[10]

That the first units of global reductions of the total investment in fossil fuels can be achieved at marginal-only costs, can be seen as a parallel to the marginal cost of direct fuel emission reductions through emissions taxes. In a state where emissions are untaxed, a tax at an arbitrarily low level would achieve emission reductions and do so at marginal-only costs per unit of emission avoided in total, that is, the reduction of the first tons of emissions costs the society approximately zero even on a per-unit basis; because the initial state did not price emissions at all, the lowest hanging fruits in terms of inexpensively available emission reductions were still available and the small tax reaps them. Only if further emission reductions are desired, the tax has to be increased to more substantial levels, where each unit of additional emissions avoided starts to have more substantive costs. The situation is analogous in the divestment case: in the initial state without any divestment considerations accounted for, fuel assets were invested into even if investment into alternative assets (or direct consumption) would have provided the same benefits. The transfer of some of the funds from fuel assets to alternative assets, comes thus to little or no costs, as long as only a small amount of an investor's funds are shifted. These (marginal) costs to the divestor rise as the magnitude of the divestment increases, but as the analysis implies, they remain strictly finite, allowing for a positive cost-benefit ratio if the taste for the reduction of global investments into fuel assets is strong enough – and if the potential geopolitical effects we emphasize in section IV are ignored. The major alternative measures to carbon divestment are climate taxes. Effective taxes are, however, currently politically infeasible; as many regions prefer to free-ride on climate protection efforts by other countries, or to simply refute the problem for the future, only unilateral taxes with limited scope are currently possible. These are subject to substantial leakage effects. In so far as the firms where funds can be divested from operate on fuel deposits distributed (and traded) across the globe, divestment has the advantage of rendering fuels more costly also in parts of the world that are beyond the reach of otherwise regionally limited climate policies. The 'investment leakage' here analysed is less than 100 %. This should in general warrant a mixture of policies or action by climate concerned parties; a limited regional direct emission tax combined with a limited regional divestment effort.

Divestment can be seen as an imperfect, but potentially more realistic alternative to the proposition by Sinn (2008) to impose a global tax on revenues from fuel extraction. The ease by which earned money can change the (official) owner, and revenue sources can be obfuscated and redeclared, as well as the difficulty to monitor and enforce a global application of a revenue tax, make it at least questionable whether Sinn's proposal could overall be more realistic than a quasi-global tax on carbon. Divestment may at least to a

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[10] *In reality, if one investor divests, the amount of sectoral investments are unlikely to shrink instantaneously. But the reduced interest in the assets excerts a (limited) downward presssure on prices of assets of the sector which in turn dampens incentives for new real investments at least marginally.*

limited degree tackle that problem by increasing the hurdle rates for financial investments into fossil fuel extraction projects for everybody through the here modelled channel. The next section points out a difficulty with divestment that may, however, render it less desirable even independent of the divestment leakage question.

Part IV

(Geo)political viewpoint

> *"Left to our own devices, citizens might decide to regulate carbon and stop short of the brink; according to a recent poll, nearly two-thirds of Americans would back an international agreement that cut carbon emissions 90 percent by 2050. But we aren't left to our own devices. The Koch brothers, for instance, have a combined wealth of $50 billion [..]. They've made most of their money in hydrocarbons, they know any system to regulate carbon would cut those profits, and they reportedly plan to lavish as much as $200 million on this year's [US presidential] elections."*
>
> Bill McKibben, 2012

The power of concentrated fossil fuel revenues to influence and potentially adominate political agendas McKibben emphasized in his Rolling Stone article (2012) widely recognized as the founding document for today's fossil fuel divestment campaign, is undeniable. The american Center for Responsive Politics lists the oil and gas sector among the top three contributors to political campaigning in 2013, with more than $150m of lobbying contributions recorded in the Senate Office of Public Records (Centre for Responsive Politics, 2014). Contributions to political campaigns for a sector-wide cause are a contribution to – dependent on the perspective – a public good from the perspective of the concerned economic sector – and potentially a public bad from society's broader perspective. This section considers the effect of a potential exacerbation of the political power of the fossil fuel sector when the concentration of the ownership over fossil fuels is increased because parts of the current owners decide to divest from the sector.

For all actors in geopolitical region covering a fraction X of total investments, the overall gain per achieved global divestment (by divesting party outside of region X) is

$$-\frac{\partial W_X}{\partial F} = -\frac{X}{s}\frac{\partial W_n}{\partial F} = X\frac{R_f - 1 - \gamma(r_o - 1) - f_d s\phi}{2\left(1-\gamma^2\right)\delta\sigma^2/\phi + (1-s)},$$

which is non-marginal. And for the here considered case of $\lim N \to \infty$, it is found to converge to

$$\lim_{N\to\infty} -\frac{\partial W_X}{\partial F} = X\phi f_i^*.$$

This is a natural result: the absolute revenue gain for the region of 'size' (in terms of investment share) X equals the amount of their total investment Xf_i^* times the rate of change of the expected rent from the investment to the change in global investment. Clearly this is a non-marginal ratio, independent of the level of unilateral divestment chosen by the divesting party. This is interesting when one recalls that the divesting party itself can achieve some initial – unilateral, as well as implied global – divestment at marginal-only costs, cf. (10). It means that taken together, the market participants gained if they lowered investments. This is the natural implication of returns from investments in a particular sector to be decreasing on a global level; in this case, market participants would, if coordinating their actions, i.e. acting monopolistically rather than competitively, optimally reduce their investments and therewith lift up per-unit returns and total net gains.

Overall, this implies that not only is fossil fuel assets ownership more concentrated after some market participants divest, but it also means that the overall gains from using the fuels increase. The (geo)political dangers this implies is apparent from a political economy viewpoint: first, and in very general, the political strength of economic sectors such as the fossil fuel sector is the concentrated form in which money is invested. As political campaigning for the sector's causes are a public good from the perspective of the sector itself, in economic sectors with a large number of small players, each has an incentive to rely on his competitor's (political) contributions for the sector's causes, meaning it is very difficult for the sector to powerfully influence the political agenda. With very large organizations dominating the market, each organization itself has a non-marginal incentive to contribute to the improving of the sector's prospects; these incentives increase more than proportionally with the size individual organizations have in the market. In addition, if more money overall is to be gained within a business-as-usual scenario, the market players will also have a stonger incentive to prevent policies if they threaten the entire profits, as could be the case with stringent climate policies. As we have seen with the quote from McKibben in the leadin to this section, the fear of the political influence of big (fuel) business, is a central theme within the divestment community. The present analysis, however, suggests that in this sense divestment could be counterproductive exactly in this sense.

Two additional points underline this scepticism. First, the western world, where divestment campaign seems to enjoy the largest sympathy, is a region of the where monetary flows from and to politics are relatively transparent compared to many other places, and even though money does play a big role in politics, there are clearly other places in the world – not seldomly key players on the fossil fuel markets –, where the the links between politics and the economy are less transparent, and where democratic institutions that could limit the influence of money in the politics, are less developed. When the western world divests from fuels, there could be a risk that even more money is concentrated in the hands of organizations with closer ties to governments in the rest of the world, and hence in organizations where it could even more easily influence some regions' political agendas in ways undesirable for climate change. Successful climate policy, however, has no choice but to be global or quasi-global in the longer run, as else leakage effects threaten to severely hamper any efforts to drastically limit greenhousegas emissions. If divestment in the West should increase the political power of vested interests in other parts of the world, which are already often less favourable to stringent climate policies, this could thus be one of the worst things achievable for the advancement of climate protection.

In the same line, and this is the second additional point, along with a conscious investment into fossil fuels comes also a voice as shareholder within the organizations. Using that voice to roll back and political campaigning against climate change by the organisation, might be a smarter – as more effective – alternative step towards achieving what McKibben (2012) described as of central importance to the divestment campaign, namely to stop the alleged negative political influence of fossil fuel players. In this sense, Harvard's response to the pressure to divestment (Faust, 2013), that it can be better to use their moderating influence as insiders in the sector rather than leaving to potentially less socially considerate investors the power that goes along with the fossil fuel ownership, seems to have a clear point.

Part V

Long-run view: depletion and fuel demand

There is an additional aspect of the global effects of unilateral divestment that the analysis above in sections III and IV may not fully capture. This aspect is related to effects that the exhaustibility of fossil fuels, and the more general equilibrium between fuel demand and supply implies. It underlines that the 'divestment leakage' effect implied by (8) may be larger than the analysis in section III suggests. Analysing effects of divestment on fuels prospectively exploited in different phases from now onwards until the end of the fuel era, suggests that, coupled with the inelasticity of demand, the exhaustible nature of the supplied fuels implies that more than an overall reduction of fuels consumption, divestment could mainly reduce the profits from their sales. There is also a Green Paradox effect when the divestment campaign gains traction slowly over time, implying that it could aggravate the climate problem by accelerating fuel sales rather than hampering them.

For depletable fossil fuels, it is a natural economic phenomenon that easy to access, cheap reserves tend to be exploited first, and less easily accessible, more expensives spared until the raising fuel prices warrant economic exploitation (Herfindahl, 1967). In general, long-run fuel prices (gross of potential carbon prices in the case of uncaptured emissions) can be expected to be capped by equilibrium prices for alternative sources of energy, of which currently renewable electric energies or biofuels seem the most important candidates. Currently, there are enormous quantities of fuels accessible at costs with which alternatives cannot compete at the volumes required to satisfy global energy demands, leading to the large amounts of fuels valued on the stock exchanges (Fig. 2). The cost difference is, however, bound to decline in the medium-term, until in a final phase the acess to fossil fuels, including potential policy costs, converge to the costs of alternatives (which may decrease with technological advancements but could also increase as demanded quantities increase). In this final phase, fossil fuel consumption progressively decreases until it approaches zero, and gross fuel prices converge to the finite prices of least-cost alternative energies. This suggests a distinction between fossil assets (reserves or projects for their exploitation and use) to be exploited soon and the less easily accessible fuels expected to be used later, when fossil fuel use declines towards low levels. Uncertainty about whether fuels can be profitably exploited is naturally much lower for the first category; fuel demand, extraction costs for fields with imminent openings, as well as the policy (e.g. carbon) costs affecting net sales revenues, are much more predictible in the short-run than in the long-run. The fuel consumption rate is high, though it is relatively inelastic in the short-run (Michielsen, 2011). For the fuel reserves to be extracted late, a distinction between early and late investments/divestments becomes relevant. Early investments into later-to-be-exploited deposits have mainly financial rather than real impacts, and can be viewn primarily as a transfer of the right to extraction, which will be executed only at a later time, subject to the development of the fuel market making it economic. At the time the expensive reserves become economic, money is invested into – or divested from – extraction projects for these reserves. The early investments into these expensive reserves are characterized by large uncertainties about returns; in fact, even small longer run changes in only one key determinant of future profitability – energy demand, resource and climate policy, and technological progress either in terms of fuel extraction or alternative energies – may be decisive for whether a resource deposit can yield high profits in future or become entirely uneconomic to exploit. A large part of this uncertainty gradually resolves as the extraction time approaches also for these expensive reserves; by the time extraction becomes imminent, returns on investments into extraction projects are bound to exhibit smaller uncertainties, analogously to current finances of present investment projects. Further, a reduction in the total amount of funds available for early, financial investments in expensive resources may reduce the current financial valuation of these resources, but the amount of existing resources available on the market, which is more related to the amount of physically available and potentially once valuable deposits, is linked to the current investment volume only in less direct ways. The money invested into fuel extraction projects, in contrast, is a direct determinant of their number; without the funds required to cover capital outlays, the deposits' fuels cannot be made accessible. Finally, the economics of the late extraction projects, defined as those far in the future where fossil fuel consumption becomes low as easily accessible resources are depleted and alternatives become competitive, are distinctive in the sense that the total volume of active investments into then to be exploited reserves is bound to decline to a lower level, due to the limited residual fuel demand, to be multiplied by a finite per-unit value.[11]

These economic and financial characteristics have direct implications on the effect of unilateral divestment on the global investment volumes, which becomes apparent when we consider the analysis from section III. Further, there are obvious links to the expected effect on prices and use of fuel globally. While we derive these effects based on the economics and finacnes of the resource market and relate them to (8), Appendix A.2 provides a stylized, dynamic stochastic economic-financial model where fuel demand and supply, and various types of fuel investments are in equilibrium, confirming the main results discussed here.

Equilibrium effect on onstream projects

For fields that are already developed and producing fuel currently, the effect of divestment is largely restricted to finances rather than to real economic impacts: major fractions of fuel deposit extraction costs are incurred at in the exploration and development phase, whilst the subsequent extraction phase is mainly characterized by the highly lucrative sales of the fuels that can now be lifted to limited marginal costs. Because the initial capital expenditures are already sunk, a continuation of the projects is financially largely self-sustaining, so that divestment concerns are unlikely to play a major role for the continuation of the activities in the onstream projects.

Equilibrium effect on early developments

For investments into current projects, the relatively low short-run price-elasticity of fuel demand implies that fuel prices, and therewith the returns for investments into fuel deposits to be extracted currently, increase relatively strongly when investments, and thus extraction, are reduced. In our financial analysis this corresponds to a high value ϕ.

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[11] Without alternative energies, the unit-value of fossil energy could diverge to very large values. Realistically, alternative energies, available in finite but substantial quantities, provide an upper limit to this price also in the longer-run.

As, in addition the limited uncertainty for current projects suggests a limited value for the variance σ^2,[12] a strong 'divestment leakage' results according to (8): unilateral divestment entails only a small reduction of global investments (and indirectly of fuel use). Economically the mechanism leading to this bottom line is straightforward. When a party divests its funds and hence threatens the investment required for some fuel projects, a small reduction of the total fuel offer suffices to increase the fuel prices, and hence returns, by enough for other market participants to increase their investments such as to largely compensate the effect on the global amount of funds invested in the sector. The offsetting effect is especially large if project returns are relatively certain, in which case concerns about the increased lumpiness of asset risk, related to the increase of investment into fuel assets by non-divestors, become of lesser importance and project return is the primordial driver of the invested amount. Annex A.2 shows this effect in the stochastic dynamic economic-financial equilibrium model; the effect of the partial divestment on the amount of reserves developed, and the real capital outlays used directly for extraction, is proportional to the demand elasticty parameter α, which according to evidence from energy studies is small.

Effect of current divestment on future developments

For current financial investments into expensive fuel deposits, to be extracted only much later, implications of unilateral divestment are very different. Uncertainties are potentially very large, and it is plausible that diversification plays a very significant role in individual actors' allocation of funds to currently not yet economically extractable fuel resource assets, meaning the standard deviation σ in section III could be large. At the same time, whilst the profitability of current extraction projects whose profitabilities increase directly when the currently invested funds for resource lifting decrease, the volume of funds financially allocated today to assets to be extracted in the future, can be reduced without that there would have to be direct, major repercussions on the real economy; the current financial valuation of the assets simply decreases, with unclear real effects, on the future extraction path, depending rather on the divestment trend in future periods. As the current financial decisions only change the valuation of the reserves without affecting the amount of them invested into and available in future, the inelasticity of real fuel demand does not directly impact the reaction of the returns to a decrease in global investments, and it is possible that expected returns react much more modestly to a general divestment, that is ϕ may be relatively modest. In terms of divestment leakage, this means two things. First, for such assets, unilateral divestment may be seen as successful in the sense that it may indeed translate to a significant reduction of global investments; with σ substantial

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[12] Even with significant shorter-run variabilities of fuel prices as exhibited by the anomaly in the market especialy in the year 2008, financial hedges and long-run contracts between producers and consumers of fuel, including long-run contracts, allow to limit the exposure to variable spot prices. Fuel commodity futures contracts tend to be liquid only over limited time periods.

and ϕ modest or small, global divestment may react strongly to unilateral divestment in (8). The downside, in terms of climate protection, is of course that even if in total these reserves are valued less, this type of divestment has little or no impact on the real economy; initial owners of the reserves may suffer lump-sum losses, but as the reserves are physical assets that exist and will be available in the future if the future market framework warrants exploitation. Current divestment from assets to be exploited in the medium or long term thus hardly yield substantial emission reductions.

This is in line with the prediction of HSBC's analysis about 'unburnable carbon' (Spedding et al., 2013), concluding that much more than really making privately owned fuel reserves redundant, a harsher environment for fuel suppliers primarily slashes their profits, with less than 1 % of currently exploited reserves becoming redundant in the case of significantly reduced returns from fossil fuel projects, and less than 10 % of future extraction projects prospectively being inhibited by severly impaired project finances, across the six major fossil fuel companies examined. These projections were based on strongly reduced fuel sales revenues, with an impact on net profitabilities well beyond what could be expected from even relatively wide-spread voluntary fuel divestments: the inelasticity of fuel demand implies that a reduced propensity to finance fuel projects would exert a strong upwards pressure on fuel projects returns, inciting additional investors to inject funds into the sector, compensating the reduced investment propoensity to a large degree. Political economy effects cannot be excluded but as the analysis in section IV suggests, plausible geopolitical repercussions may even mean divestment backfires in this regard.

Equilibrium effect of future divestment

If the divestment campaign gains traction over time, the situation when some parties are disincentivized from providing funds at times when late fuel reserves are to be exploited, has natural analogies to the first discussed case of current divestment from currently to be exploited resources. Future investments for concurrent extraction projects may be subject to relatively limited return uncertainties (modest σ), and a presumably still limited fuel demand elasticity could mean a relatively strong reaction of returns to investment volumes (high ϕ). As we have seen, in this case, divestment leakage may be substantial, as non-divestors have substantial economic incentives to make up for the retraction of funds by the divestors, which is also captured by (8). However, a dynamic view reveals that the efficiency and effectiveness of late divestments may be further undermined – and dependent on the detalied resource dynamics and the social valuation of the timing of extraction and emissions a further source for potential backfiring of the divestment is possible – by a divestment Green Paradox.

A Divestment Green Paradox?

Divestment naturally starts locally, and it is bound to remain a partial policy – it is utopian to believe that each financial investor could be convinced to voluntarily abstain from investments into fossil fuel assets, and all evidence from political processes so far suggest that *if* policy makers around the world would be able to contract stringent climate policies, these would target climate damaging emissions more directly, for example by capping or taxing greenhouse gas emissions. There is thus little scope for a rapid and quasi-complete divestment, and if divestment campaigns are to ever be successful in broadening the divestment base to a significant level, this can be expected to be a very gradual process. In this case, fuel exploiters that anticipate the future threat the divestment campaign represents for the investability of projects for the exploitation of their reserves – in asfar as it can be expected to become significant at all – may try to avoid this future pressure by extracting fuels earlier on. For climate change that would mean that rather than a reduction of carbon emissions, the divestment campaign mainly implied accelerated emissions early on, potentially aggravating the climate problem, increasing net present losses from climate damages. This is analogous to the anticipation effects along the Green Paradox that have been shown to threaten the effectiveness of gradually evolving climate policies, notably carbon taxes (Sinclair 1982; Sinn, 2008, Pittel et al., 2014). It has been shown that for carbon taxes the threat of a counterproductivity may be less strong than originally brought forward (Habermacher and Kirchgässner 2014; Habermacher 2012). Nevertheless, as divestment does not directly cap current emissions, but could theoretically risk to reduce future resource rents, we have with a gradually emerging divestment trend a formidable example where Green Paradox effects could lead to detrimental climate effects. While this is a potentially severe caveat of carbon divestment, it does not directly warrant the conclusion that divestment should currently be abandoned as a strategy to fight climate change, on the basis of insights along the lines of the Green Paradox. Instead, the apparent impossibility of current policy makers (or here financial investors) to commit to the absence of divestment in the future means that even if today we would refrain from climate divestments, proponents of divestment in the future could start a divestment campaign and reduce future rents. Hence, to a certain degree, current investors may anticipate *future* divestment today independently of whether divestments take place today already or not. In this case, the divestment to currently divest could theoretically be rational from the climate concervationists perspective even if Green Paradox effects imply that divestment would be counterproductive in the long run.[13]

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[13] The analogous commitment issue is analysed for carbon taxes in Hoel (2010) and Habermacher (2012).

Part VI

An Ethical Imperative?

“*Slavery was once an investment issue*”

Harvard Faculty For Divestment, 2014

The analysis above shows that a limited degree of divestment could be achievable at very low costs, but it equally confirms that at least a very substantial fraction of unilaterally divested funds may either be directly compensated by offsetting financial injections by third parties, or at best lead mainly to a decrease in profits from certain fuel sales rather than to primarily achieve a real reduction of the amount of fuels invested into and used. There is undeniably a substantial financial ‘leakage’ effect associated to fossil fuel divestment, strongly limiting the scope of divestment as an effective means of addressing the climate problem, as our theoretical analysis based on most fundamental financial and economic incentives shows, and as is underlined by the comparison to other historical cases. Yet, this limited economic effectiveness of divestment may not be a decisive argument for many a divestment proponent.

Hypothetically, very similar ‘large leakage’ considerations would also apply if, e.g., the world would traditionally not have recoiled from investing into big drug dealing gangs, say e.g. with investment by funds globally into companies or gangs that would aggressively make the drugs public, maybe through control of advertisements and media, say in a rogue state where these activities would be tolerated, possibly legal. Many would probably understand if in this situation, people throughout the world claimed that one ought to divest from such activities as they caused intolerable human misery; irrespective of the efficiency of the measure, this sort of divestment could be considered worthwhile in light of the sheer human toll the illicit actions by the aggressive drug companies impose. To divestments of similar sort one may also count the divestment campaign started during the late seventies against the Apartheid regime, which Ansar et al. (2013) studies as one of several campaigns with parallels to the fossil fuel divestment campaign. Depending on how severe one considers the climate threat, the situation with climate change can appear to have strong parallels, and the comparison to slavery as quoted in the leadin to this section from the Harvard Faculty for Divestment can in some sense have a point despite relevant dissimilarities between the cases. After all, the climate damage may in future threaten not only comfort but also life of many not particularly responsible for the change of the climate, with little hope for true personal compensation for them. Of course, fossil fuel use may – maybe in contrast to illegal drug sales – have large positive effects on other people, but it cannot be excluded that for parts of the fuel use the costs outweigh benefits, depending on assumptions and values even by a lot. This may mean that given some not uncommon views, standard costs and benefits analysis along the lines outlined herein, may hardly be considered as of primary importance, making it difficult to find a widely accepted measure based on which the appropriateness of fossil fuel divestment could be discussed.

Potentially, nevertheless, a cost-benefit comparison to alternative investments *for the same cause of a better climate* (or maybe for a more 'sustainable' world in a green sense in more general) could be fruitful. Could investors in fuel assets use only a fraction of the (admittedly often limited) costs they had if they divested their funds, to reliably reduce emissions anywhere in the world more cost-effectively than through fuel divestment? If so, that could mean that even if reducing fuel emissions is seen as an ethical imperative, one may resort to non-divestment measures instead. Given the indirect way divestment seem to affect emissions, and the many specific problems related to it outlined above, chances may be rather large that such other, more effective and efficient measures exist, especially if one considers the low costs by which substantial emission reductions across the world seem achievable (cf., e.g., McKinsey&Company, 2010), as well as the limited costs of certified emission reductions even with high reliability standards, chances seem rather elevated. While some unilateral emisssion reductions are themselves also likely subject to large leakage effects, for example the potentially cost-effective purchase of costly to extract, non-redundant fossil fuel reserves could offer a leakage-robust alternative (Harstad, 2012) – rather than divestment, this would require actors to actively buy the relevant fuels to subsequently ensure they are prepetually left underground. On the other hand, if divestment proponents would moderate their call, aiming for organisations to not fully divest from fuel assets but only partially, the analysis above suggests that – at least in the case where the (geo)political problems could be surmounted – limited reduction in investments might be possible and have some postive effect at even an acceptable cost-benefit ratio. In any case, given the likely very modest contribution partial fuel divestment could bring, the worst thing would probably be to invest a great effort for fossil fuel divestment at the expense of carefully working towards other, more direct ways to tackle the global climate problem.

The unavailability of effective alternatives for affecting an inhumane South African regime presumably was a main – and potentially a good – reason for a divestment case; South Africa being a geographically remote place, products from where most people may not have consumed on a daily basis, a primary chance to economically disincentivize an upholding of the system was to do the little possible to undermine it's economic viability by withdrawing funds. The abundance of alternative, potentially more efficient measures to fight climate change other than by divestment may well be the main difference to other historic cases of divestment campaigns.

Part VII

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Part VIII

Annex

A.1 Generalized model

We allow discounting of period 2 utility by β, sector specific risks σ_f and σ_o (the returns have still cross-sector correlation of γ), and a non-fuel sector return r_o decreasing in the amount of global non-fuel sector investements O, $r_o = R_o - \omega O$. Number N of investors $i = \{1..N\}$. One of them is the divestor called d; there are $N-1$ standard investors. Size of each investor $s = \frac{1}{N}$. Fuels return, in expectation, r_f and clean return r_o, decreasing in global investments F and O respectively,

$$\begin{aligned} r_f &= R_f - \phi F, \\ r_o &= R_o - \omega O. \end{aligned} \tag{A.1}$$

Be correlation between the two asset types' returns $-1 < \gamma < 1$, here typically assumed positive, $\gamma > 0$. Returns expressed as gross returns or so, $R = E(R_k) > 1$, where k designate the possible states of the world. Returns within a sector perfectly correlated; variances (or 'volatilities') σ_f^2 and σ_o^2.

Be i the index for the parties, and $c_{i,t} = \frac{C_{i,t}}{s}$ party i's per capita consumption in period t. We assume the same utility form as in the main text,

$$u_{i,t} = s \cdot (E[c_{i,t}] - \delta V[c_{i,t}]),$$

where $E[\cdot]$ and $V[\cdot]$ are the expected values and the variances, respectively. Each party i's welfare is the NPV-sum $W_i = u_{i,1} + \beta u_{i,2}$, with $0 < \beta < 1$ the time discount rate. Assume unitary 'per-capita' endowments s (per-capita here means per size of the party; in reality it rather corresponds to the share of the parties in the world's investments rather than in a genuine head-count). Let F_i and O_i be region i's investment in the fuel and clean assets, and $f_i \equiv \frac{F_i}{s}$ and $o_i \equiv \frac{O_i}{s}$ the corresponding per-capita investments. Per-capita consumption becomes (for any state with a certain materialized returns r)

$c_{i,1} = 1 - (f_i + o_i)$ and $c_{i,2} = r_f f_i + r_o o_i$. The global sectoral investments sum to

$$\begin{array}{rcl} F & = & \sum_{i=1}^N F_i = \sum_{i=1}^N s f_i, \\ O & = & \sum_{i=1}^N o_i = \sum_{i=1}^N s o_i, \end{array}$$

and we note $Ns = 1$. The variances of per-capita consumption, zero in the first period, in the second period become

$$V(c_{i,2}) \quad = \quad \left(\sigma_f^2 f_i^2 + \sigma_o^2 o_i^2 + 2\gamma\sigma_f\sigma_o f_i o_i\right).$$

A.1.1 Unconstrained Solution

Part (a) Investment rule (portfolio choice) for as fct. of some expected returns $\hat{r}_f$ and $\hat{r}_o$

$$W_i \quad = \quad u_{i,1} + u_{i,2} = s \cdot \left\{(1 - (f_i + o_i)) + \beta\left(r_f f_i + r_o o_i - \delta\left[\sigma_f^2 f_i^2 + \sigma_o^2 o_i^2 + 2\gamma\sigma_f\sigma_o f_i o_i\right]\right)\right\},$$

and to simplify terms later on, we substitute

$$\begin{array}{rcl} q_f & \equiv & r_f - \dfrac{1}{\beta}, \\ q_o & \equiv & r_o - \dfrac{1}{\beta}, \\ \upsilon_f & \equiv & \sqrt{\delta}\sigma_f, \\ \upsilon_o & \equiv & \sqrt{\delta}\sigma_o, \end{array}$$

so that we can rewrite welfare as

$$W_i = u_{i,1} + u_{i,2} = s \cdot \left\{1 + \beta\left(q_f f_i + q_o o_i - \left[\upsilon_f^2 f_i^2 + \upsilon_o^2 o_i^2 + 2\gamma\upsilon_f\upsilon_o f_i o_i\right]\right)\right\}, \tag{A.2}$$

We further define

$$\begin{array}{rcl} Q_f & \equiv & R_f - \dfrac{1}{\beta}, \\ Q_o & \equiv & R_o - \dfrac{1}{\beta}, \end{array}$$

so that (A.1) rewrites

$$\begin{array}{rcl} q_f & = & Q_f - \phi F, \\ q_o & = & Q_o - \omega O. \end{array} \tag{A.3}$$

Assuming individual investors to be small relative to the market, so that they consider themselves as price-takers, the FOCs (we assume parameters such that interior solution; requires notably that both returns are high enough for a strictly positive investment to be warranted) become:

$$\tfrac{\partial W_i}{\partial f_i}=0: \quad q_f \quad = 2\upsilon_f\left(\upsilon_f f_i+\gamma\upsilon_o o_i\right) \quad , \quad \tfrac{\partial W_i}{\partial o_i}=0: \qquad q_o = 2\upsilon_o\left(\upsilon_o o_i+\gamma\upsilon_f f_i\right) \tag{A.4}$$

Solving for f_i and o_i yields

$$\begin{aligned} f_i &= \tfrac{q_f\upsilon_o-q_o\gamma\upsilon_f}{2(1-\gamma^2)\upsilon_f^2\upsilon_o}, \\ o_i &= \tfrac{q_o\upsilon_f-q_f\gamma\upsilon_o}{2(1-\gamma^2)\upsilon_f\upsilon_o^2}. \end{aligned} \tag{A.5}$$

Part (b) Equilibrium: investments f_i and o_i and equilibrium returns r_f and r_o

From (A.5) we know that the investments of all parties are the same, so we can write *global* investments $F=Nsf_i=f_i$ and $O=Nso_i=o_i$, hence

$$\begin{aligned} F &= \tfrac{q_f\upsilon_o-q_o\gamma\upsilon_f}{2(1-\gamma^2)\upsilon_f^2\upsilon_o}, \\ O &= \tfrac{q_o\upsilon_f-q_f\gamma\upsilon_o}{2(1-\gamma^2)\upsilon_f\upsilon_o^2}. \end{aligned} \tag{A.6}$$

Using (A.3) in (A.6) yields

$$\begin{aligned} F &= \tfrac{(Q_f-\phi F)\upsilon_o-(Q_o-\omega O)\gamma\upsilon_f}{2(1-\gamma^2)\upsilon_f^2\upsilon_o}, \\ O &= \tfrac{(Q_o-\omega O)\upsilon_f-(Q_f-\phi F)\gamma\upsilon_o}{2(1-\gamma^2)\upsilon_f\upsilon_o^2}, \end{aligned}$$

and solving for F and O and thus also f_i and o_i yields:

$$F^*=f_i^* \quad = \quad \frac{Q_f\left(2\upsilon_o^2+\omega\right)-2Q_o\gamma\upsilon_f\upsilon_o}{\upsilon_f^2\left(4\left(1-\gamma^2\right)\upsilon_o^2+2\omega\right)+\phi\left(2\upsilon_o^2+\omega\right)}, \tag{A.7}$$

$$O^*=o_i* \quad = \quad \frac{Q_o\left(2\upsilon_f^2+\phi\right)-2Q_f\gamma\upsilon_f\upsilon_o}{\upsilon_f^2\left(4\left(1-\gamma^2\right)\upsilon_o^2+2\omega\right)+\phi\left(2\upsilon_o^2+\omega\right)}. \tag{A.8}$$

The per-capita investments, and the global investments are thus independent of the size of the individual investing parties, s, that is, they are independent of the number of investing parties N that constitute the totality of global investors.

Interior solutions with strictly positive investments f_i^* and o_i^* obtain when the time-discounting adjusted net returns Q_f and Q_o are close enough to each other to respect $Q_f > Q_o\frac{2\gamma\upsilon_f\upsilon_o}{2\upsilon_o^2+\omega}$ and $Q_o > Q_f\frac{2\gamma\upsilon_f\upsilon_o}{2\upsilon_f^2+\phi}$. For low enough correlations γ this is necessarily the case as long as the initial investment gross returns R_f and R_o are large enough for savings to pay off despite the time discounting, in absence of uncertainty considerations, $R_f > \frac{1}{\beta}$

and $R_o > \frac{1}{\beta}$. This is an essential criteria for investments to potentially pay out, and in the following it is assumed that the interior solution with positive investments in both sector prevails.

Equilibrium fuel interest rates r_f^* and r_o^*:

$$\begin{aligned}
q_f^* &= Q_f - \phi F^* = Q_f - \phi \frac{Q_f\left(2\upsilon_o^2+\omega\right) - 2Q_o\gamma\upsilon_f\upsilon_o}{\phi\left(2\upsilon_o^2+\omega\right) + 2\upsilon_f^2\left(2\left(1-\gamma^2\right)\upsilon_o^2+\omega\right)}, \\
q_o^* &= Q_o - \omega O^* = Q_o - \omega \frac{Q_o\left(2\upsilon_f^2+\phi\right) - 2Q_f\gamma\upsilon_f\upsilon_o}{\phi\left(2\upsilon_o^2+\omega\right) + 2\upsilon_f^2\left(2\left(1-\gamma^2\right)\upsilon_o^2+\omega\right)}
\end{aligned}$$

We directly evaluate welfare from (A.2),

$$\begin{aligned}
W_i^* &= s \cdot \left\{1 + \beta\left(q_f^* f_i^* + q_o^* o_i^* - \left[\upsilon_f^2 f_i^{*2} + \upsilon_o^2 o_i^{*2} + 2\gamma\upsilon_f\upsilon_o f_i^* o_i^*\right]\right)\right\} \\
&= \frac{s}{\left(\phi\left(2\upsilon_o^2+\omega\right) + 2\upsilon_f^2\left(2\left(1-\gamma^2\right)\upsilon_o^2+\omega\right)\right)^2} \\
&\quad \cdot [Q_o^2\beta\upsilon_o^2\left(4\left(1-\gamma^2\right)\left(\upsilon_f^4+\upsilon_f^2\phi\right)+\phi^2\right) - 2Q_fQ_o\beta\gamma\upsilon_f\upsilon_o\left(4\left(1-\gamma^2\right)\upsilon_f^2\upsilon_o^2-\phi\omega\right) \\
&\quad + \left(2\upsilon_o^2\left(2\left(1-\gamma^2\right)\upsilon_f^2+\phi\right)+\left(2\upsilon_f^2+\phi\right)\omega\right)^2 + Q_f^2\beta\upsilon_f^2\left(4\left(1-\gamma^2\right)\upsilon_o^2\left(\upsilon_o^2+\omega\right)+\omega^2\right)].
\end{aligned}$$

A.1.2 Divestment Solution

One among the N investors, the 'divestor', indexed d, decides freely on an investment level f_d; with a partial or full divestment being expressed as $f_d < f_i^*$. The FOC from (A.4) for party d now implies

$$o_d = \frac{q_o}{2\upsilon_o^2} - \gamma\frac{\upsilon_f}{\upsilon_o} f_d. \tag{A.9}$$

The other investors are indexed $n = \{i | i \neq d\}$. Their investments f_n and o_n are still guided by the optimal investment reaction rules (3).

The equilibrium for investments $F = sf_d + \sum_{i\neq d} sf_n = sf_d + (1-s)f_n$ and $O = so_d + (1-s)o_n$, and the fuel return rate according to (1) solves to

$$\begin{aligned}
F &= \frac{\left(Q_f(1-s) + 2f_d s\left(1-\gamma^2\right)\upsilon_f^2\right)\left(2\upsilon_o^2+\omega\right) - 2Q_o(1-s)\gamma\upsilon_f\upsilon_o}{(1-s)\phi\left(2\upsilon_o^2+\omega\right) + 2\upsilon_f^2\left(2\left(1-\gamma^2\right)\upsilon_o^2 + \left(1-s\gamma^2\right)\omega\right)}, \\
O &= \frac{2\upsilon_f\left(Q_o\left(1-s\gamma^2\right)\upsilon_f - \gamma\left(Q_f(1-s) + 2f_d s\left(1-\gamma^2\right)\upsilon_f^2\right)\upsilon_o\right) + Q_o(1-s)\phi}{(1-s)\phi\left(2\upsilon_o^2+\omega\right) + 2\upsilon_f^2\left(2\left(1-\gamma^2\right)\upsilon_o^2 + \left(1-s\gamma^2\right)\omega\right)}, \\
q_f &= Q_f - \phi\frac{\left(Q_f(1-s) + 2f_d s\left(1-\gamma^2\right)\upsilon_f^2\right)\left(2\upsilon_o^2+\omega\right) - 2Q_o(1-s)\gamma\upsilon_f\upsilon_o}{(1-s)\phi\left(2\upsilon_o^2+\omega\right) + 2\upsilon_f^2\left(2\left(1-\gamma^2\right)\upsilon_o^2 + \left(1-s\gamma^2\right)\omega\right)}, \\
q_o &= Q_o - \omega\frac{Q_o\left(2\left(1-s\gamma^2\right)\upsilon_f^2 + (1-s)\phi\right) - 2\left(Q_f(1-s) + 2f_d s\left(1-\gamma^2\right)\upsilon_f^2\right)\gamma\upsilon_f\upsilon_o}{(1-s)\phi\left(2\upsilon_o^2+\omega\right) + 2\upsilon_f^2\left(2\left(1-\gamma^2\right)\upsilon_o^2 + \left(1-s\gamma^2\right)\omega\right)}.
\end{aligned}$$

and while d's non-fuel investment was already fully known from (A.9), independent of r_f but dependent on the directly chosen f_d, having pinned down the equilibrium interest rate, the investments in the rest of the world from (A.5) can be written out explicitly:

$$\begin{aligned} f_n &= \frac{2\upsilon_o\big(Q_f\upsilon_o-Q_o\gamma\upsilon_f-f_ds\upsilon_o\phi\big)+\big(Q_f-f_ds\big(2\gamma^2\upsilon_f^2+\phi\big)\big)\omega}{(1-s)\phi(2\upsilon_o^2+\omega)+2\upsilon_f^2(2(1-\gamma^2)\upsilon_o^2+(1-s\gamma^2)\omega)}, \\ o_n &= \frac{\upsilon_o\big(2Q_o\upsilon_f^2+Q_o(1-s)\phi-2\gamma\upsilon_f\upsilon_o\big(Q_f-f_ds\phi\big)\big)-s\gamma\upsilon_f\big(Q_f-f_d\big(2\upsilon_f^2+\phi\big)\big)\omega}{(1-s)\upsilon_o\phi(2\upsilon_o^2+\omega)+2\upsilon_f^2\upsilon_o(2(1-\gamma^2)\upsilon_o^2+(1-s\gamma^2)\omega)}. \end{aligned}$$

We directly evaluate welfare from (A.2),

$$\begin{aligned} W_d &= s\cdot\Big\{1+\beta\left(q_ff_d+q_oo_d-\left[\upsilon_f^2f_d^2+\upsilon_o^2o_d^2+2\gamma\upsilon_f\upsilon_of_do_d\right]\right)\Big\} \\ &= s\left[1+\beta\frac{A+B-C}{\big((1-s)\phi\left(2\upsilon_o^2+\omega\right)+2\upsilon_f^2\left(2\left(1-\gamma^2\right)\upsilon_o^2+\left(1-s\gamma^2\right)\omega\right)\big)^{2}}\right], \end{aligned}$$

with

$$\begin{aligned} A &\equiv \Big(Q_o\upsilon_o\Big(2\left(1-\gamma^2\right)\upsilon_f^2+(1-s)\phi\Big)+Q_f(1-s)\gamma\upsilon_f\omega\Big)^{2}, \\ B &\equiv 2f_d\left(1-\gamma^2\right)\upsilon_f^2(4\upsilon_o^3\left(Q_f\upsilon_o-Q_o\gamma\upsilon_f\right)\Big(2\left(1-\gamma^2\right)\upsilon_f^2+(1-s)\phi\Big)+Q_f\Big(2\left(1-s^2\gamma^2\right)\upsilon_f^2+(1-s)\phi \\ &\quad +2\upsilon_o\Big(2Q_f\upsilon_o\Big(\left(2-(1+s)\gamma^2\right)\upsilon_f^2+(1-s)\phi\Big)-Q_o(1-s)\gamma\upsilon_f\Big(2\upsilon_f^2+(1-s)\phi\Big)\Big)\omega), \\ C &\equiv f_d^2\left(1-\gamma^2\right)\upsilon_f^2[\left(1-s^2\right)\phi^2\left(2\upsilon_o^2+\omega\right)^{2}+4\upsilon_f^2\phi\left(2\upsilon_o^2+\omega\right)\Big(2\left(1-\gamma^2\right)\upsilon_o^2+\left(1-s^2\gamma^2\right)\omega\Big) \\ &\quad +4\upsilon_f^4\Big(4\left(1-\gamma^2\right)^2\upsilon_o^4+4\left(1-\gamma^2\right)\upsilon_o^2\omega+\left(1-s^2\gamma^2\right)\omega^2\Big)]. \end{aligned}$$

The reaction of global fuel investment F to divestor's per-capita fuel investment choice f_d is

$$\frac{\partial F}{\partial f_d}=s\frac{2\left(1-\gamma^2\right)\upsilon_f^2\left(2\upsilon_o^2+\omega\right)}{(1-s)\phi\left(2\upsilon_o^2+\omega\right)+2\upsilon_f^2\left(2\left(1-\gamma^2\right)\upsilon_o^2+\left(1-s\gamma^2\right)\omega\right)}\in(0,1).$$

It is a constant ratio independent of the divestment choice f_d itself. Per unit of absolute amount of fuel investment $F_d=\frac{f_d}{s}$, the ratio becomes also largely independent of the size of the divestor, s, and it is strictly larger than zero,

$$\frac{\partial F}{\partial F_d}=\frac{\partial F}{\partial f_d}/\frac{\partial F_d}{\partial f_d}=\frac{\partial F}{\partial f_d}/s=\frac{2\left(1-\gamma^2\right)\upsilon_f^2\left(2\upsilon_o^2+\omega\right)}{(1-s)\phi\left(2\upsilon_o^2+\omega\right)+2\upsilon_f^2\left(2\left(1-\gamma^2\right)\upsilon_o^2+\left(1-s\gamma^2\right)\omega\right)}\in(0,1),$$

that is, the 'leakage' which the unilateral divestment is subject to, is clearly smaller than 100 %, and the share of non-offset investment reductions remains stable even when the size of the divesting region converges to zero.

Welfare reacts to the fuel divestment or investment at the rate

$$\frac{\partial W_d}{\partial f_d} = 2s\beta\left(1-\gamma^2\right)\upsilon_f^2 \frac{XX+YY+ZZ}{\left((1-s)\phi\left(2\upsilon_o^2+\omega\right)+2\upsilon_f^2\left(2\left(1-\gamma^2\right)\upsilon_o^2+\left(1-s\gamma^2\right)\omega\right)\right)^2},$$

where

$$\begin{aligned}
XX &\equiv 4\upsilon_o^3\left(2\left(1-\gamma^2\right)\upsilon_f^2+(1-s)\phi\right)\left(\upsilon_o\left(Q_f-2f_d\left(1-\gamma^2\right)\upsilon_f^2-f_d(1+s)\phi\right)-Q_o\gamma\upsilon_f\right), \\
YY &\equiv 2\upsilon_o\omega[2\upsilon_o\left(Q_f\left(2-(1+s)\gamma^2\right)\upsilon_f^2-4f_d\left(1-\gamma^2\right)\upsilon_f^4+\left(Q_f(1-s)-2f_d\left(2-\left(1+s^2\right)\gamma^2\right)\upsilon_f^2\right)\phi \\
&\quad -Q_o(1-s)\gamma\upsilon_f\left(2\upsilon_f^2+\phi(1-s)\right)\right)], \\
ZZ &\equiv \left(2\left(1-s^2\gamma^2\right)\upsilon_f^2\left(Q_f-2f_d\upsilon_f^2\right)+\left(Q_f(1-s)-4f_d\left(1-s^2\gamma^2\right)\upsilon_f^2\right)\phi-f_d\left(1-s^2\right)\phi^2\right)\omega^2.
\end{aligned}$$

Expressed per absolute unit of divestment or investment, the ratio becomes

$$\frac{\partial W_d}{\partial F_d} = \frac{\partial W_d}{\partial f_d}/s = 2\beta\left(1-\gamma^2\right)\upsilon_f^2 \frac{XX+YY+ZZ}{\left((1-s)\phi\left(2\upsilon_o^2+\omega\right)+2\upsilon_f^2\left(2\left(1-\gamma^2\right)\upsilon_o^2+\left(1-s\gamma^2\right)\omega\right)\right)^2}.$$

We are concerned about unilateral divestments of one party among a large number of investors, $\lim N \to \infty$. Focusing on this case is harmless in the sense that the key qualitative findings all extend to the case of fewer investors (and divestors), with thus a significant market share by each. The present focues makes the analysis conservative in the sense that larger divestment 'leakage' is naturally more plausible for a relatively small party, where there there is a relatively large remainder of the world that could compensate the unilateral fuel investment reductions. Practically, the focus on relatively small divestors or investors implies that market-power considerations on behalf of the divestor become negligible. This facilitates the analysis.[14]

We are now ready to do the cost-benefit analysis in terms of unilateral cost of the divestment, per unit of reduction in *global* fuel investments F that the unilateral divestment implies. For a marginal change in investment or divestment this is

$$\frac{\partial W_d}{\partial F} = \beta\frac{EE+FF+GG}{\left(2\upsilon_o^2+\omega\right)\left((1-s)\phi\left(2\upsilon_o^2+\omega\right)+2\upsilon_f^2\left(2\left(1-\gamma^2\right)\upsilon_o^2+\left(1-s\gamma^2\right)\omega\right)\right)}, \tag{A.10}$$

---

[14] Whilst our non-divestment scenario considers the standard Nash solution for optimal investment, a large player could theoretically deviate from this standard equilibrium investment and, as a Stackelberg leader, chose his his investments optimally in the sense that he'd know how the other players will adapt their investments in reaction. Such considerations are in practice unlikely to play a role for investors, and it would be unclear why one specific investor would be able to behave as a Stackelberg leader while others would not.

$$
\begin{aligned}
EE &\equiv 4\upsilon_o^3 \Big(2\left(1-\gamma^2\right)\upsilon_f^2 + (1-s)\phi\Big)\Big(\upsilon_o\Big(Q_f - 2f_d\left(1-\gamma^2\right)\upsilon_f^2 - f_d(1+s)\phi\Big) - Q_o\gamma\upsilon_f\Big), \\
FF &\equiv 2\upsilon_o\omega(-Q_o(1-s)\gamma\upsilon_f\Big(2\upsilon_f^2 + \phi(1-s)\Big), \\
&\quad +2\upsilon_o\Big(Q_f\left(2-(1+s)\gamma^2\right)\upsilon_f^2 - 4f_d\left(1-\gamma^2\right)\upsilon_f^4 + \Big(Q_f(1-s) - 2f_d\left(2-\left(1+s^2\right)\gamma^2\right)\upsilon_f^2\Big)\phi - f_d \\
GG &\equiv \Big(2\left(1-s^2\gamma^2\right)\upsilon_f^2\Big(Q_f - 2f_d\upsilon_f^2\Big) + \Big(Q_f(1-s) - 4f_d\left(1-s^2\gamma^2\right)\upsilon_f^2\Big)\phi - f_d\left(1-s^2\right)\phi^2\Big)
\end{aligned}
$$

Partly separating f_d this writes

$$
\frac{\partial W_d}{\partial F} = \beta\frac{HH - f_d II}{\left(2\upsilon_o^2+\omega\right)\Big((1-s)\phi\left(2\upsilon_o^2+\omega\right) + 2\upsilon_f^2\left(2\left(1-\gamma^2\right)\upsilon_o^2 + \left(1-s\gamma^2\right)\omega\right)\Big)},
$$

with

$$
\begin{aligned}
HH &\equiv 4\upsilon_o^3\Big(2\Big(1-\gamma^2\Big)\upsilon_f^2 + (1-s)\phi\Big)\left(\upsilon_o Q_f - Q_o\gamma\upsilon_f\right) + Q_f\Big(2\Big(1-s^2\gamma^2\Big)\upsilon_f^2 + (1-s)\phi\Big)\omega^2, \\
&\quad + + 2\upsilon_o\omega\Big(-Q_o(1-s)\gamma\upsilon_f\Big(2\upsilon_f^2 + \phi(1-s)\Big) + 2\upsilon_o Q_f\Big(\Big(2-(1+s)\gamma^2\Big)\upsilon_f^2 + (1-s)\phi\Big)\Big), \\
II &\equiv 4\upsilon_o^4\Big(2\Big(1-\gamma^2\Big)\upsilon_f^2 + (1-s)\phi\Big)^2 + 4\upsilon_o^2\omega\Big(4\Big(1-\gamma^2\Big)\upsilon_f^4 + \Big(2\Big(2-\Big(1+s^2\Big)\gamma^2\Big)\upsilon_f^2\Big)\phi + \Big(1-s^2\Big) \\
&\quad +\omega^2\upsilon_f^2\Big(4\Big(1-s^2\gamma^2\Big)\left[\upsilon_f^2+\phi\right] + \Big(1-s^2\Big)\phi^2\Big).
\end{aligned}
$$

Hence, the costs of divestment per unit of global fuel investment achieved is linearly increasing in the level of divestment (i.e. with decreasing residual domestic fuel investment f_d).

For marginal initial divestment, this simplifies to

$$
\lim_{f_d\to f_i^*}\frac{\partial W_d}{\partial F} = s\beta\frac{4Q_o\gamma\upsilon_f\upsilon_o\Big(\upsilon_o^2\phi + \Big(\upsilon_f^2+\phi\Big)\omega\Big) - Q_f\Big(4\upsilon_o^4\phi + 4\upsilon_o^2\Big(\gamma^2\upsilon_f^2+\phi\Big)\omega + \phi\omega^2\Big)}{\left(2\upsilon_o^2+\omega\right)\Big(\upsilon_f^2\left(4\left(1-\gamma^2\right)\upsilon_o^2 + 2\omega\right) + \phi\left(2\upsilon_o^2+\omega\right)\Big)}.
$$

For complete investment, it becomes

$$
\begin{aligned}
\lim_{f_d\to 0}\frac{\partial W_d}{\partial F} &= \frac{\beta}{WW}[4\upsilon_o^3\left(Q_f\upsilon_o - Q_o\gamma\upsilon_f\right)\Big(2\Big(1-\gamma^2\Big)\upsilon_f^2 + (1-s)\phi\Big) + Q_f\Big(2\Big(1-s^2\gamma^2\Big)\upsilon_f^2 + (1-s)\phi\Big) \\
&\quad -2\upsilon_o\Big(Q_o(1-s)\gamma\upsilon_f\Big(2\upsilon_f^2 + (1-s)\phi\Big) - 2Q_f\upsilon_o\Big(\Big(2-(1+s)\gamma^2\Big)\upsilon_f^2 + (1-s)\phi\Big)\Big)\omega], \\
WW &\equiv \Big(2\upsilon_o^2+\omega\Big)\Big((1-s)\phi\Big(2\upsilon_o^2+\omega\Big) + 2\upsilon_f^2\Big(2\Big(1-\gamma^2\Big)\upsilon_o^2 + \Big(1-s\gamma^2\Big)\omega\Big)\Big).
\end{aligned}
$$

More importantly, as we consider the case of $\lim s \to 0$, we find

$$
\begin{aligned}
\lim_{f_d\to f_i^*}\frac{\partial W_d}{\partial F} &= 0, && \text{(A.11)} \\
\lim_{f_d\to 0}\frac{\partial W_d}{\partial F} &= \beta\left(Q_f - \frac{2Q_o\gamma\upsilon_f\upsilon_o}{2\upsilon_o^2+\omega}\right), && \text{(A.12)}
\end{aligned}
$$

and as the marginal welfare costs are linear in f_d thus

$$\frac{\partial W_d}{\partial F} = \left[1 - \frac{f_d}{f_d^*}\right] \beta \left(Q_f - \frac{2Q_o \gamma \upsilon_f \upsilon_o}{2\upsilon_o^2 + \omega}\right) \forall f_d \in [0, f_i^*]. \tag{A.13}$$

where the first condition from above for an interior solution, $Q_f > Q_o \frac{2\gamma \upsilon_f \upsilon_o}{2\upsilon_o^2 + \omega}$, implies that the marginal welfare costs (per unit of global fuel investment achieved) are always (weakly) positive. Properties (A.11) through (A.13) show that the key qualitative results from the simpler case in the main text continue to hold in the more complex model used here, where we have added time-discounting, decreasing returns in the non-fuel sector, and sector-specific return volatilities: even if arbitrarily low, any strictly positive valuation of global fuel divestment by the (potential) divestment party implies that that party will benefit from a strictly positive level of unilateral divestment; and a well-defined, finite valuation of global fuel divestment suffices to make the party best off when fully divsting from any fuel investments. It confirms that a marginal, unilateral divestment by the divesting fuel investor reduces the total of global fuel investments at marginal-only costs to the divestor.

A.2 Economic-Financial Model relating Short- and Long-Term Effects

This section provides a small economic and financial equilibrium model with exhaustible fossil fuels, distinguishing three types of fossil fuel divestments related to fuel development projects and purely financial investments into fuel assets. The results confirm that the impact of partial fuel divestment appears to mainly affect the valuation of fuel deposits rather than the amount of fuels extracted.

Setup

There are two periods, $i = \{1, 2\}$, in which demand for fuels s_i decreases in the period's real fuel price p_i at rate α, $s_1 = D_1 - \alpha p_1 + \mu_1$, $s_2 = D_2 - \alpha p_2 + \eta + \mu_2$, with μ_i and η white noises showing demand uncertainties at various stages: μ_i iid short-term demand uncertainty at end of period i, when fuels extracted during period i are sold, unresolved when period-i investment decisions made; η, which may best be described as an uncertainty about a general demand growth, is an independent uncertainty about demand in the second period that is resolved at end of period 1 already. Fuel consumption feeds on a single initial stock of size s. The fuels are extractable at a normalized marginal cost of one, and scarce for any partial divestment scenario considered, so that we have

$$s_1 + s_2 = s, \tag{A.14}$$

and we assume a parameter space to be such as to imply strictly positive demand levels, $s_i > 0$. Without loss of generality we proportionally scale the variances and write

$$p_1 = \frac{D_1 - s_1}{\alpha} + \varepsilon_1, \qquad p_2 = \frac{D_2 - s_2}{\alpha} + \varepsilon_h + \varepsilon_2, \tag{A.15}$$

with all three stochastic components ε iid white noise processes, with $E[\varepsilon_i] = 0$, $V[\varepsilon_i] = \sigma^2$ and $E[\varepsilon_i] = 0$, $V[\varepsilon_h] = \sigma_h^2$, with ε_h known at the beginning of period 2 (index h for 'hold' i.e. reserves that are held/preserved for lifting in period 2), and where the assumption of the equality of the variances of both period's short-run fuel demand noise parameters, ε_i, is an assumption purely for convenience without any particular qualitative repercussions in the analysis.

In the simplified time-structure we propose, risk-averse investors can at each period allocate money for the periods' extraction projects, as well as in period to financially hold deposits for lifting in period 2. In each period an alternative investment a safe asset offers a real return $R > 1$, assumed to be large enough to outweigh a potential time-preference of consumption. The interest rate is exogenous, which seems a justified simplification given that despite their volume, fossil fuels account for a limited fraction of the entire universe of investment possibilities; cf. Annex A.1 for an analysis with endogenised alternative investment returns. We assume overall endowments of all investors are large enough (and the fraction of divestors small enough) for all investors to be willing to hold some of the save asset at all times. This would be the natural outcome in a simple world where governments have to raise *some* money via bonds considered to be save (the government is forced to pay high enough interests for investors to be willing to buy), and it can alternatively be considered an approximation for a risk-adjusted return for assets whose risks have a not overly strong correlation with the fossil fuel return risks. As all investors in equilibrium hold some of the save asset, and all uncertainties are orthogonal, there is no direct inference between investors's holding of the various fuel investment types: arbitrages in terms of risk-adjusted returns relative to the safe asset are strictly defining the equilibrium asset holdings, with other arbitrages, between the various risky assets, holding but being redundant. For simplicity we again resort to the simplification of investors' $k = \{1..n\}$ payoff function from profit π_k as linearly separable in expected profit $E[\pi_k]$, and the variance of that profit, $V[\pi_k]$,

$$u_k \equiv E[\pi_k] - \delta V[\pi_k]. \tag{A.16}$$

There are n investors, but some divest, so only $n_i \leq n$ and $n_h \leq n$ invest into period i extraction and in *h*olding deposits until period 2 respectively. For s_i of fuel to be consumable in period i, we have a financial investment into a physical amount $\frac{s_i}{n_i}$ of deposit extraction projects in each period, and a physical amount $\frac{s_2}{n_h}$ of deposits *h*eld until period 2.

Analysis

We first assume the levels of divestment from fuels, pinning down the corresponding values of n_i and n_h, as being anticipated. An appreciation of the dynamics to be expected if future divestment levels differ from the anticipated levels follows at the end.

We express the value of deposits per unit of fuel contained. Be Q the (deterministic) initial per-unit deposit value in period 1, and Q_2 the deposit valuation at the beginning of period 2, when the uncertainty about the demand growth implying the fuel price component ε_h is resolved, so that Q_2 is a stochastic value seen from period 1, but a constant in period 2. Returns from different investment options are as follows:

1. Saving $Q+1$ in the first period yields $R \cdot (Q+1)$ at end of the first period and saving this in the second period yields $R^2 \cdot (Q+1)$,
2. Buying a unit of deposit (cost Q) and lifting it (cost 1) yields stochastic revenue p_1 at the end of period 1, $E[p_1] = \frac{D_1 - s_1}{\alpha}$ and $V[p_1]{=}\sigma^2$,
3. Buying a unit of deposit (cost Q) and investing 1 in the save asset (cost 1) yields $R + Q_2$ at the end of period 1, with Q_2 the stochastic value of a deposit for period 2 as a function of the prospective demand,
4. Buying, in period 2, a unit of deposit (deterministic cost Q_2) and investing 1 to lift its fuel (cost 1) costs $Q_2 + 1$ and yields stochastic revenue p_2 at the end of the period, $E[p_2] = \frac{D_2 - s_2}{\alpha} + \varepsilon_h$, $V[p_2] = \sigma^2$, and
5. Saving $Q_2 + 1$ in period 2 yields $R \cdot (Q_2 + 1)$.

As the non-divesting investors are free to choose their investment levels in each of the three asset types, and the risks from each are orthogonal,[15] the following arbitrage conditions between the investment choices listed above hold for rational investors:

4. vs. 5.: From perspective of period 2, when ε_h is known, demand implies $p_2 = \frac{D_2 - s_2}{\alpha} + \varepsilon_2 + \varepsilon_h$, and for n_2 non-divesting investors, the risk aversion implies that each holds the same amount of deposits, $\frac{s_2}{n_2}$. Indifference between extraction, that is, equal payoff from a marginal investment into the save asset and the risky fuel extraction project requires: $\frac{D_2 - s_2}{\alpha} + \varepsilon_h - \delta \frac{s_2}{n_2} \sigma^2 \overset{!}{=} R\,(Q_2 + 1)$, with Q_2 a specific, now known materialized value for Q_2. This shows, from the perspective of period 1:

$$E[Q_2] = \frac{\frac{D_2 - s_2}{\alpha} - \delta \frac{s_2}{n_2} \sigma^2}{R} - 1, \qquad V[Q_2] = \frac{\sigma_h^2}{R^2}. \tag{A.17}$$

---

[15] The fact that both, ε_h and ε_2 affect the second period's demand doesn't complicate matters further. When the uncertainty about ε_h has been resolved at the beginning of period 2, and the financial value for ownership, Q_2, adjusted to that level ε_h, the gain from extraction, net of the investment value Q_2 of that field becomes independent of ε_h.

1. vs. 2.: As demand implies $p_1 = \frac{D_1 - s_1}{\alpha} + \varepsilon_1$, and of the n_1 non-divesting, risk-averse investors into fuel extraction projects in period 1, each will hold $\frac{s_1}{n_1}$ of deposits in equilibrium, we have

$$Q = \frac{\frac{D_1 - s_1}{\alpha} - \delta \frac{s_1}{n_1} \sigma^2}{R} - 1. \tag{A.18}$$

1. vs. 3.: With n_h (non-divesting) investors into purely financial fuel holdings in period 1, each of which holding $\frac{s_2}{n_h}$ of deposits, we have $R + E[Q_2] - \frac{s_2}{n_h} V[Q_2] = R(Q+1)$. Using (A.17), this shows

$$s_2 \left(\frac{1}{\alpha} + \delta \frac{\sigma^2}{n_2} + \frac{\sigma_h^2}{n_h R} \right) = \frac{D_2}{\alpha} - R^2 Q - R \tag{A.19}$$

Combining (A.18) and (A.19) allows to substitute out Q, yielding

$$R \left(\frac{D_1 - s_1}{\alpha} - \delta \frac{s_1}{n_1} \sigma^2 - R \right) = \frac{D_2}{\alpha} - R - s_2 \left(\frac{1}{\alpha} + \delta \frac{\sigma^2}{n_2} + \frac{\sigma_h^2}{n_h R} \right),$$

and substituting out s_2 with (A.14) allows to solve for period 1 consumption,

$$s_1 = \frac{s \left(1 + \alpha \delta \frac{\sigma^2}{n_2} + \alpha \frac{\sigma_h^2}{n_h R} \right) + \alpha R + R D_1 - D_2 - R^2}{1 + \alpha \delta \sigma^2 \left(\frac{1}{n_2} + \frac{R}{n_1} \right) + \alpha \frac{\sigma_h^2}{n_h R} + R}. \tag{A.20}$$

Further, using (A.20) in (A.14) and (A.15) and (A.18), allows directly provides also explicit expressions for period 2 consumption, s_2, the equilibrium fuel prices, p_i, and the deterministic period 1 value of fuel deposits, Q.

The partial divestments we consider, correspond to reductions of n_i and n_h to values below n. From (A.20) we derive

$$\frac{\partial s_1}{\partial n_1} = \alpha \frac{s_1}{n_1} \frac{n_2 n_h R^2 \sigma^2 \delta}{n_1 n_2 (n_n R(1+R) + \sigma_h^2 \alpha) + n_h R (n_1 + n_2 R) \sigma^2 \alpha \delta}. \tag{A.21}$$

The negative of this derivative (A.21) is the effect of some period 1 divestment from extraction projects. It becomes thus apparent that divestment from period 1 reduces period 1 fuel extraction. As conjectured, however, the effect becomes small when the fuel price elasticity of demand is small (small α). The same holds for the amount of physical capital invested into the fuel extraction projects, which, with unitary fuel extraction cost, equals s_1 as well.[16]

Assuming all divestors to divest from all fuel assets in parallel, so that $n_1 = n_2 = n_3 = N$, we find

$$\frac{\partial s_1}{\partial N} = \frac{R\alpha(-\sigma_h^2(D_2 + R(R + s - D_1 - \alpha)) - \delta R(1+R)\sigma^2(D_2 + R(R - \alpha - D_1)))}{(\sigma_h^2 \alpha + R(R+1)(n + \delta \sigma^2 \alpha))^2}.$$

---

[16] See section V for the economic explanation of this implication of fuel demand.

The proportionality factor α means that the withdrawal of funds from all considered fuel investment categories is subject to the same limitation in terms of physical effect; the inelasticity of fuel demand, i.e. the presumably relatively small value of α, suggests a small effect of overall divestment on the amount of fuels extracted in period 1. Nevertheless, it appears that even uniform divestment from all types of fuel investments allows to shift a small part of fuel consumption from period 1 to period 2, hence alleviating climate change at least to a small degree in the short run.

The situation for the withdrawal of funds specifically from period 2 extraction projects is largely analogous to that of period 1 divestment. Also here we identify the effect of divestment as proportional to the demand elasticity parameter α, and of a form very similar to that from period 1 divestment on period one consumption, with the natural exception of the effect of the uncertainty about the additional demand growth effect, σ_h:

$$\frac{\partial s_2}{\partial n_2} = \alpha \frac{s_2}{n_2} \frac{n_1 n_h R \sigma^2 \delta}{n_1 n_2 (n_h R(1+R) + \sigma_h^2 R(n_1 + n_2 R)\sigma^2 \alpha \delta}.$$

Divestment from period 1 asset holdings for future extraction, increase the economic pressure to instead use fuels in period 1 and hence accelerates fuel extraction, and is in this sense counterproductive in terms of climate protection. The effect is, however, again limited by the reaction of fuel demand to fuel price changes, as the corresponding derivative of (A.20) shows:

$$\frac{\partial s_1}{\partial n_h} = -\alpha n_1 n_2^2 R \sigma_h^2 \frac{D_2 n_1 + n_1 R(s + R - D_1 - \alpha) + \delta \alpha s R \sigma^2}{[n_1 n_2 (n_h R(1+R) + \sigma_h^2 \alpha) + n_h R(n_1 + n_2 R)\sigma^2 \alpha \delta]^2}. \tag{A.22}$$

As conjectured in section V, *financially* this does not mean that for arbitrarily small demand reactivities α, divestment per se would be nearly entirely offset by an inflow of money from other sectors. Instead, while (A.22) shows that in this case the physical effect vanishes, the divestment keeps a non-marginal effect of reducing the value of the fuel holdings. To see this, consider the funds invested in period 1 into fuel deposits to be held until period 2, $Q \cdot s_2$. With the financial deposit value Q from (A.18), and fuel exhaustion, (A.14), the effect of a marginal decision between divesting or investing into such holdings is given by the total derivative

$$\begin{aligned} \frac{\partial [Q \cdot s_2]}{\partial n_h} &= s_2 \frac{\partial Q}{\partial n_h} + Q \frac{\partial s_2}{\partial n_h} \\ &= -\frac{\partial s_1}{\partial n_h} \left(\frac{s_2}{R} \left[\frac{1}{\alpha} + \frac{\delta}{n_1} \sigma^2 \right] + Q \right). \end{aligned} \tag{A.23}$$

Because period 1 fuel consumption decreases when sparing fuel for period two is made more economic, $\frac{\partial s_1}{\partial n_h} < 0$, divestment clearly reduces the volume of financial assets invested in fuel stocks, $\frac{\partial Q s_2}{\partial n_n} > 0$. The element $\frac{1}{\alpha}$implies that the proportionality of $\frac{\partial s_1}{\partial n_h}$ to α is offset in one term in (A.23), meaning that contrary to the physical effect, the financial investment volume effect of partial divestment from fuel deposit holdings does not vanish when the price reactivity of demand becomes arbitrarily small, confirming what was conjectured in section V.[17]

We so far considered a world with perfect foresight in terms of divestment decisions. In reality, it can be hard to anticipate which fraction of investors would explicitly refrain from which types of investments in the future. Given that in our framework, decisions to lift deposits in period 1 and decisions to financially invest in not-yet-to-be-lifted deposits are made simultaneously at the beginning of the modeled time horizon, the only divestment decision which can ultimately differ from the initialy expected level is that about the investment in period 2 into fuels to be lifted in that period. It is straightforward to extend the analytics from above to disentangle effects from *expected* future divestment (relevant for investors' period 1 extraction choice s_1) and its really occuring level (influencing the period outcome once the decisions about period 1 extraction s_1 cannot be changed anymore). We spare the replication of the analytical results and instead focus only on the economic effects identified. The initially *anticipated* level of period 2 divestment influences both, the amount of fuel extracted in period 1, as well as the financial value of fossil fuel deposits spared from period 1 extraction: a higher level makes period 1 extraction seem more economic overall, and reduces the financial value of fuel holdings for period 2. There is thus in this sense a divestment Green Paradox effect for future divestments, as they can exacerbate the climate problem by speeding up fuel extraction. Once period 1 fuel extraction and holdings are determined and cannot be changed anymore, a change in the level of period 2 divestment has different effects: it cannot influence the period 1 extraction level anymore, and hence also cannot change period 2 extraction. It has thus purely a financial effect without direct physical repercussions. In this sense, divestments in period 2, or more generally in the final phase of the fuel era, can optimally be abstained from even in the case where divesting agents have a very strong taste for the avoidance of climate damage. At least in this stylized framework, there appears not to be any time-inconsistency problem with the choice whether to divest or not: for climate's sake, divestment candidates that care about the climate would want the remainder of the market to believe that no divestment takes place in the second period, and even after the period 1 extraction decisions are irrevokably set, climate divesters will not have any incentive to deviate from their initial stance, as the financial burden from divesting would not imply any climate gains. In a multi-period world, however, the situation becomes more complex, and in order to slow down the fuel consumptions, and the analogy of the situation to that of dynamic fuel extraction with anticipated carbon taxes, suggests that agents divesting for climate's sake would ideally like the remainder of the market to believe, each period anew, that no future divestment will takes place, but as soon as the

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[17] See section V for the economic explanation of this effect.

past extraction decisions are made they would see benefit at least from some short term divestments if their taste for climate protection was large enough.[18]

This analysis is based on the assumption of a fixed amount of fossil fuels to be extracted fully over time. The main insights seem, however, relatively general, and most seem to extend also to more complex setups with multiperiod dynamics. The simplification of full extraction here seems more pertinent than in the case of other environmental policies such as carbon taxes. When, for example no effect of a (global) carbon tax on long-run emissions is found (e.g., Sinn, 2008), one can see this attributable to a missing appreciation of the increasing extraction costs that reach arbitrarily high levels as the stocks get closer to exhaustion, in which case the existing surrogates for fossil energy mean taxes tend to reduce overall fuel consumption at least to some degree (cf., e.g., Habermacher, 2012, and Habermacher and Kirchgässner, 2014). In the present case, this is does not directly apply; partial divestment coupled with uncertainty of returns from extraction, can (slightly) *slow down* the pace of extraction, but even if sustained in perpetuity, divestment has no direct impact on the ultimate amount of fuel consumed. It acts basically as a tax on (risk averse) non-divesting investors, but only for bulk investments; when, for given overall investment endowments, the amount of investments into the fuel sector becomes small – which happens at the time when full (economic) exhaustion of the fuels approaches and fuel prices remain finite due to the presence of natural surrogates – the effect vanishes, as for small per-investor investments in the sector, the expected return becomes the main determinant of whether *some* investment takes place, with the sector-specific risk becoming of vanishing importance in the optimal portfolio choice. As divestment does not hamper the expected return of field developments, this means that when fuels deplete and the extraction rate becomes small, the divestment effect on the total amount of funds invested to field developments vanishes as well, meaning that ultimately, the amount of fuels extracted converges to the same amount as what is extracted without any divestment. This zero long-run effect is a natural result of the risk-related channel through which divestment can be expected to have some effect on the sum of funds invested globally; it is a direct consequence of the way investment weights within a Markov portfolio choice framework become small rather than zero when a sector-specific risk is increased. In (A.20), the effect is visible in that s_1 is *scaled* down by a lower number of non-divesting investors, but remains positive for any parameterisation where it is positive without divestment ($n_1 = n$), independent of the degree to which divestment takes place, i.e., independent of the number n_1.

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[18] Cf., e.g., Hoel (2010) and Habermacher (2012) for an analysis of the commitment problem related to carbon taxation.