Modeling and empirically assessing climate policies and asset stranding

Patterns of policy-induced losses in the fossil fuel extraction, power, and financial sector

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SUMMARY

THE IMPLEMENTATION OF EFFECTIVE CLIMATE POLICIES facilitates reducing greenhouse gas emissions and thereby mitigating climate change. Such policies, however, have adverse effects on stakeholders directly or indirectly engaged in the fossil industry if they find the value of their assets ”stranded”. This thesis contributes to our understanding of the interaction between climate policies and asset stranding: It studies supply-side policies in the upstream fossil fuel extraction industry, the extent and distribution of stranded assets at the asset owner level in the power sector, and the interaction of asset stranding, expectations of climate policies, and financial systemic crises. Further, the thesis surveys the climate economics literature on stranded assets and fossil fuel producers' lost profits due to climate policies. The thesis is a compilation of five articles (Chapters 2-6) encased by a general introduction and a conclusion.

A literature review in article 1 surveying recent contributions on climate policies and asset stranding provides an overview of the state of research and identifies literature gaps. In article 2, we compare estimates of fossil fuel producers' profits at stake due to climate policies in the literature. Further, we discuss how supply-side policies alter the magnitude of such estimates compared to demand-side policies with relevant implications for compensation claims and political feasibility.

Article 3 analyzes deposit markets, a supply-side policy option, where actors trade the right to exploit in-situ fossil fuels. In a partial equilibrium model two groups of countries with different climate ambitions trade deposits of fossil fuels, which differ in their emission intensity and extraction costs. This set-up facilitates studying distributional effects of deposit policies and conditions necessary for the implementation of deposit markets with market power covering multiple fossil fuels. In article 4, we present a novel data set suitable for assessing stranded

assets in emission-intense sectors at the asset owner level globally. We employ this data set to analyze the owners and distribution of stranded assets in the power sector across the globe. Further, we study whether exposure to asset stranding correlates with ownership of alternative energy assess. Article 5 focuses on financial systemic crises induced by asset stranding. It employs a partial equilibrium model to analyze a regulator's decision to set a carbon tax when climate change is stochastic. While high carbon taxes are necessary under severe climate change, they lower the rates of return on fossil-related capital. The model allows studying multiple equilibria arising from investors' expectations for the carbon tax and policies to arrive at the socially more desirable equilibrium.

Results of this thesis may support policymakers in implementing effective climate policies despite asset stranding risks. Article 1 shows that the interaction of climate policies and stranded assets has largely been ignored in the climate economics literature. It especially lacks research on the distributional effects of asset stranding, which is essential for providing effective policy advice. Further, more research should study compensation schemes for adversely affected stakeholders, the impact of asset stranding on labor markets, and political economy challenges associated with climate policies and asset stranding. Article 2 shows that fossil fuel producers' profits at stake due to climate policies have only been analyzed to a limited extend. The extant literature lacks estimates covering supply-side policies and properly accounting for price and cost changes. Such estimates would result in lower profits at stake, thereby justifying much small compensation claims by fuel producers and supporting policy acceptance.

Focusing on a prominent example of such a supply-side policy, article 3 shows that deposit markets covering multiple fossil fuels lead to complex carbon leakage channels between both, fuels and the groups of countries trading deposits. We identify conditions, where these carbon leakage effects even prevent the implementation of deposit markets. Compared to a unilateral, domestic supply-side policy, deposit markets can induce countries to supply a cleaner fuel mix even if they lack climate ambitions. Regardless of a country group's climate ambition, deposit markets covering multiple fuels can improve each group's welfare compared to those covering only one fuel. A unilateral, domestic policy is Pareto-dominated by deposit policies even if market power is exerted on the deposit market. Consumer and producer surplus differ in their ranking between the supply-side policies considered, which has relevant implications for the support for and opposition to climate policy implementation.

Article 4 shifts the focus from climate policies targeting the upstream fossil fuel extraction industry down to asset stranding in the power sector. Results suggest that predominantly coal power plants in Asia-Pacific, Europe, and the US must be stranded to reach the 2 °C goal of the Paris Agreement. In some countries (e.g. India) stranded assets are highly concentrated in a few asset owners, while the distribution is more equal in others (e.g. the US). Due to differences in plant fleets' age profile, asset owners vary considerably in the timing of asset stranding. Internationally invested European, US, and Chinese asset owners face additional stranded assets in foreign countries. Asset owners listed on stock markets may be exposed to asset stranding of almost 78 % of their share price. For some, asset stranding exceeds 80 % of their equity. There is a positive correlation between asset owners' asset stranding exposure and ownership of alternative energy assets. India presents an outlier owning a considerable share of stranded assets but little alternative energy assets.

The fifth article moves from the power sector on to the financial sector: It shows that endogenous climate policymaking under the threat of a financial systemic crisis can lead to multiple equilibria: While the crisis equilibrium features carbon-intense investments and a low carbon tax, the socially more desirable one rapidly phases out fossil fuels under a stringent carbon tax. To achieve the latter equilibrium, we suggest instruments for the regulator: She can either increase the banking system's equity buffer or expand in the wedge between funding costs for fossil versus renewable assets. These policy mix financial supervision and climate policy objectives.

Climate policies required to mitigate climate change leave fossil fuel-related assets stranded. This thesis addresses some of the most pressing challenges associated with this dilemma in the upstream fossil fuel extraction industry, the power sector, and the financial system. Hopefully, the results support policymakers in designing and implementing feasible, effective climate policies and sustainably guiding our society towards a carbon-free economy.

ZUSAMMENFASSUNG

DIE UMSETZUNG EINER EFFEKTIVEN KLIMAPOLITIK ermöglicht die Verringerung von Treibhausgasemissionen und damit die Eindämmung des Klimawandels. Eine solche Politik hat jedoch negative Auswirkungen auf die direkt oder indirekt in der fossilen Industrie tätigen Akteure, wenn deren Vermögensgegenstände wertlos werden (auch „Asset Stranding“ genannt). Diese Arbeit leistet einen Beitrag zum Verständnis der Wechselwirkung zwischen Klimapolitik und Asset Stranding: Sie untersucht angebotsseitige Politikmaßnahmen in der fossilen Brennstoffindustrie, das Ausmaß und die Verteilung von Asset Stranding auf Ebene der Anlagenbesitzer im Energiesektor und die Wechselwirkungen zwischen Asset Stranding, Erwartungen über Klimapolitik und systemischen Finanzkrisen. Darüber hinaus gibt die Arbeit einen Überblick über die Literatur im Bereich Klimaökonomie zu Asset Stranding und zu entgangenen Gewinnen der Produzenten fossiler Brennstoffe aufgrund von Klimapolitik. Die Arbeit besteht aus fünf Artikeln (Kapitel 2-6), die von einer allgemeinen Einleitung und einer Schlussfolgerung umschlossen werden.

Ein Literaturüberblick in Artikel 1, der die neusten Beiträge zu Klimapolitik und Asset Stranding zusammenfasst, gibt einen Überblick über den Stand der Forschung und zeigt Literaturlücken auf. In Artikel 2 vergleichen wir Schätzungen der durch Klimapolitik gefährdeten Gewinne der Produzenten fossiler Brennstoffe in der Literatur. Darüber hinaus erörtern wir, wie angebotsseitige Politikmaßnahmen die Größenordnung solcher Schätzungen im Vergleich zu nachfrageseitigen Maßnahmen verändern, mit entsprechenden Auswirkungen auf Entschädigungsansprüche und politische Durchsetzbarkeit.

Artikel 3 analysiert Depositenmärkte, eine angebotsseitige Politikoption, bei der Akteure das Recht zur Extraktion von fossilen In-situ-Brennstoffen handeln.

In einem partiellen Gleichgewichtsmodell handeln zwei Gruppen von Ländern mit unterschiedlichen Klimazielen mit Depositen fossiler Brennstoffe, die sich in ihrer Emissionsintensität und ihren Förderkosten unterscheiden. Dieser Aufbau ermöglicht die Untersuchung der Verteilungseffekte von Depositenmärkten und der Bedingungen, die für die Implementierung von Depositenmärkten für mehrere fossile Brennstoffe bei Marktmacht erforderlich sind. In Artikel 4 stellen wir einen neuen Datensatz vor, der geeignet ist, Asset Stranding in emissionsintensiven Sektoren auf Ebene der Anlageneigentümer weltweit zu bewerten. Wir verwenden diesen Datensatz, um die Eigentümer und die Verteilung von Stranded Assets im Energiesektor auf der gesamten Welt zu analysieren. Darüber hinaus untersuchen wir, ob die Belastung durch Asset Stranding mit dem Eigentum an alternativen Energien korreliert. Artikel 5 befasst sich mit systemischen Finanzkrisen, die durch Stranded Assets ausgelöst werden. Es wird ein partielles Gleichgewichtsmodell verwendet, um die Beschlussfassung eines politischen Entscheidungsträgers zu analysieren, eine Kohlenstoffsteuer festzulegen, wenn Klimawandel stochastisch ist. Während hohe Kohlenstoffsteuern bei gravierendem Klimawandel notwendig sind, senken sie die Renditen auf fossiles Kapital. Das Modell ermöglicht die Untersuchung multipler Gleichgewichte, die sich aus den Erwartungen der Investoren über die Kohlenstoffsteuer ergeben, und der politischen Maßnahmen, um das sozial wünschenswertere Gleichgewicht zu erreichen.

Die Ergebnisse dieser Arbeit können politischen Entscheidungsträgern dabei helfen, eine effektive Klimapolitik trotz des Risikos von Asset Stranding umzusetzen. Artikel 1 zeigt, dass die Wechselwirkung von Klimapolitik und Stranded Assets in der Literatur im Bereich Klimaökonomie weitgehend ignoriert wurde. Insbesondere fehlt es an Untersuchungen zu den Verteilungseffekten von Asset Stranding, die für eine effektive Politikberatung unerlässlich sind. Darüber hinaus sollten weitere Forschungsarbeiten die Entschädigungsregelungen für nachteilig betroffene Interessengruppen, die Auswirkungen von Stranded Assets auf Arbeitsmärkte und die mit Klimapolitik und Asset Stranding verbundenen politökonomischen Herausforderungen untersuchen. Artikel 2 zeigt, dass die Gewinne der Produzenten fossiler Brennstoffe, die durch Klimapolitik gefährdet sind, bisher nur in begrenztem Umfang analysiert wurden. In der vorhandenen Literatur fehlen Schätzungen, die angebotsseitige Maßnahmen abdecken und Preis- und Kostenänderungen angemessen berücksichtigen. Solche Schätzungen würden zu niedrigeren Gewinnausfällen führen, was wesentlich geringere Entschädigungsforderungen der

Brennstoffproduzenten rechtfertigen und die Akzeptanz der Politik fördern würde.

Anhand eines prominenten Beispiels einer solchen angebotsseitigen Politik zeigt Artikel 3, dass Depositenmärkte, die mehrere fossile Brennstoffe abdecken, zu komplexen „Carbon Leakage“ Effekten sowohl zwischen den Brennstoffen als auch zwischen den Gruppen von Ländern, die mit Depositen handeln, führen. Wir zeigen Bedingungen auf, unter denen diese Carbon Leakage Effekte sogar die Einführung von Depositenmärkten verhindern. Im Vergleich zu einer unilateralen, nationalen Angebotspolitik können Depositenmärkte Länder dazu veranlassen, einen saubereren Brennstoffmix anzubieten, selbst wenn sie keine Klimaziele verfolgen. Unabhängig von den Klimazielen einer Ländergruppe können Depositenmärkte, die mehrere Brennstoffe abdecken, die Wohlfahrt jeder Gruppe im Vergleich zu Märkten, die nur einen Brennstoff abdecken, verbessern. Eine unilaterale, nationale Politik wird von Depositenmärkten Pareto-dominiert, selbst wenn auf dem Depositenmarkt Marktmacht ausgeübt wird. Verbraucher- und Produzentenrente unterscheiden sich in ihrer Rangfolge zwischen den betrachteten angebotsseitigen Politikmaßnahmen, was relevante Implikationen für die Unterstützung für und den Widerstand gegen die Umsetzung der Klimapolitik hat.

Artikel 4 verlagert den Schwerpunkt von der Klimapolitik, die auf die fossile Brennstoffindustrie abzielt, hin zum Asset Stranding im Energiesektor. Die Ergebnisse deuten darauf hin, dass vor allem Kohlekraftwerke im asiatisch-pazifischen Raum, in Europa und in den USA stillgelegt werden müssen, um das 2 °C-Ziel des Pariser Klimaabkommens zu erreichen. In einigen Ländern (z. B. Indien) sind Stranded Assets stark auf einige wenige Eigentümer konzentriert, während die Verteilung in anderen Ländern (z. B. den USA) gleichmäßiger ist. Aufgrund von Unterschieden im Altersprofil der Kraftwerkparks variieren die Eigentümer der Anlagen erheblich in Bezug auf den Zeitpunkt von Asset Stranding. Europäische, US-amerikanische und chinesische Anlagenbesitzer, die international investieren, sind mit zusätzlichen Stranded Assets im Ausland konfrontiert. Bei börsennotierten Anlagenbesitzern kann Asset Stranding fast 78 % ihres Aktienkurses ausmachen. Bei einigen übersteigt Asset Stranding 80 % ihres Eigenkapitals. Es besteht eine positive Korrelation zwischen der Belastung mit Asset Stranding und dem Besitz von Anlagen im Bereich der alternativen Energien. Indien stellt einen Ausreißer dar, der einen beträchtlichen Anteil an Stranded Assets, aber nur wenige alternative Energieanlagen besitzt.

Der fünfte Artikel geht vom Energiesektor auf den Finanzsektor über: Er zeigt, dass endogene Klimapolitik unter der Gefahr einer Finanzsystemkrise zu mehreren Gleichgewichten führen kann: Während das Krisengleichgewicht kohlenstoffintensive Investitionen und eine niedrige Kohlenstoffsteuer vorsieht, führt das gesellschaftlich wünschenswertere Gleichgewicht zu einem raschen Ausstieg aus fossilen Brennstoffen unter einer hohen Kohlenstoffsteuer. Um das letztgenannte Gleichgewicht zu erreichen, schlagen wir Instrumente für politische Entscheidungsträger vor: Sie können entweder den Eigenkapitalpuffer des Bankensystems erhöhen oder den Unterschied zwischen den Finanzierungskosten für fossile und erneuerbare Anlagen vergrößern. Diese politischen Vorschläge verbinden Finanzaufsicht mit klimapolitischen Zielen.

Die zur Eindämmung des Klimawandels erforderlichen klimapolitischen Maßnahmen führen dazu, dass mit fossilen Brennstoffen verbundene Vermögenswerte wertlos werden. Diese Arbeit befasst sich mit einigen der dringlichsten Herausforderungen, die mit diesem Dilemma in der fossiler Brennstoffindustrie, im Energiesektor und im Finanzsystem verbunden sind. Ich hoffe, dass die Ergebnisse politische Entscheidungsträger bei der Gestaltung und Umsetzung einer realisierbaren, effektiven Klimapolitik unterstützen und unsere Gesellschaft nachhaltig zu einer kohlenstofffreien Wirtschaft führen.

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List of Acronyms and Abbreviations

APS	Announced Pledges Scenario
BAU	Business as usual
CCUS	Carbon capture, utilization, and storage
ECB	European Central Bank
GHG	Greenhouse gas
IEA	International Energy Agency
OCC	Overnight capital costs
OECD	Organisation for Economic Co-operation and Development
SDG	Sustainable Development Goal
SDS	Sustainable Development Scenario
WEO	World Energy Outlook

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Angelika

1

Introduction

Climate change has disastrous effects on natural and human systems. Among others, sea level rise, ocean acidification, increases in the frequency and intensity of extreme weather events, such as heat waves, heavy precipitation, and drought, have caused substantial damages and irreversible losses in ecosystems, reduced food and water security, and adversely affected human physical and mental health (IPCC, 2022a). Mitigation of this ongoing crisis requires a sharp reduction in greenhouse gas (GHG) emissions: The Intergovernmental Panel on Climate Change states that compared to 2019 GHG emissions must fall by 43 % by 2030 to reach the goal of the Paris Agreement, namely limiting global warming to 1.5 °C compared to pre-industrial levels, with a probability higher than 50 % (IPCC, 2022b).

Climate policies aim at reducing GHG emissions to mitigate this advancing crisis. They include policies targeting the demand of fossil fuels, for instance in the form of energy taxes, emission standards or cap-and-trade mechanisms for emissions (cf. Ishikawa & Kiyono, 2006, Paltsev et al., 2008, Pizer & Sexton, 2019). Supply-side policies, such as extraction quota, production bans or export taxes, aim at reducing the supply of fossil fuels (cf. Asheim, 2013, Richter et al., 2018). Further, energy efficiency programs or research and development subsidies to boost the diffusion of alternative energy technologies can facilitate a reduction in GHG emissions (cf. Gillingham et al., 2006, Yu et al., 2016). Many more climate policy designs as well as combinations of them have been studied in theory (cf. Hoel, 1994, Fæhn et al., 2017) and their practical application at the (sub-)national level and across sectors has increased consistently (IPCC, 2022b).

Despite the implementation of climate policies in many nation states across the globe average annual GHG emissions between 2010 and 2019 were higher compared to any previous decade (IPCC, 2022b). Further, even if all Nationally Determined Contributions announced prior to the 26th United Nations Climate Change Conference of the Parties were to be implemented, global warming in the 21st century would likely overshoot the 1.5 °C goal (probability of 66-100 %) (IPCC, 2022b).

A central challenge to implementing effective climate policies is that they can lead to a premature devaluation of fossil fuel-dependent assets, leaving them 'stranded'. To reach the 1.5 °C goal of the Paris Agreement with a 50 % probability 90 % of coal and almost 60 % of oil and gas must remain unextracted (Welsby et al., 2021). Power plants using these fossil fuels as input are likewise at risk of stranding: For instance, coal power plants estimated to be worth \$1.4 trillion must decommission prematurely to meet the 1.5 °C goal (Edwards et al., 2022). Many other asset types related to these assets, such as human capital or durable goods, also face risks of asset stranding. Ultimately, climate policies may strand between 1 % and 3.5 % of banks' and investment funds' total assets (Roncoroni et al., 2021) and threaten financial stability (Carney, 2015).

While the benefits of mitigating climate change are regionally diffuse and stretch over longer time horizons, costs are often concentrated and they can hit economic actors immediately. Then, strong political resistance to the implementation of climate policies can be expected from adversely affected stakeholders (Olson, 1965, Douenne & Fabre, 2022). Such resistance has been shown to play a crucial role in shaping climate policymaking (Cheon & Urpelainen, 2013, Colgan et al., 2020, Mildenberger, 2020). As a result, climate policies have only had limited success in reducing GHG emissions (Green, 2021).

This thesis advances our knowledge on the interaction of climate policies and asset stranding. It studies both, demand- and supply-side climate policies and it covers the upstream fossil fuel sector, the power sector, and the financial sector. It starts with a survey of the climate economics literature on stranded assets in Chapter 2 highlighting research gaps – some of which are addressed in the subsequent chapters – and providing policy recommendations.

Climate policies have distributional consequences, which are crucial for political feasibility and policy acceptance: Economic actors experiencing negative distributional effects due to a policy have been shown to fiercely oppose policies (Olson, 1965, Persson, 1998, Meng & Rode, 2019). This, in turn, can hamper the implementation of stringent climate policies (Cheon & Urpelainen, 2013). Thus, knowledge on the exact size of profits at stake due to climate policies is highly relevant for political feasibility – in particular for the upstream fossil fuel sector given the mere size of assets at risk of stranding (McGlade & Ekins, 2015, Welsby et al., 2021). In Chapter 3, we review estimates of fossil fuel producers' profits at stake due to climate policies in the extant literature comparing implemented approaches and underlying assumptions.

The previous chapter distinguishes between profits at stake resulting from demand- and supply-side policies, as this can be crucial for the size of stranded assets and therefore policy resistance. Policies aiming at the reduction of fossil fuel supply have become a recent research focus (Bohm, 1993, Asheim, 2013, Fæhn et al., 2017) and scientists have called for a supply-side treaty to strengthen the Paris Agreement (Asheim et al., 2019). Deposit markets, where actors trade the right to exploit in-situ fossil fuels, are a promising example of a supply-side policy (Harstad, 2012). These markets, however, may suffer from market failure leading to inefficient outcomes (Eichner & Pethig, 2017b). Extant studies have focused on deposit markets covering a single fuel (Harstad, 2012, Eichner & Pethig, 2017a). If such deposit markets instead cover more fuels, market failure could amplify inefficiencies and even impede the implementation of these markets. In Chapter 4, we investigate effects that may cause deposit markets covering multiple fuels to malfunction and we identify conditions necessary for their implementation.

Asset stranding due to climate policies and political feasibility concerns only begin at the upstream fossil fuel sector studied in the previous chapters. The power sector is likewise affected requiring the premature retirement of fossil-fuel burning energy infrastructure to reach the Paris goal (Tong et al., 2019). Coal power plants must be decommissioned decades earlier than historically (Cui et al., 2019) resulting in stranded assets worth between $0.1-1.4 trillion depending on the exact climate target and time horizon (Johnson et al., 2015, Edwards et al., 2022). Extant studies mostly focus on assessing stranded assets at the country or global level (Fisch-Romito et al., 2021). Knowledge on adversely affected owners at the asset level, however, is key to account for policy resistance and to produce realistic policy recommendations (Cheon & Urpelainen, 2013, Dixit, 1996, Acemoglu & Robinson, 2013). In Chapter 5, we identify the direct and indirect owners of stranded assets in the power sector across the globe and we analyze the extent and patterns of their asset stranding exposure.

Finally, I turn my attention to the financial sector: Stranded assets due to climate policies are highly relevant for financial markets: The abrupt tightening of climate policies could destabilize financial markets via revaluations of fossil fuel-dependent assets and financial assets backing them (Carney, 2015, Campiglio & van der Ploeg, 2022). Financial institutions have even demanded measures to reduce this transition risk (ESRB, 2016). Investors' expectations on climate policies are crucial for financial stability: If they expect weak policies, this incentivizes high fossil investments and thus, policymakers implement lax climate policies to prevent financial instability (Kalkuhl et al., 2020). In Chapter 6, we analyze endogenous climate policies that evolve alongside investors' expectations on stranded assets and result in multiple equilibria. We propose policies to reach the socially more desirable equilibrium.

The thesis employs a mix of methodologies to approach the research targets outlined above. In the first two chapters (systemic) literature reviews are used to identify economic research on asset stranding and estimates of fossil fuel producers' profits at stake due to climate policies (cf. Fisch-Romito et al., 2021). Chapters 4 and 6 both employ partial equilibrium models and they focus on second-best climate policies: Chapter 4 represents the fossil fuel extraction industry in a partial equilibrium model and assumes climate change to be deterministic (cf. Harstad, 2012, Eichner & Pethig, 2017a). In contrast, the environment is stochastic in the carbon economy model in Chapter 6 (cf. Kalkuhl et al., 2020). Chapter 5 assesses asset stranding in the power sector empirically by combining a data set on power plants and their owners with the scenario data of a large-scale energy markets simulation model (cf. Edwards et al., 2022, IEA, 2021b).

Chapters 2 – 6 each present a self-contained research article targeting different aspects of the thesis' topic. Table 1.1 shows the manuscript status of each article, three of which are already published in peer-reviewed scientific journals. At the beginning of each chapter, additional information, including the names of co-authors, is provided. Chapter 5 is single-authored. In Chapter 7, I conclude the thesis by summarizing and discussing general results and limitations of the above chapters. I shortly summarize each chapter in what follows.

Table 1.1: Overview on manuscript status of the main chapters of the thesis.

Chapter	Title	Manuscript status
2	Stranded assets: Research gaps and implications for climate policy	Accepted for publication in the *Review of Environmental Economics and Policy*
3	Politics, profits and climate policies: How much is at stake for fossil fuel producers?	Published in *Energy Research & Social Science*
4	Buy coal and gas? Interfuel carbon leakage on deposit markets with market power	Published in *Energy Economics*
5	Disentangling the exposure of asset owners to power sector stranded assets across the globe	'Revise and resubmit' in *Nature Communications*
6	Endogenous climate policy, systemic risks, and asset stranding	Working Paper

Chapter 2 provides a review of the economics literature at the intersection between climate policies and stranded assets. As owners of assets, which stand to lose value, will likely oppose the implementation of climate policies, contributions in this field are crucial for realistic policy advice. Our results, however, point at a relative lacuna in research on this topic, especially concerning distributional effects, compensation and labor market impacts, and political economy questions. We recommend policies, including a ban on fossil-intensive investments, which face less resistance and pave the way for credible future carbon pricing.

Chapter 3 discusses estimates of profits, which fossil fuel producers stand to lose due to climate policies. This chapter targets at some of the open research questions identified in Chapter 2 as such estimates are highly relevant for political feasibility and compensation claims. In the extant literature most estimates of profits at stake do not account for price and cost changes and they only cover policies targeting the demand of fossil fuels. Policies reducing the supply of fossil fuels have been ignored by researchers. We show that proper estimates focusing on supply-side policies would justify much smaller compensation claims with important implications for policy acceptance.

Chapter 4 analyzes deposit markets covering multiple fuels. This study advances our understanding of supply-side policies and addresses distributional effects, thereby targeting some of the research gaps outlined in Chapters 2-3. We employ a partial equilibrium model composed of two groups of countries characterized by differing climate goals and market power. Fossil fuels differ in emission intensity and extraction costs. Our results show that deposit markets covering multiple fuels entail complex carbon leakage channels including all fuels and deposit trade participants. Under certain conditions these leakage effects can even render deposit markets as a policy option obsolete. We show that deposit policies covering multiple fuels Pareto-dominate a unilateral, domestic supply-side policy despite market power exertion on the deposit markets. Even if countries lack climate ambition, they produce a cleaner fuel mix with deposit markets compared to the unilateral policy. Regardless of climate ambition, countries' welfare improves with deposit markets covering all fuels compared to those covering only one fuel. Across the supply-side policies analyzed consumer and producer surplus rank differently with highly relevant implications regarding their support for each policy option.

Chapter 5 assesses the owners and distribution of stranded assets in the power sector globally. It complements the previous chapter by focusing on the power sector as opposed to the upstream fossil fuel extraction and addresses research gaps on distributional impacts of climate policies set out in Chapter 2. We employ a novel data set, which maps assets from energy-intense sectors across the globe to their direct and indirect owners. We combine this data set with the output of a large-scale simulation of energy markets. Our results show that regions such as Asia-Pacific, Europe, and the US are predominantly exposed to asset stranding. Especially power plants using coal as input are at risk of stranding. The distribution of stranded assets across owners varies considerably between countries. For instance, in India one single asset owners is highly exposed to stranded assets, while in the US stranded assets are more equally distributed between owners. Further, the timing of stranded assets differs between asset owners as their plant fleets vary in age profile. Predominantly in Europe, the US, and China internationally invested asset owners are additionally exposed to stranded assets abroad. Regarding listed asset owners, their asset stranding exposure reaches almost 78 % of their share price and even exceeds 80 % of their equity. Ownership of stranded assets positively correlates with that of alternative energy assets. India shows a particularly high exposure to asset stranding combined with little ownership of alternative energy assets.

Chapter 6 analyzes financial systemic risks resulting from climate policy-induced asset stranding. It assesses expectations-driven equilibria that create systemic instability, thereby addressing the lack of research on policies evolving alongside stranding expectations mentioned in Chapter 2. In a partial equilibrium model with stochastic climate change, the regulator endogenously sets a carbon tax. We show that under severe climate change, a high carbon tax is necessary. This, however, lowers the rate of return to fossil capital and may induce a financial crisis. The model features one equilibrium characterized by intense investments in fossil capital and a low carbon tax, and another equilibrium with little fossil investments and a stringent carbon tax. To achieve the latter, we propose and discuss policies that mix financial supervision and climate policy objectives: The regulator can increase the banking system's equity buffer or increase in the wedge between funding costs for fossil versus renewable assets.

2

Stranded assets: Research gaps and implications for climate policy

Abstract

Many types of capital stocks – natural, physical, and human – stand to lose value due to climate policy and become ”stranded”. The owners of such assets will resist climate policies. We survey the recent climate economics literature and highlight research gaps related to stranded assets. In line with recent literature in political science, we argue that economists can provide more effective policy recommendations by putting greater emphasis on the distributional consequences of asset stranding. Our recommended policies focus on targeting new capital stocks related to energy production and consumption: banning fossil-intensive investment and encouraging investment into renewable and energy-efficient capital. These policies face may less resistance than price-based mechanisms and could improve the credibility of future carbon pricing.

Reference: von Dulong, A., Gard-Murray, A., Hagen, A., Jaakkola, N. & Sen, S. (2023). Stranded assets: Research gaps and implications for climate policy, *Review of Environmental Economics and Policy, forthcoming.*

2.1 Introduction: Why do stranded assets matter?

Decarbonization requires ambitious climate policies that put fossil fuel–dependent assets at risk. When risks materialize as unanticipated declines in value and capital is too costly to reallocate, assets are ”stranded” (Van der Ploeg & Rezai, 2020). We argue that increased attention to asset stranding and related political frictions in climate economics will yield policy-relevant insights mindful of political constraints.

We focus on assets threatened by mitigation policy.[1] Fossil reserves face the most obvious risk: meeting the 2 °C target requires stranding 80 percent of coal reserves (McGlade & Ekins, 2015), and plausible policies could strand over $1 trillion in the upstream oil and gas sector (Semieniuk et al., 2022). Climate change mitigation also threatens carbon-intensive firms, especially energy firms (IEA, 2011). Fossil power plants worth between $0.5 and $1.4 trillion may be stranded (Edwards et al., 2022). Human capital, residential property, durable goods, urban infrastructure and many other asset types also face stranding risks. Climate policies could strand 3 percent of banks and investment funds’ total value at risk (Roncoroni et al., 2021). As a result, rapid decarbonization could have severe macroeconomic impacts (Diluiso et al., 2021). Abrupt policy tightening could threaten financial stability (Carney, 2015, Campiglio & van der Ploeg, 2022), and many financial institutions have called for transition risk-reducing measures (ESRB, 2016).

With so much at stake, asset stranding potentially determines the success or failure of climate policies. Economic actors’ perceived self-interest shapes climate policymaking. Many benefits of mitigation are diffuse in space and time and contingent on global action, while costs are often immediate, salient, and concentrated, incentivizing resistance (Olson, 1965, Douenne & Fabre, 2022). Many costs ultimately fall on existing strandable assets, such as resource reserves, physical capital, and human capital, and the owners of these assets have played a crucial role in opposing mitigation (Oreskes & Conway, 2010, Cheon & Urpelainen, 2013, Aklin & Mildenberger, 2020, Colgan et al., 2020, Stokes, 2020). Workers with specific carbon-complementary skills have incentives to back their employers

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[1] We do not discuss physical risk (i.e., stranding from climate impacts; see Dietz et al. (2016)) or transition risk unrelated to policy – e.g., fossil divestment due to changing social norms (Besley & Persson, 2019).

(Mildenberger, 2020). As a result, political limitations on carbon pricing have reduced its impact (Green, 2021).

Realistic policy recommendations must consider political feasibility (Dixit, 1996, Acemoglu & Robinson, 2013).[2] Economists typically evaluate mitigation policies from the perspective of economic efficiency – i.e., maximizing aggregate well-being at the lowest cost. The preferred mechanism is generally carbon pricing, where prices are set to equal the social cost of carbon. Distributional questions are addressed according to the Kaldor-Hicks criterion: admitting policies which leave some agents worse off, providing transfers could make them whole. In practice, compensatory transfers face informational and political hurdles, making it difficult to defuse resistance to mitigation policies. Economists interested in providing practical advice should recognize that first-best policy will usually be implemented in a second-best form, implying complementary policies are needed.

In this article, we present findings from our review of the recent literature on climate economics,[3] arguing that political frictions and stranded assets remain relatively under-researched in climate economics. We highlight lessons gleaned from our review, identify areas for further research, and conclude with policy implications. Our review suggests that near-term climate policy could focus on banning fossil-intensive investment and encouraging investment into renewable and energy-efficient capital. These policies may face less resistance than price-based mechanisms and could improve the credibility of future carbon pricing.

2.2 THE RESEARCH GAP

Despite stranded assets' importance for climate policy, economics has paid them relatively little attention. Using a bibliometric analysis of relevant keywords on Web of Science, we only identified a small number of papers focused on stranded assets and climate. We searched for article abstracts, titles, or topics mentioning ”stranded” or ”stranding” and one of ”climate change,” ”climate policy,” ”greenhouse,” or ”global warming”.[4] Figure 2.1 suggests that very few articles (41) on climate policies and stranded assets have been published in economics journals,

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[2] Our focus is on political feasibility; see Caldecott et al. (2021) for a review of broader social challenges.

[3] For comprehensive literature reviews, see Van der Ploeg & Rezai (2020) and Campiglio & van der Ploeg (2022).

[4] See Appendix 2.A.

even when including adjacent fields where economists might plausibly publish (285). Manually excluding irrelevant papers narrowed results further (99). The bibliometric approach suggests economic research on climate and stranded assets has lagged other fields, only taking off in 2019. While there is no objective benchmark for the appropriate share of publications on a certain topic, we consider the current level of attention insufficient given the importance of the topic.

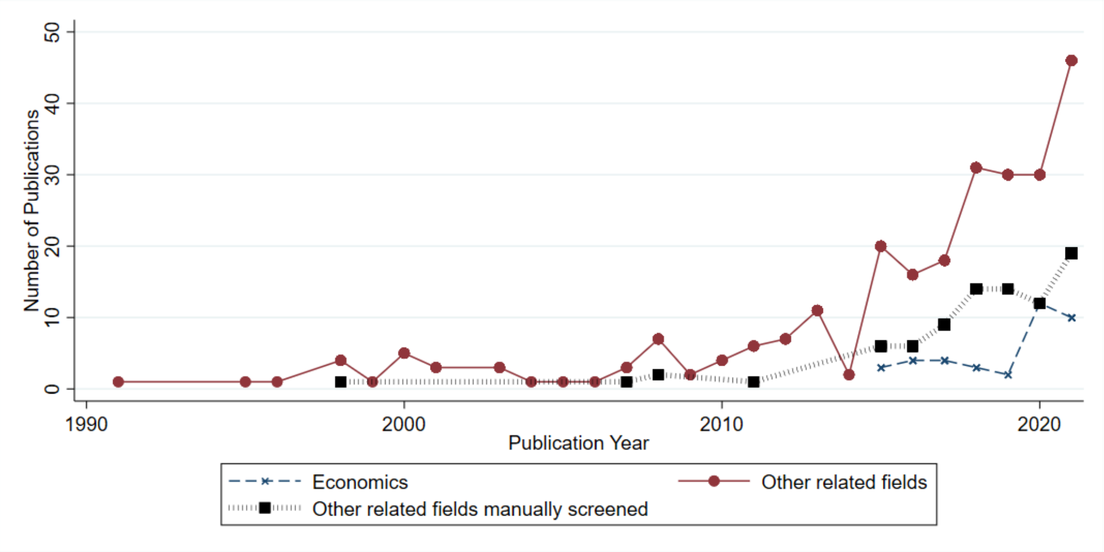

Figure 2.1: Number of publications on stranded assets and climate in economics and related field journals by year, identified by bibliometric search. Years without markers indicate zero observations.

Keyword searches may fail to catch relevant articles (e.g., those referencing ”unburnable” reserves, not ”stranded” assets). To overcome this problem and explore the literature in more depth, we conducted an expert review, systematically classifying all articles on climate policy in four leading field journals – the Journal of Environmental Economics and Management, Journal of the Association of Environmental and Resource Economics, Journal of Public Economics, and Environmental and Resource Economics – in 2017–2020, when scholarship on stranded assets and climate began growing.[5]

We focused on (i) whether papers explicitly consider questions related to asset stranding; (ii) whether analyses focus on aggregate welfare, or consider welfare and distribution at a more disaggregated level; and (iii) whether papers analyze compensatory policies, political economy issues, or labor market impacts (Figure 2.2).

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[5] See Appendices 2.B and 2.C.

We also examined various distributional dimensions.

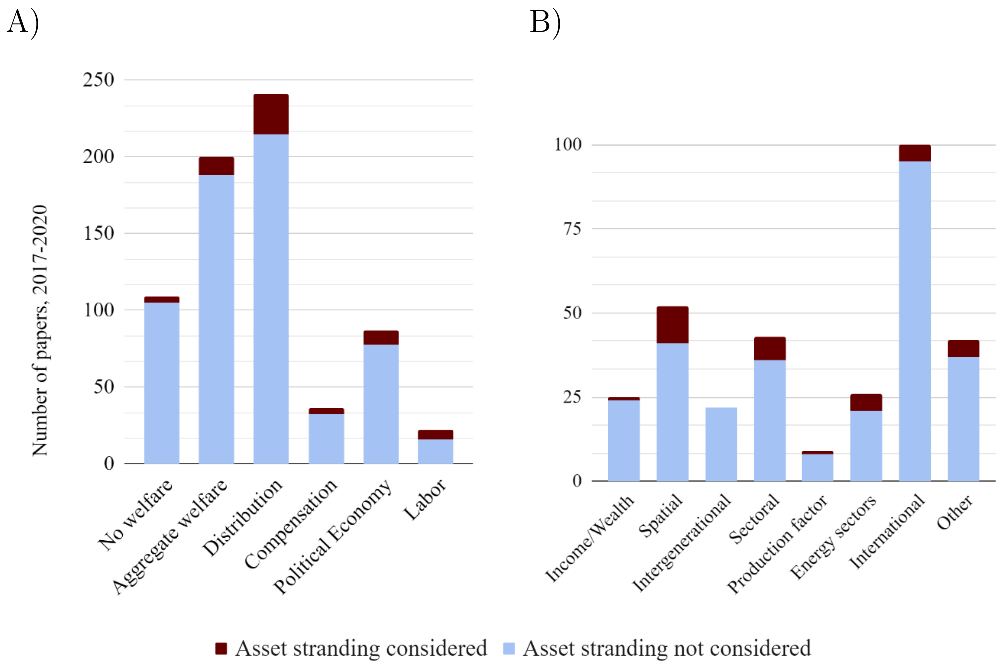

Figure 2.2: Consideration of asset stranding and related topics in climate economics. One article may span multiple categories (n=488).

Asset stranding remains largely ignored in recent literature. Only a few papers analyze asset stranding and welfare at the aggregate level. Despite the policy-making relevance of stranding, political economy approaches are similarly rare. Stranding is mostly ignored in articles on compensation and labor markets, topics which themselves appear under-researched.

A larger share of articles study distributional effects of asset stranding, especially across countries. Within-country spatial distribution, sectorally disaggregated impacts, and incidence on energy sectors are the next most common. The interaction of stranding with intra- or intergenerational distribution of income/wealth has mostly been ignored by climate economists, despite their political relevance.

2.3 WHAT HAVE WE LEARNED?

A variety of different asset types are prone to stranding, with varying distributional and political consequences. Here we discuss selected results and key political mechanisms.

Stranded capital. Most fossil fuels must be left unburned to meet climate targets (McGlade & Ekins, 2015). Some are associated with extremely high rents. One response is a moratorium on extraction (Collier & Venables, 2014) or compensation to owners for unused reserves (Bohm, 1993, Harstad, 2012, Gard-Murray, 2022). Geographic concentration means compensation could involve politically difficult international transfers.

Energy-generating and energy-intense infrastructure is often long lived; reducing the emissions intensity of these can be expensive or impossible. Investment in polluting assets must stop soon (Rozenberg et al., 2020); however, investment moratoria may increase short-run returns to fossil fuel–related assets (Baldwin et al., 2020). Distributional impacts of different instruments, like grandfathering versus auctioning emissions permits, have been analyzed extensively (e.g., Fischer et al., 2017, Rozenberg et al., 2020).

A growing literature studies whether stock returns reflect carbon risk (Bolton & Kacperczyk, 2021, Giglio et al., 2021). Institutional investors believe carbon emissions represent a material risk increasingly reflected in prices (Krueger et al., 2020). Sen & von Schickfus (2020) show investors expect stranded coal plants will receive compensation, perhaps because of lobbying power. Meng & Rode (2019) find financial markets price in vested interests' lobbying power.

Stranded labor. The existing literature finds climate policies have mixed effects on employment (e.g., Martin et al., 2014). Asset stranding for labor depends on sectoral carbon intensity and skill-specificity (Marin & Vona, 2019). For example, British Columbia's revenue-neutral carbon tax reduced employment in the most carbon-intensive sectors and increased it in the least (Carbone et al., 2020), disproportionately affecting less-educated workers (Yip, 2018).

Focusing on aggregate impacts ignores important limitations on labor mobility, given stranded assets' regional and sectoral concentration. Aggregate shocks can have spatially heterogeneous effects (Autor et al., 2020). In particular, carbon taxes may be progressive in aggregate (Goulder et al., 2019) but not for exposed workers, who often help employers block mitigation (Bechtel et al., 2019, Mildenberger, 2020). Carattini & Sen (2019) show investors' reactions to pricing proposals may depend on their distributional features. Work on trade politics of sunset sectors (Dixit & Londregan, 1995) may inform the green transition; see also the large literature on trade lobbying (e.g., Bombardini et al., 2023).

Multiple equilibria. Very few papers explore how policies evolve alongside stranding expectations. With endogenous policies, stranded assets can involve multiple mitigation and fossil investment equilibria (Kalkuhl et al., 2020). Once weak policy is expected and accompanied by correspondingly high fossil investment, political feedback incentivizes implementing weak policy. Commitment problems are particularly important, as typical policy recommendations use future taxes to redirect investment (e.g., Baldwin et al., 2020). One potential solution is tackling fossil investment directly (Kalkuhl et al., 2020).

Multiple equilibria may imply policy uncertainty. Uncertainty over legal challenges against US regulations delayed investment into sulfur abatement (Dorsey, 2019). Continued uncertainty over future policies may reduce energy-related investment and slow switching toward green capital.

2.4 Future research

In our view, stranded assets and their policy effects have received insufficient attention. In particular, work on politico-economic effects remains rare and largely theoretical. Our review highlights a few key issues going forward.

First, climate policies, transition risk, and policy uncertainty are endogenous. Existing papers almost invariably treat policy uncertainty as exogenous (van der Ploeg & Rezai, 2020). But optimal policy depends on capital stocks, and investment decisions determining those stocks depend on policy expectations. Policy decisions should be determined endogenously within models that account for multiple, expectations-driven equilibria.

Second, economists and political scientists should collaborate on the political economy of stranded assets. Studying past initiatives' distributional impacts (especially compensation schemes) would help explain which designs succeed. Empirical research on politico-economic interactions is an important complement to theoretical models and could help design "second-best" climate policies with realistic political constraints.

Third, research is needed on key dimensions of inequality and stranded assets. We found remarkably few papers considering stranding and income or wealth inequality, given very different asset portfolios and policy exposure across social classes. Intergenerational incidence of stranding and the fine details of incidence on sector-specific human capital are similarly under-researched. Political outcomes can depend on relatively small groups losing from policies that otherwise lead to aggregate gains (Autor et al., 2020, Gard-Murray, 2020, Stokes, 2020).

A better understanding of how asset stranding constrains domestic politics also will help understand international (non-)cooperation (Aklin & Mildenberger, 2020, Colgan et al., 2020, Tavoni & Winkler, 2021).

2.5 Policy implications

Although stranded assets need more economic investigation, we draw some preliminary lessons for policymakers.

First, without commitment, carbon pricing may not be the optimal mitigation strategy. First-best mitigation policies redirect investments toward low-carbon assets mainly via high future carbon prices. But without commitment to future policies, market actors may not expect rising prices and thus may continue investing in irreversible, carbon-intensive capital. The policymaker may then have to set carbon taxes below the ex-ante optimal level – e.g., for reasons of political economy (Kalkuhl et al., 2020) or efficiency, even with rational expectations. Stranded assets imply mitigation should target expectations; it is not clear price-based schemes do this.

Second, policymakers should target durable capital stocks in addition to immediate emissions flows since they determine both long-term emissions and political coalitions. Stated climate targets imply development of new fossil-related assets must halt (IEA, 2021a). But reducing fossil investment also limits strandable assets in the future, allowing future policymakers to pass stronger policy, thereby improving present credibility. Subsidizing low-carbon investments also could increase the political scope for ambitious policies (Strunz et al., 2016, Meckling et al., 2017). Regulating new carbon-intensive investment will likely provoke political resistance. But it does not reduce and may even increase the value of existing capital (Baldwin et al., 2020), creating relatively less resistance than policies which devalue already-developed assets. That said, desirable climate effects must be considered in relation to any deleterious effects, including on energy security.

Third, policymakers should consider socioeconomic tipping points (Farmer et al., 2019). Unpalatable steps like compensating incumbents may be worthwhile if they enable rapid change (Goulder, 2020, Stern & Stiglitz, 2021). Decisively subsidizing low-carbon assets through ”Green Deals” could also tip expectations-driven equilibria. Of course, socioeconomic tipping points also may trigger rapid devaluations of stranded assets, causing major financial instability. Economic policymakers should plan ahead to minimize negative impacts of a rapid transition.

Appendices

2.A Bibliometric review

All searches were conducted on the Web of Science platform. For all the searches below, we only included academic journal articles. We limited our search to terms present in the Abstract, Title, or Topic of an article, to capture pieces which were substantially focused on our target areas.

Our first goal was to identify the overall amount of work on climate change in economics. We began by searching for articles in the ”Economics” category on Web of Science which included the terms ”climate change”, ”climate policy”, ”greenhouse”, or ”global warming” (n = 10,896). We also cast a wider net using just the term ”climate”. This allows for more permutations (”climate crisis”) but also may draw in articles unrelated to climate change (”investment climate”). The results were similar (n = 11,443), suggesting that the first search had relatively few false negatives. We only use this search to provide a denominator, so to be conservative we use the lower number of articles.

We then searched for articles in the ”Economics” category on Web of Science which included either ”stranded” or ”stranding”, as well as ”climate change”, ”climate policy”, ”greenhouse”, or ”global warming” (n = 41). We do not include a noun paired with stranded or stranding because there are many ways to phrase this relationship (e.g. ”stranded assets”, ”fossil fuel stranding”, ”stranding reserves”). Including the word ”strand” on its own adds 7 additional articles, all of which use it to refer to a ”strand” in the literature). A search using the broader net of ”stranded” or ”stranding” and ”climate” returns the same number of results (n = 41).

Work by economists is not always confined to economics journals. There are a range of other fields where economists might be publishing work on stranded assets. So we conducted a search for articles with the terms ”stranded” or ”stranding”, as well as ”climate change”, ”climate policy”, ”greenhouse”, or ”global warming”, but *excluded* the Web of Science category ”Economics” (n = 285). This captured many irrelevant articles, so we manually excluded results unrelated to stranded assets (e.g. ”Factors Affecting Harp Seal (Pagophilus groenlandicus) Strandings in the Northwest Atlantic”). This left us with a smaller sample of articles plausibly connected to economics but not in economics journals (n = 99).

2.B Paper identification criteria and classification guidelines

The following guidelines were used in identifying and classifying articles in the literature review. Aware of the fact that some articles cannot be clearly identified and assigned to one or another category, we have chosen the following procedure to be as transparent and consistent as possible: i) We developed the identification and classification guidelines jointly in an iterative process of identifying and classifying articles, discussing the selection and classification, and refining the identification criteria and categories several times to ensure a consistent understanding of both. ii) We chose to have each article assessed by at least two authors (also iterating the combination of authors jointly identifying and classifying articles to maximize intercoder reliability) and compared the selection and classification. iii) If there was no complete consensus on the selection or classification of an article, we discussed the article and its classification to find consensus.

To identify articles for inclusion, we went through the entire output of the journals and volumes in question. We first excluded papers based on the title as clearly not relevant to our topic. All other articles we read the abstract of, and based on this we could exclude some further articles. For the remaining articles, we skimmed through the paper itself to evaluate whether it fit our criteria: being relevant for climate policy; and being relevant for at least one of stranded assets, distributional questions, and political economy. We then classified each article selected. A single article may contribute to multiple categories.

Stranded assets. This category includes articles covering stranded assets either explicitly, e.g. papers on buying up fossil deposits, or implicitly, e.g. papers discussing how labor movements between sectors are hindered by a mismatch in human capital before and after the green transition.

Theory/Empirics. This category is used to select the main field in which the paper makes a contribution. For theoretical contributions, we included both analytical theory and numerical work primarily focused on demonstrating theoretical mechanisms, including very stylised calibrations. Empirical studies include policy evaluation pieces, experimental work, climate damage estimations, and detailed and calibrated simulation models intended to yield quantitatively meaningful results, e.g. computational general equilibrium, input-output, and trade models.

Welfare evaluation. This category indicates whether a paper evaluates welfare (e.g. cost minimisation, the goal of finding efficient policies) or direct impacts closely related to welfare (mortality, unemployment). Papers that do not take a normative stance or do not conduct a normative evaluation of any sort are classified to have ”no welfare” evaluation. Papers with a welfare evaluation are classified to perform an ”aggregate welfare” evaluation if they only focus on the aggregate level, e.g. by using an aggregative social welfare function, or by focusing on the sum of the impacts (on e.g. costs of achieving a given emission target).

Distribution. This category is selected whenever papers consider distributional consequences of climate policies or damages from climate impacts. The category is further split into subcategories. ”Income/wealth” includes papers assessing economic inequality, e.g. by focusing on income or wealth deciles or quintiles. ”Spatial” distribution covers papers studying spatial inequality, e.g. between rural and urban regions. ”Intergenerational” considerations concern distributional impacts across age groups or generations. Papers in the subcategory ”sectoral” assess distributional effects between industry sectors. ”Production factor” includes papers evaluating differentiated effects between holders of e.g. labor and capital. The subcategory ”energy sectors” covers papers on the distributional consequences on energy assets, e.g. fossil or renewable assets. The ”international” subcategory includes papers assessing internationally heterogeneous distribution. If there is distribution along some other dimension, papers are categorized as ”other” (many of these consider a consumer/producer surplus differentiation).

Compensation. This category covers papers discussing compensation including e.g. papers looking at profit-neutral allocations of emission permits in a cap-and-trade scheme, and intergenerational redistribution of climate action.

Political economy. Here, papers are categorized if they discuss the political implications of climate policy. Some papers use a second-best approach, e.g. ruling out carbon taxes based on political considerations. Others use explicit political economy models, or study e.g. the electoral politics of environmental issues directly. Papers are also included in the “political economy” category if they discuss the political implications of findings without conducting explicit modeling. Finally, papers discussing institutions were also included.

Labor. This category is meant to select papers considering the employment or wage impacts of climate policies.

2.C References of classified papers

This appendix appears in the online publication only.

3

Politics, profits and climate policies: How much is at stake for fossil fuel producers?

Abstract

Stabilizing greenhouse gas concentrations requires that a substantial share of fossil fuel reserves is not combusted. In countries and industries producing oil, coal, or gas, substantial profits are at stake, which are estimated to be up to US$ 185 trillion. In this Perspective, we review the existing estimates in the literature with respect to the approaches used and the underlying assumptions made, and we argue that these figures are misleading without contextualization. Current studies assess those climate policies that target the demand-side of fossil fuels and lead to particularly large estimates. Sound estimates of foregone profits due to climate policies are yet of utmost importance: if estimated losses are large, strong resistance to ambitious climate policies can be expected. For instance, Saudi Arabia has already sought financial compensation for profits foregone due to climate policies. To explain the broad range of numbers and to judge the validity of compensation claims, we present a theory-grounded way for appropriately conceptualizing foregone fossil fuel profits. If previous quantitative estimates are adjusted to account for policy options that target the supply-side and for resulting fuel price changes, they justify much smaller or even negative compensation.

Reference: Eisenack, K., Hagen, A., Mendelevitch, R. & Vogt, A. (2021). Politics, profits and climate policies: How much is at stake for fossil fuel producers? *Energy Research & Social Science 77*, 102092.

3.1 INTRODUCTION

CARBON DIOXIDE EMISSIONS can only be reduced if a substantial amount of fossil fuel reserves remains unextracted (Meinshausen et al., 2009). McGlade & Ekins (2015) determine the optimal cost-efficient distribution of unextracted reserves to reach the 2 °C target. According to them, this amount globally involves 80% of coal reserves, half of the gas reserves and a third of the oil reserves. On the one hand, to facilitate this reduction in fuel extraction, climate policies are needed. On the other hand, climate policies alter the distribution of profits, e.g. for fossil fuel extraction industries. Existing studies estimate profits at stake up to US$185 trillion (Linquiti & Cogswell, 2016).

The political relevance of such profits at stake must be carefully considered. Strong political resistance can be expected if well-organized groups suffer large losses from redistribution due to a policy (Olson, 1965, Persson, 1998, Meng & Rode, 2019). Such groups are incentivized to engage in rent-seeking activities to avoid climate policies and are able to do so. Rent-seeking, ultimately motivated by obtaining profits in the case of private sector organizations, and sometimes also governments, can be expected to be particularly strong if climate policies result in high profits at stake. This, in turn, hampers policy implementation (see Lamb & Minx (2020) for a literature survey on policy implementation constraints). Given that fossil fuels are a foundational pillar for many national economies, including non-petrostates, resistance to climate policies is an increasingly relevant geopolitical issue. Therefore, it is crucial to know how much is at stake for fossil fuel producers when fuels are left unextracted.

To achieve progress in climate policies, we argue in this Perspective that it is crucial for research to devote much more attention to study profits at stake in a precise way. However, we demonstrate in the following that currently published figures which estimate profits at stake due to climate policies are misleading. The existing studies cover a very broad range of figures resulting from a diversity of approaches. We argue that the estimated profits at stake are inflated for up to three reasons, depending on the approach: First, some studies disregard cost savings resulting from leaving reserves [1] unextracted. Second, some approaches evaluate

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[1] For this Perspective, we focus on a broad definition of reserves and do not differentiate between developed and undeveloped reserves, i.e. we are ambiguous whether an initial investment or a final investment decision is made or not (see Trout et al. (2022) for more details on the

future reserves at current prices, which are potentially too high. Finally, all studies assume climate policies targeting the demand side of fossil fuels, which leads to particularly large profits at stake. Yet, sound estimates of foregone profits can help prevent unnecessary pushback: Exaggerated numbers easily become political instruments for fossil fuel producers hampering effective communication. For both undeveloped and developed reserves, foregone profits may lay claim to compensation for producers, as in the cases of Ecuador's Yasuni-IIT initiative (Sovacool & Scarpaci, 2016) or Saudi Arabia's oil producers (Helman, 2015). Fossil fuel producers might also demand compensation to sustain employment in fossil fuel dependent regions (Vogt-Schilb & Hallegatte, 2017). Yet, in many cases profits are a precondition for employment. Claiming compensation raises plenty of concerns: First, producers might act strategically and engage in lobbying efforts to maximize their compensation. Second, governments might lack the capacity to compensate producers if foregone profits are of large value. This is particularly cumbersome considering the time dimension of compensations vis-à-vis climate change: Fossil fuel producers demand compensation at the point of policy implementation. The society's cost savings from avoided climate damages, however, will only be realized in the future. Therefore, it may be impossible for governments to cover such compensation. Finally, one could argue from a normative perspective, that fossil reserve owners should be targeted with litigation instead of compensation, as they are responsible for significant climate damages (Van der Ploeg & Rezai, 2020). Therefore, the value of unextracted reserves and the profits at stake are key to political feasibility, implementation, and acceptance of climate policies.

In this Perspective, we show, that the profits at stake have only been analyzed to a limited extend. We highlight this literature gap and stress the need for further estimates, covering a different set of policy options and properly accounting for price and cost changes. For expository reasons, we mostly refer to fossil fuels in general, and acknowledge differences between oil, coal and gas further below. Although climate policies put profits at stake along the complete value chain, here we concentrate on the estimates of foregone profits in fossil fuel extraction. We argue that such estimates could justify compensation on a much smaller scale (if at all), thereby supporting the implementation of efficient climate policies.

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relevance of developed reserves).

3.2 How much is at stake?

Current estimates of profits at stake vary significantly, as they are computed using different approaches and focus only on a subset of possible climate policies, as summarized in this section and in Table 3.1. Channell et al. (2015) compute the ”total value of stranded assets” by multiplying the quantities of fossil fuels declared ”unburnable” by McGlade & Ekins (2015) with their respective current prices.[2] They obtain a value surpassing US$100 trillion. Other authors choose a more sophisticated approach, but still focus on revenues instead of profits. Bauer et al. (2015), for instance, compare nine integrated assessment models with different parameterizations and modeling approaches to determine revenues lost if less fuel is extracted. These models consider how fuel prices change according to different carbon budgets for the 21^{st} century, and come up with smaller numbers (US$5 trillion to US$67 trillion). The models implicitly assume that the carbon budget is achieved by introducing a shadow price of carbon which is not collected by fossil fuel producers.

Similarly, Linquiti & Cogswell (2016) base their estimates on foregone revenue and value unextracted reserves accordingly. They also consider future fuel prices which are assumed to decline if climate policy substantially limits fossil fuel demand. The computations are based on figures reported in the World Energy Outlook (WEO) 2015 from the International Energy Agency (IEA) (IEA, 2015). More specifically, they use the ”Current Policy Scenario”, the ”2 °C Scenario,” and their own extrapolations running until 2115. The same approach as Linquiti & Cogswell (2016) is underlying the much smaller estimate of US$28.3 trillion in fossil fuel revenues at risk by Lewis (2014). He compares the ”New Policies Scenario” with the ”2 °C Scenario,” taken from the WEO 2013 (IEA, 2013), and chooses a shorter analysis timeframe (until 2035).

In contrast to these methodologies, Nelson et al. (2014) and Bauer et al. (2016) go beyond determining lost revenues. They also consider the cost savings accrued through extracting less, which are aggregated with the effect of changing

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[2] Stranded assets are defined as assets that become devaluated prematurely, revaluated downwards or turned into a liability (Caldecott et al., 2013). This is closely connected to the concept of unburnable carbon (Carbon Tracker Initiative, 2013). If the amount of stranded fossil fuel assets is large, this could lead to a destabilization of the financial system (Carney, 2015), i.e. the burst of the resulting ”carbon bubble” (Carbon Tracker Initiative, 2011). The fossil fuel divestment movement acknowledges this risk and motivates investors to take action (Ayling & Gunningham, 2017).

Table 3.1: Summary of different values reported in the literature with attribution to respective areas in Figure 3.1 and respective policy interpretation.

	Reported value	Areas in Fig. 3.1	Policy interpretation
Channell et al. (2015)	Just over US$100 trillion (2015$)	b	No policy assumptions
Bauer et al. (2015)	US$5 to 67 trillion (2011$)	$b + c$	Demand-side policy
Linquiti & Cogswell (2016)	US$185 trillion (2014$)	$b + c$	Demand-side policy
Lewis (2014)	US$28.3 trillion (2012$)	$b + c$	Demand-side policy
Nelson et al. (2014)	US$24.6 trillion (2013$)	$a + c$	Demand-side policy; supply-side also discussed, but discarded
Bauer et al. (2016)	US$9 to 12 trillion (2005$)	$a + c$	Demand-side policy
IEA (2020)	US$6 trillion (2019$), oil and gas only	$a + c$	Demand-side policy

fuel prices, thus estimating lost profits. While Nelson et al. (2014), similar to Linquiti & Cogswell (2016), compare the ”New Policies Scenario” with the ”2 °C Scenario” from the WEO 2013 (IEA, 2013), Bauer et al. (2016) endogenously compute fossil fuel rents (for emissions consistent with a 2 °C) with an integrated assessment model. Also using an integrated approach and thus incorporating endogenous price and cost adjustments, IEA (2020) assesses reductions in present value of future oil and gas production due to the economic downturn associated with the COVID-19 crisis of about US$6 trillion. Another US$6 trillion reduction is calculated for the case of a shift from the ”STEPS” scenario (assuming the implementation of currently announced policies) to the ”SDS” scenario (assuming an emissions trajectory roughly in line with a 2 °C target).[3] The differences between these various methods are significant: The profits at stake estimated range from US$6 trillion (IEA, 2020) to US$185 trillion (Linquiti & Cogswell, 2016).

3.3 POLICY-EFFECTS: PRICES AND QUANTITIES

So far, we see that methods for estimating foregone fossil fuel profits result in very different figures. The reasons for the differences become transparent when comparing the stylized Figure 3.1a with Figure 3.1b. While these kinds of figures

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[3] Calculated from changes in reported values of estimated present value of future oil and national gas production (2019 to 2040) in IEA (2020), Figure 1.7.

are standard in economic analysis, they are a quite helpful tool for our discussion. In the "business-as-usual" (BAU) case without a climate policy in place (Figure 3.1a), the demand curve for fossil fuel intersects the supply curve at the equilibrium fuel price determining the quantity of extracted reserves.[4] The total profits obtained from extracting the reserves, i.e. the producer surplus, are depicted in the diagram. Figure 3.1b assumes that a climate policy is introduced, i.e. a carbon price on the demand-side. Then, fossil fuel consumers must pay an additional price per unit of fuel, e.g. through a carbon tax collected by a government. Thus, consumers face a higher gross price ($p_{pol,gross}$), while fossil fuel producers face the policy price (p_{pol}), which is lower than the BAU price (p_{BAU}). Consequently, the policy achieves less extraction.

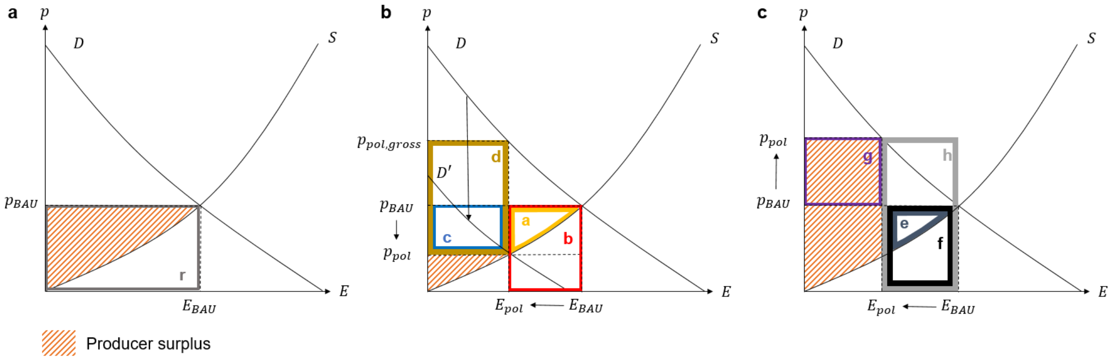

Figure 3.1: Partial equilibrium diagrams. Panel (a): Without a climate policy. Fuel demand D and supply S determine the fuel quantity E_{BAU}, which is sold at the market price p_{BAU}. Total revenues are represented by the rectangular area r. It is conventional economic theory that the area under the supply curve represents extraction costs. The red hatched areas thus represent producer surplus (revenues net of costs). Panel (b): For a demand-side carbon price, the demand curve shifts downwards to D', the quantity E_{pol} is extracted and producers obtain the price p_{pol}, while consumers need to pay $p_{pol,gross}$. The difference is the carbon price. The areas a to d represent different gains and losses from the climate policy compared to the BAU (see explanation in the text). Panel (c): Implications of a supply-side policy as discussed in the text. Areas e to h again represent different gains and losses.

One method of determining profits at stake is to value unextracted reserves at

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[4] Here we consider a long-term supply cost curve which aggregates all cost categories (development costs, investment costs, variable costs etc.), sorts them from lowest to highest, and reports them on a per unit of output basis. The curve thus includes both developed and undeveloped reserves (see Footnote 1, for further details), and the demand curve includes correctly anticipated changes in demand. Therefore, the economic argument holds for both a narrow and a broad definition of reserves.

the BAU fuel price (foregone profits are then represented by area *b* in Figure 3.1b). This method disregards that producers can save costs from extracting less. Thus, foregone profits are overestimated. Furthermore, since the policy changes the fuel price to p_{pol}, an evaluation at the BAU price can be criticized. Accounting for these price changes of the policy adds area *c* to *b*: there are further profits at stake if the remaining reserves can only be sold at a lower price. This valuation further increases calculated losses compared to valuation at the BAU price. Requested compensations based on this method will likely be much larger. However, savings from decreased extraction costs are disregarded again. Therefore, a valuation that fairly accounts for all producers' gains and losses due to a climate policy should consider both, the policy price change and the extraction costs reduction. Then, the foregone profits from unextracted reserves are represented by area *a*, and the foregone profits for reserves that are still extracted under the policy, yet at a lower price, are represented by area *c*. In sum, the total foregone profits are the combined areas of *a* and *c*. However, there are even more ways to determine foregone profits, because they also depend on the particular institutional arrangements in place.

3.4 TARGETING THE SUPPLY SIDE

The aforementioned methods of valuing forgone profits all assume that climate policies target the demand for fossil fuels, which is in line with existing policies (Erickson et al., 2018). However, policies that target the production (supply) of fossil fuels might also lead to sufficient emission reductions (Sinn, 2008, Harstad, 2012, Asheim et al., 2019). It is also important to appropriately estimate foregone fossil fuel profits for supply-side policies.

While previous quantitative studies assess demand-side policies, supply-side policies have become a focus in the theoretical economic literature (Bohm, 1993, Hoel, 1994, Asheim, 2013, Fæhn et al., 2017, Richter et al., 2018, Hagem & Storrøsten, 2019, Eichner et al., 2021). Such policies target at limiting fossil fuel supply and include, e.g. extraction quota, extraction moratoria, or ”deposit markets” (discussed below). Political scientists and sociologists found that supply-side policies have a high potential of citizens' support and public mobilization (Erickson et al., 2018, McAdam, 2017, Green & Denniss, 2018, Piggot, 2018). They can be monitored at lower costs, e.g. because fossil fuel extraction is under direct control of easily identifiable actors (Collier & Venables, 2014, Lazarus & van Asselt, 2018). Although not very common in climate politics yet, supply-side instruments are well established in other policy contexts where governments limit supply of harmful substances such as asbestos (Kameda et al., 2014) or Chlorofluorocarbons (Green & Denniss, 2018, Haas, 1992).

Economic theory shows that the total costs of globally optimal demand- and supply-side policies are identical. However, total forgone profits for producers differ between the two policy options. Considering supply-side policies, foregone profits can be discussed using Figure 3.1c. Since the policy introduces fuel scarcity, the policy price (faced by producers) rises. First, the value of reserves that remain unextracted at the BAU fuel prices would equate to area f in Figure 3.1c. However, since the fuel price rises to a larger policy price, one could value the unextracted reserves at the policy price yielding the even larger area h. But why should producers be compensated at a higher price than they expected before the policy implementation? Second, areas f or h again disregard extraction costs reductions. Total foregone profits, however, are the difference between expected profits without climate policies and realized profits with climate policies implemented. Since climate policies reduce the amount of fuels extracted leading to price changes, a sound estimate of total forgone profits includes both, extraction cost reductions and price effects of the policy. This is possible with areas e and g. Area e expresses the loss due to selling less reserves at the BAU price, net of saved extraction costs. Area g expresses the gain from selling the remaining reserves, which are still extracted under the policy, at the higher policy price. If area g is larger than area e, producers obtain an additional profit from supply-side policies. Consequently, the implementation of supply-side climate policies can technically turn fossil fuel producers into winners.

One prominent proposal of a supply-side climate policy are ”deposit markets” (Harstad, 2012, Eichner & Pethig, 2017b): Deposits are in-situ fossil fuels reserves which are not extracted yet. In deposit markets, actors trade the rights to extract fossil fuel deposits. For instance, a country willing to implement climate policies could purchase fossil fuel deposits from a fuel producing country. The deposits purchased are left unextracted resulting in a fuel supply cut. Thus, world market fuel prices increase and both, demand and emissions decrease. The positive effect of this policy for fuel producing countries is twofold: First, they receive a payment or compensation for the unextracted deposits from the deposit market, which depends on the price and the amount of deposits sold. Second, as the fuel price increases, producers generate higher profits from the remaining reserves which can still be extracted. If the second effect is strong enough, i.e. area g is greater than area e, fossil fuel producers can technically gain from this policy, even absent compensation payments from the deposit market. Although deposit markets have, to date, only been analyzed theoretically, research results highlight their potential for efficient emission reductions (Harstad, 2012, Eichner & Pethig, 2017a, von Dulong et al., 2023b).

3.5 Policies, rents, and compensation

Ultimately, whether producers lose or gain depends on the policy design. With a demand-side policy, the maximum gain is area d, coined the ”climate rent” (Eisenack et al., 2012, Schwerhoff et al., 2020). For instance, if a carbon tax is implemented, the climate rent is captured by the government as tax revenues. Then, total forgone profits are represented by the combined areas of a and c. However, producers might obtain parts of the climate rent, e.g. via redistribution of tax revenues. Then, total forgone profits are less than area a. Existing estimates of the climate rent show that this is realistic. For a demand-side policy, Bauer et al. (2016) determine that producer profits are reduced by US$9 - 12 trillion, i.e. areas $a + c$. At the same time, tax revenues from carbon pricing (the carbon rent) range from US$21 - 32 trillion (area d). Consequently, tax revenues can in principle be redistributed to producers such that they gain under this policy. Without redistribution, the same outcome could be realized using a supply-side policy: Looking at Figures 3.1b and c, we see that area $d-(a+c)$ is equivalent to area $(g-e)$. Thus, if the same policy targets are implemented with a supply-side policy, fossil fuels producers can gain. Eisenack et al. (2012) also find that area d can be greater than area a. Equivalently, area g could be greater than area e, meaning that profits can even rise due to climate policies. Therefore, with supply-side policies, the range of estimated fossil fuel profits at stake extends at the lower end.

Sound estimates of these foregone profits are challenging, regardless of the policy design: Since extraction and policies develop over time, a simple, static partial equilibrium view as outlined here (Figure 3.1) is not sufficient. General equilibrium effects, time horizons and discount rates matter. So does the spatial distribution and disaggregation of foregone profits. Our argument focuses on foregone profits in upstream operations, i.e. the extraction of fossil fuels reserves. Substantial foregone profits are also at stake in the mid- and downstream, e.g. associated with port infrastructure and combustion plants (cf. Mercure et al., 2018). Considering them more carefully requires further research. Moreover, changes in fuel prices and quantities due to climate policies, and thus rent-seeking motives and economic implications are different for and interdependent between oil, coal and gas markets. A more detailed analysis of the foregone profits in the oil market will need to account for strategic behavior of oil exporting countries. If extraction quantities decline, this could result in a higher concentration of production. This might help exporters to increase the cohesiveness of quota agreements to raise prices, or on the contrary, lead to price wars resulting in lower prices (Van de Graaf & Verbruggen, 2015). The strength of extraction oligopolies also affects the dynamics of a "race to burn the last ton of carbon", which is fiercer under stronger competition in the market (van der Ploeg, 2020).

3.6 CONCLUSION

To summarize this Perspective, decisions on climate policies and the assessment of their political prospects for implementation require a thorough evaluation of foregone fossil fuel profits. High foregone profits may raise producers' resistance hampering the implementation of climate policies. Besides lobbying against policies, producers may raise compensation claims. We do not discuss the legitimacy of compensation, but the relevance of such claims certainly depends on the size of foregone profits. So far, only numbers for foregone profits at the high end of the spectrum have been estimated, exclusively covering demand-side policies and partially disregarding endogenous price changes and reduced extraction costs. Economic theory suggests that other policies, especially supply-side policies, are more favorable for fossil fuel producers, who might even gain without compensation. We argue that it has become highly important that future research complements the existing high estimates of foregone profits from demand-side policies with theoretically-grounded quantifications for supply-side polices, which will be much lower as explained above. Such research will strongly help decision-makers and can avoid unjustified high compensations for fossil fuel producers.

4

Buy coal and gas? Interfuel carbon leakage on deposit markets with market power

Abstract

Unilateral climate policies can lead to carbon leakage between countries. Deposit markets, where participants trade the right to keep fossil fuels unexploited in-situ, are a promising policy proposal to prevent leakage. For a single fossil fuel, deposit markets can only restore efficiency if there is no market power on the deposit market. With multiple fuels, however, multiple (interdependent) deposit markets could give rise to additional market power. We thus study deposit markets with market power and multiple fuels, and focus on comparing second-best policies. In contrast to a setting with a single fuel, more complex carbon leakage channels between both, countries and fuels, arise. Such effects can even hinder deposit markets covering all fuels from being implemented. At the same time, we identify conditions where deposit markets induce countries without emission reduction incentives to supply a cleaner fuel mix. Regarding the political economy, deposit markets covering all fuels can improve each country's welfare compared to those covering only one fuel. Deposit markets which cover only a single fuel or multiple fuels rank differently in terms of consumer and producer rents. These welfare rankings can have highly relevant implications for policymaking. Even with market power, deposit markets covering multiple fuels can Pareto-dominate a situation with unilateral, domestic policies.

Keywords: Fossil fuel, Climate policy, Deposit market, Carbon leakage, Supply-side

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4.1 Introduction

Reaching the 2°C goal of the Paris Agreement requires the implementation of effective climate policies. Yet, the last decades have shown that first-best policies have not been feasible. One reason for this is the challenge of carbon leakage: If a country unilaterally imposes a policy to reduce the demand of a fossil fuel, in short ”fuel”, emissions in countries with laxer policies increase. With multiple fuel types, this problem amplifies: Capping the extraction of coal, for instance, might increase gas production. To prevent carbon leakage, supply-side policies have been suggested, in particular deposit markets (Harstad, 2012). On deposit markets, participants trade the right to extract in-situ fuel reserves (called ”deposits”) and keep those fuels in the ground. The Yasuní-ITT Initiative, where Ecuador's president demanded international compensation to leave crude oil unexploited, is a prominent example closely related to the idea of deposit markets (Sovacool & Scarpaci, 2016). It is plausible to assume that deposit markets might suffer from market failure, i.e. market power exertion, when considering the mere size of fuel resource rents. Then, Eichner & Pethig (2017b) show that, for a single fuel, efficiency cannot be restored. This becomes more important if there are several fuels addressed by multiple deposit markets: At least two additional problems may result. First, exerting market power on multiple deposit markets simultaneously possibly raises the inefficiencies of market failure and further compromises environmental effectiveness. Second, distortions at the deposit market for one fuel might impede the implementation of the deposit market for the other fuel. In such cases, some countries might prefer unilateral climate policies over supplying or demanding deposits at distorted markets, thereby rendering them politically obsolete.

In this paper we investigate the effects which might cause deposit markets to malfunction in a setting with multiple fuels, and identify conditions, where this is not the case. More precisely, we study deposit markets covering multiple fuels in the presence of market power. We employ an analytical model, where two (groups of) countries produce and consume two fuels. The fuels are substitutes in consumption and they differ in emission intensity and extraction costs. Some countries are affected by climate damages, while others are not or neglect climate damages. We assume that fuel consumers are price-takers. Furthermore, only countries adversely affected by climate damages buy deposits, and deposits are purchased for preservation only.

We show how deposit markets suffer from what we call ”interfuel” carbon leakage effects between both, countries and fuels. We identify three distinct interfuel effects, which affect the deposit and fuel markets. The implications of interfuel effects are compared to a cap policy scenario, where some countries unilaterally limit domestic fuel supply. We find that interfuel effects can indeed render deposit markets obsolete as a policy option. Through two of the interfuel effects, it is possible that the existence of one deposit market crowds-out another. However, we also find conditions where deposit markets cover both fuels. Then – even in the presence of multiple distortions – all countries gain from implementing both deposit markets, compared with a case with only one or no deposit market. Disaggregating the welfare of the country buying deposits, consumers and producers differ in their preferences over these policy options. Moreover, we show that deposit markets can induce countries selling deposits to produce a cleaner fuel mix, regardless of their incentives for emission reductions.

We contribute to the economic literature on climate policies under carbon leakage. Climate policies can target the supply or the demand of fuels (or both, e.g. Hoel, 1994, Fæhn et al., 2017, Hagem & Storrøsten, 2019). If a country unilaterally introduces a demand-side policy, this can lead to carbon leakage between countries (e.g. Hoel, 1991, Felder & Rutherford, 1993, Böhringer et al., 2014). Furthermore, if climate policies cover multiple fuels and the policies’ stringency varies across fuels, carbon leakage can also occur between fuels. Yet, the theoretical literature on multiple fuels mostly focuses on demand-side policies, or on a mix of the demand and supply side (e.g. Golombek et al., 1995, Michielsen, 2014, Fischer & Salant, 2017, Daubanes et al., 2021). Instead, we focus on pure supply-side policies when carbon leakage between multiple fuels is possible, and give specific consideration to distortions due to market power on deposit markets. Asheim (2013) provides a distributional argument in favor of supply-side policies and Asheim et al. (2019) propose a complementary supply-side treaty in conjunction with the Paris Agreement. Further, Eisenack et al. (2021) highlight the political feasibility and policy acceptance of supply-side policies compared with policies targeting the demand of fuels. To the best of our knowledge, Bohm (1993) was the first to suggest deposit markets, where countries suffering from emissions could purchase or lease deposits from other countries. Harstad (2012) shows that countries adversely affected by climate damage can set their demand and supply of fuels strategically and buy deposits, thereby implementing the first-best regardless of their market power on the fuel market. These countries buy deposits which would have otherwise been exploited by the countries selling deposits and preserve or exploit them to serve the fuel market. Eichner & Pethig (2017a) adopt the framework of Harstad (2012), and show that the first-best can also be implemented if deposits are purchased for preservation only. Eichner & Pethig (2017b) find that the outcome is inefficient, if the countries purchasing fuels and/or deposits can act strategically. Then, deposit markets do not fully prevent carbon leakage between countries. Finally, Eichner et al. (2021) extend the framework to a two-period model with climate damages in both periods and where deposits can be bought or leased. This literature considers only the case of a single fuel,[1] so that strategic action on one deposit market cannot spill-over to another. Our results show, however, that such spill-overs between deposit markets for different fuels can influence whether deposit markets are a viable or obsolete policy option. Studying a setting with multiple fuels further reveals how deposit markets affect the fuel mix of countries without emission reduction targets.

The remainder of the paper is structured as follows. We present the model in section 4.2 and we analyze the general properties of the policy scenarios in section 4.3. In section 4.4, we turn to a detailed analysis of the interfuel effects before we conclude in section 4.5.

4.2 BASIC MODEL ASSUMPTIONS

We model a world economy where countries i extract and consume two different fuels $f \in \{K, G\}$, where K might represent coal and G gas. Country i's consumption of fuel f is denoted $y^{i,f}$ and the benefit derived from this consumption is $B^i(y^{i,K}, y^{i,G})$, with decreasing marginal benefits $\forall i, f : B^i_f > 0$ and $B^i_{K,G} \leq B^i_{f,f} < 0$, where subscripts denote partial derivatives to the respective argument, so that $B^i_f = \frac{dB^i}{dy^{i,f}}$ and $B^i_{K,G} = \frac{d^2B^i}{dy^{i,K}dy^{i,G}}$, for instance. Country i's extraction of fuel f is denoted by $x^{i,f}$, which imposes costs $C^{i,f}(x^{i,f})$, with $\forall i, f : C^{i,f}_f > 0$ and $C^{i,f}_{f,f} > 0$. We assume that some countries suffer from carbon emissions, while other countries are not affected by or neglect climate damage (cf. Harstad, 2012, Eichner & Pethig, 2017a). We assume carbon emissions generated from fuel combustion to

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[1] With the exception of Harstad (2012), who covers a very specific case in section IV.C.

be equivalent to those from fuel extraction. The adversely affected countries aim at reducing climate damage. We denote the two (groups of) countries by i=M, N, where M might be considered as a climate coalition that acts as one player implementing policies to reduce emissions and N represents all other countries. To simplify terminology, we refer to the two (groups of) countries *pars pro toto* as country M and country N subsequently.

Both countries' producers and consumers act as price-takers on the world markets for the two fuels. The equilibrium price for fuel f is denoted by p^f. Country M suffers from the aggregate emissions from both countries and both fuels, which differ in their emission intensities η^f. The climate damage function is written as $H(\sum_i \sum_f \eta^f x^{i,f})$ and we assume non-decreasing marginal climate damage $H' > 0$, $H'' \geq 0$. The welfare of country i is denoted by U^i and we have

$$\begin{aligned} U^M =& B^M(y^{M,K}, y^{M,G}) - C^{M,K}(x^{M,K}) - C^{M,G}(x^{M,G}) \\ & - p^K \cdot (y^{M,K} - x^{M,K}) - p^G \cdot (y^{M,G} - x^{M,G}) - H(\sum_i \sum_f \eta^f x^{i,f}) \end{aligned} \tag{4.1}$$

and

$$\begin{aligned} U^N =& B^N(y^{N,K}, y^{N,G}) - C^{N,K}(x^{N,K}) - C^{N,G}(x^{N,G}) \\ & - p^K \cdot (y^{N,K} - x^{N,K}) - p^G \cdot (y^{N,G} - x^{N,G}). \end{aligned} \tag{4.2}$$

4.3 POLICY ANALYSIS

In the following, we first introduce two benchmarks, namely the social planner case and the case of a domestic cap on fuel production by country M. We then move on to the policy scenario with deposit markets. It is important to note that this model assumes perfect competition on both fuel markets. In contrast, we admit strategic action on the markets for fuel deposits, as will be introduced below. The intuition is that countries' governments have a say in the deposit market design, but leave trade on the fuel markets to many competitive firms. We analyze interfuel effects for the deposit market scenario and compare the results with those of the benchmarks. We conduct a more detailed analysis of interfuel effects in a parametric version of the model, which follows in section 4.4.

4.3.1 BENCHMARKS: SOCIAL PLANNER AND DOMESTIC CAP

The social planner chooses the globally first-best solution and thus maximizes aggregate welfare with respect to demand and supply, i.e. $\forall i, f : y^{i,f}$, $x^{i,f}$, while balancing the supply and demand of both fuels. From the Lagrangian, the first-order conditions yield

$$\forall f : \lambda^f = B_f^M = B_f^N = C_f^{M,f} + \eta^f H' = C_f^{N,f} + \eta^f H', \tag{4.3}$$

where λ^f are the shadow prices of the fuels. We see that in the efficient outcome externalities from emissions are fully internalized. Now, assume that country M aims at reducing climate damage. While there are no climate policies in country N, country M caps its domestic production of fuels by choosing a cap on each fuel individually. To obtain more clarity, we thus only compare supply-side policies in this paper, in contrast to other studies where demand-side caps are present at the same time (Hoel, 1994, Eichner & Pethig, 2017b). The equilibrium outcome is then characterized by the following conditions:

$$\forall f : p^f = B_f^M = B_f^N = C_f^{N,f} = C_f^{M,f} + \eta^f H'. \tag{4.4}$$

Comparing the first-order conditions of the benchmark scenarios, we confirm that a unilateral production cap in country M does not lead to an efficient outcome because country N does not account for the climate damage in country M.

4.3.2 DEPOSIT MARKETS

We now consider that, to mitigate climate damage, country M can trade deposits with country N. A deposit is defined as a (yet) unextracted amount of fuel, which is particularly characterized by its extraction costs. On a deposit market, countries trade the right to exploit deposits. For instance, country M could buy the right to exploit some of country N's deposits and leave those fuels unexploited, thereby reducing country N's fuel extraction.

MARKET DESIGN

This subsection describes the deposit market design. For expository reasons, we state some details that might be known to readers that are familiar with deposit markets. The main difficulty in extending the market design of Eichner & Pethig

(2017a) for multiple fuels is to precisely account for the new effects which stem from the possible interdependence of their demand. We study the case where country M purchases country N's deposits to preserve them, i.e. purchased deposits will not be extracted. Country N's deposits are ordered by increasing extraction costs, so that extracting a marginal unit of fuel of the $x^{N,f}$th deposit comes at the cost $C_f^{N,f}(x^{N,f})$. Country N's endowment with deposits is represented by an interval with increasing extraction costs. The interval of deposits that country M would purchase from country N lies within this endowment interval and is denoted by $[\underline{\xi}^f, \bar{\xi}^f]$.

We assume the following sequence: First, country M chooses its deposit demand $z^{M,f}$. Second, country N chooses its deposit supply $z^{N,f}$, after which the deposit markets clear at the deposit prices $p^{z,f}$. Third, country M caps domestic fuel supply and the fuel markets clear. We thus assume that country M acts like a monopsonist on the deposit markets. Since this paper focuses on the effects of market failure on the deposit markets, we abstain from considering additional strategic action on the fuel markets and consequently assume that both countries are price-takers on these markets. Further, in contrast to Eichner & Pethig (2019), who study the pure case of a deposit policy, we analyze a mixed policy scenario of a cap policy and a deposit policy.

We proceed backwards, starting with the third stage. By adding the balance from deposit trade, the welfare functions become

$$\begin{aligned} U^M = {} & B^M(y^{M,K}, y^{M,G}) - C^{M,K}(x^{M,K}) - C^{M,G}(x^{M,G}) \\ & - p^K \cdot (y^{M,K} - x^{M,K}) - p^G \cdot (y^{M,G} - x^{M,G}) \\ & - H(\sum_i \sum_f \eta^f x^{i,f}) - p^{z,K} z^{M,K} - p^{z,G} z^{M,G} \end{aligned} \tag{4.5}$$

and

$$\begin{aligned} U^N = {} & B^N(y^{N,K}, y^{N,G}) - K^{N,K}(x^{N,K}, \underline{\xi}^K, \bar{\xi}^K) - K^{N,G}(x^{N,G}, \underline{\xi}^G, \bar{\xi}^G) \\ & - p^K \cdot (y^{N,K} - x^{N,K}) - p^G \cdot (y^{N,G} - x^{N,G}) \\ & + p^{z,K} z^{N,K} + p^{z,G} z^{N,G}, \end{aligned} \tag{4.6}$$

where $K^{N,f}(x^{N,f}, \underline{\xi}^f, \bar{\xi}^f)$ is country N's cost function once the deposit trade has occurred. Country M caps domestic fuel supply and the representative consumers in both countries choose fuel demand. The outcome in this stage is characterized by the conditions:

$$\forall f : p^f = B_f^N = B_f^M = C_f^{M,f} + \eta^f H'. \tag{4.7}$$

In choosing its fuel supply, country M considers the respective fuel price and climate damage, so that its supply functions are given by the inverse cost functions $C_f^{M,f-1}(p^f - \eta^f H')$ according to

$$\forall f : x^{M,f} = X^{M,f}(p^f) := C_f^{M,f-1}(p^f - \eta^f H'). \tag{4.8}$$

Country N's cost functions depend on the deposit policies (from the earlier stage) and are further specified below. The supply function of each fuel only depends on the marginal climate damage and the price of this respective fuel. Matters are more complicated on the demand side, since we explicitly admit $\forall i : B_{K,G}^i \neq 0$. Demand for fuels K and G in both countries requires to solve the equation system

$$\forall i, f : B_f^i(y^{i,K}, y^{i,G}) = p^f \tag{4.9}$$

for $(y^{i,K}, y^{i,G})$. This solution yields the demand functions for both fuels

$$\forall i, f : y^{i,f} = Y^{i,f}(p^K, p^G). \tag{4.10}$$

The representative producer in country N has sold deposits in the second stage in the interval $[\underline{\xi}^f, \bar{\xi}^f]$, where

$$\forall f : \bar{\xi}^f = \bar{\xi}^f(p^f) := C_f^{N,f-1}(p^f) \,\text{and}\, \underline{\xi}^f = \underline{\xi}^f(p^{z,f}, p^f) := C_f^{N,f-1}(p^f - p^{z,f}). \tag{4.11}$$

The marginal cost functions change due to the deposit trade to

$$\forall f : K_f^{N,f}(x^{N,f}, \underline{\xi}^f, \bar{\xi}^f) := \begin{cases} C_f^{N,f}(x^{N,f}) & \text{for}\, x^{N,f} \leq \underline{\xi}^f, \\ C_f^{N,f}(x^{N,f} + \bar{\xi}^f - \underline{\xi}^f) & \text{for}\, x^{N,f} \geq \underline{\xi}^f. \end{cases} \tag{4.12}$$

Country N's supply functions are given by the inverse cost functions (as for M). Consequently, the representative producer in country N chooses fuel supply according to

$$\forall f : X^{N,f}(p^f, \underline{\xi}^f, \bar{\xi}^f) := \begin{cases} C_f^{N,f-1}(p^f) & \text{for}\, p^f \leq C_f^{N,f}(\underline{\xi}^f), \\ \underline{\xi}^f & \text{for}\, p^f \in [C_f^{N,f}(\underline{\xi}^f), C_f^{N,f}(\bar{\xi}^f)], \\ C_f^{N,f-1}(p^f) - \bar{\xi}^f + \underline{\xi}^f & \text{for}\, p^f \geq C_f^{N,f}(\bar{\xi}^f). \end{cases} \tag{4.13}$$

Inserting these demand and supply functions, i.e. Eq. (4.8), (4.10), and (4.13), into the fuel market clearings conditions, we obtain

$$\forall f : X^{M,f}(p^f) + X^{N,f}(p^f, \underline{\xi}^f, \bar{\xi}^f) = Y^{M,f}(p^K, p^G) + Y^{N,f}(p^K, p^G). \tag{4.14}$$

This yields the equilibrium fuel prices as functions of the upper and lower bounds of deposits supplied by country N. From Eq. (4.11) we know that the upper and lower bounds of deposits in turn depend on the fuel and deposit prices, so that the solution can be expressed by functions P^f with

$$\forall f : p^f = P^f(p^{z,K}, p^{z,G}). \tag{4.15}$$

These functions characterize the outcome of the third stage.

In the second stage, deposit owners in country N chose which deposits they sell. In absence of deposit markets, all deposits that are profitable at the fuel market prices would be extracted in country N, so that $\forall f : x^{N,f} = \bar{\xi}^f(p^f) = C_f^{N,f-1}(p^f)$. If deposit markets are introduced, country N sells those deposits that are costly to extract and extracts all low-cost deposits, so that

$$\forall f : x^{N,f} = \bar{\xi}^f(p^f) - z^{N,f}. \tag{4.16}$$

Then, country N's first-order conditions for welfare maximization yield

$$\forall f : C_f^{N,f}(x^{N,f}) = p^f - p^{z,f}. \tag{4.17}$$

Using Eq. (4.11), the solution can be expressed by deposit supply $Z^{N,f}$ functions which depend on the fuel and deposit prices:

$$\forall f : z^{N,f} = Z^{N,f}(p^f, p^{z,f}) = \bar{\xi}^f(p^f) - \underline{\xi}^f(p^f, p^{z,f}). \tag{4.18}$$

Then, the deposit markets clear according to

$$\forall f : Z^{N,f}(p^f, p^{z,f}) = z^{M,f}. \tag{4.19}$$

Accounting for Eq. (4.15), equilibrium deposit prices can be expressed as functions $P^{z,f}$:

$$\forall f : p^{z,f} = P^{z,f}(z^{M,K}, z^{M,G}). \tag{4.20}$$

General results

In the first stage, country M maximizes welfare by choosing the optimal amount of deposits for purchase considering the equilibrium fuel and deposit prices determined in stages two and three (see Eq. (4.15) and (4.20)). Following the calculations in Appendix 4.A, country M's first-order conditions are equivalent to

$$\begin{aligned} \forall f : \frac{dU^M}{dz^{M,f}} =& \eta^f H' - p^{z,f} - z^{M,K} \cdot P_f^{z,K} - z^{M,G} \cdot P_f^{z,G} \\ & - (y^{M,K} - x^{M,K} + \eta^K H' \bar{\xi}_K^K) \cdot \frac{dp^K}{dz^{M,f}} \\ & - (y^{M,G} - x^{M,G} + \eta^G H' \bar{\xi}_G^G) \cdot \frac{dp^G}{dz^{M,f}} = 0, \end{aligned} \tag{4.21}$$

where $\forall f, s \in \{K, G\} : P_s^{z,f} = \frac{dP^{z,f}}{dz^{M,s}}$, $\bar{\xi}_f^f = \frac{d\bar{\xi}^f}{dp^f}$, and $P_s^f = \frac{dP^f}{dp^{z,s}}$. By solving these equations to obtain country M's deposit demand $z^{M,f}$ and plugging the results into the functions of the previous section the complete solution can be determined. For several of the terms in Eq. (4.21), we obtain the following novel general comparative statics properties (see all proofs in Appendix 4.A):

Proposition 4.1. *In the equilibrium of deposit trade with strategic action, the following holds:* $\forall f, s \in \{K, G\} : \bar{\xi}_f^f > 0$ *and for the case of identical benefit functions:* $P_s^f \in]0, 1[$, $P_f^{z,f} > 0$. *Furthermore,* $P_G^{z,K} > 0$ *if and only if* $C_{G,G}^{N,G}(x^{N,G}) > C_{G,G}^{N,G}(\bar{\xi}^G)$ *and* $P_K^{z,G} > 0$ *if and only if* $C_{K,K}^{N,K}(x^{N,K}) > C_{K,K}^{N,K}(\bar{\xi}^K)$.

These results hold independent of the concrete specification of cost, benefit and damage functions. We now interpret Proposition 4.1 from the perspective of coal ($f = K$, statements can be made for $f = G$ in analogy). First, if the fuel price of coal increases, the upper bound of purchased coal deposits must increase in order to incentivize country N not to extract them. Further, we find that coal becomes more expensive if coal deposits are purchased at a higher price. Such an effect also spills over from the gas to the coal deposit market: If gas deposits are purchased at a higher price, coal becomes more expensive, too.

Interestingly, the price which country M must pay for coal deposits can either increase or decrease if it purchases more gas deposits. Both deposits can be complements in the sense that a higher price of gas deposits (with more demand) leads to a higher price of coal deposits (with more demand). They might also be substitutes. Then, an increase in gas deposits purchases reduces the coal deposit price, in the extreme case down to a level where no coal deposits are sold, i.e. one deposit market might crowd out the other. Whether gas deposits are a substitute or complement for coal deposits depends on the slope of the marginal extraction costs of gas compared between the extraction level and the most expensive purchased deposit. This comparison is an empirical question and we are not aware of principal reasons that one should be the case rather than the other. Second, we can make several observations about the implications of strategic action in interlinked deposit markets. Simply, if we do not allow for strategic action in Eq. (4.21), such that $P_s^{z,f} \equiv 0$, solving the first-order conditions yields the optimal deposit prices $\forall f : p^{z,f} = \eta^f H'$. Inserting this into Eq. (4.17) shows that the first-best is achieved, as in Eq. (4.3). This efficiency result generalizes the single fuel case for multiple fuels with interfuel leakage.

Yet, since we admit strategic action, country M can manipulate the deposit prices, which is represented by the non-vanishing terms $P_s^{z,f}$ and $P_s^{z,f} P_s^f$. Looking at the inefficiencies more closely, we observe that *both* fuels, K and G, are relevant for the distortions on the deposit markets. For instance, in Eq. (4.21), when country M chooses the optimal coal deposit purchase, its demand for gas deposits affects this choice through the terms $z^{M,G} \cdot P_f^{z,G}$. Moreover, the marginal climate damage of gas multiplied with the price elasticity of gas deposits, $\eta^G H' \bar{\xi}_G^G$, and the trade balance of gas, $(y^{M,G} - x^{M,G})$, affect the choice of coal deposit purchase. Consequently, on top of the inefficiencies that Eichner & Pethig (2017a) detect in their analysis, we find that *interfuel* effects additionally distort the first-best.

To gain a better understanding on how these distorting interfuel effects impact the deposit markets, we solve Eq. (4.21) implicitly for country M's optimal coal deposit demand, $z^{M,K}$, and set $f = K$ (the results hold for $f = G$ in analogy).

By using $\frac{dp^s}{dz^{M,f}}/P_f^{z,f} = P_f^f$, we obtain

$$\begin{aligned} z^{M,K} = & \frac{\eta^K H' - p^{z,K}}{P_K^{z,K}} - (y^{M,K} - x^{M,K} + \eta^K H' \bar{\xi}_K^K) \cdot P_K^K \\ & \underbrace{-z^{M,G} \cdot \frac{P_K^{z,G}}{P_K^{z,K}}}_{\text{I}} \underbrace{-\eta^G H' \bar{\xi}_G^G P_K^G}_{\text{II}} \underbrace{-(y^{M,G} - x^{M,G}) \cdot P_K^G}_{\text{III}} . \end{aligned} \tag{4.22}$$

Eq. (4.22) decomposes three interfuel effects (I-III). The *interfuel deposit effect* (I) describes how the deposit demand for one fuel affects the other fuel's deposit demand. We observe that the deposit demand of coal, $z^{M,K}$, changes ceteris paribus with the deposit demand of gas, $z^{M,G}$. The sign of the effect depends on $C_{G,G}^{N,G}(x^{N,G}) \lesseqgtr C_{G,G}^{N,G}(\bar{\xi}^G)$ according to Proposition 4.1. If $C_{G,G}^{N,G}(x^{N,G}) < C_{G,G}^{N,G}(\bar{\xi}^G)$, coal deposit demand decreases the price for gas deposits and term (I) is positive, i.e. coal deposits are ceteris paribus complements for gas deposits. If, however, $C_{G,G}^{N,G}(x^{N,G}) > C_{G,G}^{N,G}(\bar{\xi}^G)$, effect (I) is negative. If there is (ceteris paribus) more trade with gas deposits, it becomes more likely that there is no trade with coal deposits at all (and vice versa). The *interfuel climate damage effect* (II) relates to how climate damages from one fuel affect the deposit choice of the other fuel. Since $P_K^G > 0$, term (II) is always negative, so that the interfuel climate damage effect for one fuel reduces deposit demand for the other fuel. The *interfuel trade effect* (III) describes how the trade balance of one fuel affects the deposit demand for the other fuel. Since $P_K^G > 0$, we find that the coal deposit demand is increasing (decreasing) in the trade balance of gas if and only if country M is a net gas exporter (importer). We summarize the findings in

Proposition 4.2. *Given country M trades deposits of fuels $f \in \{K, G\}$ with country N and acts strategically on the deposit markets, the first-best choice of deposits is distorted in particular by (I) an interfuel deposit effect, (II) an interfuel climate damage effect, and (III) an interfuel trade effect. For the case of identical benefit functions, the interfuel deposit effect increases country M's deposit choice of fuel K if and only if $C_{G,G}^{N,G}(x^{N,G}) < C_{G,G}^{N,G}(\bar{\xi}^G)$ (this result holds for fuel G in analogy). The interfuel climate damage effect decreases deposit demand. The interfuel trade effect increases (decreases) demand for deposits of one fuel if and only if country M is a net exporter (importer) of the other fuel.*

Further, we can study how climate damage affects deposit demand (ceteris paribus). We rearrange Eq. (4.22) to obtain

$$
\begin{aligned}
z^{M,K} =& H' \cdot \left(\eta^K \cdot \left(\frac{1}{P_K^{z,K}} - P_K^K \bar{\xi}_K^K \right) - \eta^G P_K^G \bar{\xi}_G^G \right) \\
& - \frac{p^{z,K}}{P_K^{z,K}} - z^{M,G} \cdot \frac{P_K^{z,G}}{P_K^{z,K}} - (y^{M,K} - x^{M,K}) \cdot P_K^K - (y^{M,G} - x^{M,G}) \cdot P_K^G.
\end{aligned}
\tag{4.23}
$$

If fuel G has a higher emission intensity, deposit demand for K is lower. On the other hand, if the emission intensity of K increases, country M's demand for K deposits increases, since, using Eq. (4.35) from Appendix 4.A, we have that $\frac{1}{P_K^{z,K}} - P_K^K \bar{\xi}_K^K = -(\frac{d\bar{\xi}^K}{dp^{z,K}} - \frac{dz^{M,K}}{dp^{z,K}}) = -\frac{dx^{N,K}}{dp^{z,K}} > 0$. Moreover, it is theoretically ambiguous whether deposit trade is increasing or decreasing in marginal climate damage.

We have thus disentangled the effects for deposit policies with strategic action if more than a single fuel exists. While the efficiency results are not surprising, we find that the distortions from strategic action can work in different directions – which particularly depend on the shape of extraction cost curves. Deposits of multiple fuels can become substitutes, so that trade with deposits of one fuel type crowds out trade of deposit of the other fuel. Further, the effect of marginal climate damage on deposit trade is ambiguous. In the presence of multiple fuels it is also possible that dirtier fuels lead to less purchase of deposits (ceteris paribus).

Comparing welfare and climate damage in the deposit market case with the benchmarks of the social planner and the cap policy case, denoted by subscripts D, SP, and C, respectively, we find (for proof see Appendix 4.A)

Proposition 4.3. *Suppose country M is a net importer of both fuels, the benefit functions are identical, and $\forall f : C_{f,f}^{N,f}(x^{N,f}) \geq C_{f,f}^{N,f}(\bar{\xi}^f)$. Then, the welfare of country M and the climate damage in the different policy scenarios are ranked in the following order:*

$$
\begin{aligned}
& U_{SP}^M \geq U_D^M \geq U_C^M, \\
& H_C \geq H_D \geq H_{SP}.
\end{aligned}
\tag{4.24}
$$

The derivation for this proposition is based on Eq. (4.23). The proof exploits Proposition 4.1 (so that the condition for the cost functions is the same) and employs the envelope theorem. Under these conditions country M is always at least as well off when trading deposits of both fuels in addition to implementing a domestic cap policy. Climate damage can be mitigated by implementing deposit policies on top of a cap on fuel extraction. Such an importing country has no strategic incentive to use deposit markets in a way that reduces harm further below the socially optimal level. It would support the implementation of an international deposit market as this would improve welfare compared to a domestic cap policy.

4.4 INTERFUEL EFFECTS ANALYSIS

Since we are interested in the implications of deposit markets in the second-best and the prospects for such policies being implemented, we now compare deposit policies with the benchmark policies and provide a more detailed analysis of the interfuel effects and their implications for fuel trade, welfare, climate damage as well as consumer and producer surplus. To derive further insights, we resort to a common parametric functional form for the benefit function with two goods (Dixit, 1979):[2]

$$\forall i : B^i(y^{i,K}, y^{i,G}) = \alpha \cdot (y^{i,K} + y^{i,G}) - \frac{\beta}{2} \cdot ((y^{i,K})^2 + (y^{i,G})^2) - \gamma y^{i,K} y^{i,G}, \quad (4.25)$$

with parameters $\alpha > 0$, $\beta > 0$, and $\beta \geq \gamma \geq 0$. Interfuel effects are captured by γ. If $\gamma = 0$, all strategic interfuel effects disappear from our generals results. If $\gamma = \beta$, the fuels are perfect substitutes in demand, so that interfuel effects become most prevalent.

Furthermore, in extension of Dixit (1979), who assumes linear cost functions, we assume

$$\forall i, f : C^{i,f}(x^{i,f}) = \frac{\kappa^{i,f}}{2}(x^{i,f})^2, \quad (4.26)$$

with cost parameters $\forall i : \kappa^{i,G} > \kappa^{i,K} = 1$, so that coal is cheaper to extract than gas. Except for the last part in Appendix 4.B, we will assume $\forall f : \kappa^{M,f} \equiv \kappa^{N,f}$, so that both countries are symmetric with respect to their endowment of deposits. Thus, we will drop the country index i for the most part.

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[2] Thanks to Mark Schopf for pointing out the original source of this specification.

Finally,

$$H(\sum_i \sum_f \eta^f x^{i,f}) = \delta \cdot (\eta^K \cdot (x^{M,K} + x^{N,K}) + \eta^G \cdot (x^{M,G} + x^{N,G})), \qquad (4.27)$$

where the marginal climate damage is $\delta > 0$. For the emission intensities, we assume that $\eta^K > \eta^G$, since the emissions from coal production have more severe environmental effects compared to those created from gas (similar to Chakravorty et al., 2008).

With the general results from the previous section, this specification admits closed-form solutions for the quantities and prices of fuels and deposits for both countries. To highlight the interfuel effects detected in the preceding section, we now turn to studying the case when both fuels are perfect substitutes (i.e. $\gamma = \beta$), so that interfuel effects become most pronounced. We will use the superscript $f = r, s$, with $r \neq s$, to refer to either of the two fuels. For comparison, we also study perfectly segmented fuel markets, where no interfuel effects occur (see Appendix 4.B).

First, we can explicitly determine the prices and quantities in all scenarios (see Tables 4.1, 4.2), which provides further interesting insights on differences in the fuel mix. In the social planner case, demand and supply of one fuel are decreasing in the same fuel's emission intensity and increasing in the other fuel's emission intensity for both countries. As shown in section 4.3.2, we see that the fuel supply and demand in the case of deposit markets without strategic action coincide with the quantities of the social planner. For the case of deposit markets with strategic action, we observe that the fuel prices are increasing in the sum of both cost-weighted emission intensities, since the fuels are perfect substitutes (see Table 4.2). Both countries' demand for a fuel r decreases in the emission intensity of fuel r, and increase in the emission intensity of fuel s. Due to the cap policy, country M's supply of fuel r decreases with this same fuel's emission intensity, while the supply increases with the emission intensity of fuel s. Comparing fuel supply and demand, we obtain that country M is a net importer of fuels. Regarding deposits, both fuel deposit demand and deposit price are increasing in the same fuel's emission intensity and decreasing in the other fuel's emission intensity. Since $\eta^K > \eta^G$, country M's demand for deposits of the dirtier fuel is always (strictly) positive. More interestingly, however, we find:

Proposition 4.4. *When strategic action is admitted, no deposits of fuel G are* *traded, if*

$$\eta^K > \frac{7\eta^G}{5}. \tag{4.28}$$

Every additional gas deposit that country M buys results in a gas supply cut. Since the fuels are perfect substitutes, consumers will substitute this gas supply cut with an increase in coal consumption. This leads to additional climate damage and, if $\eta^K > \frac{7\eta^G}{5}$, this additional climate damage is larger than the welfare gain of reduced emissions from lower gas production. This leads to a discussion of the prospects for deposit markets to be implemented in a setting with multiple fuels. It seems to be a reasonable assumption that the implementation of a deposit market for one fuel leads to transaction costs for at least one participant. This assumption implies that a deposit market will not be established in the first place if rational countries can anticipate that no trade will happen on such a market. This means that Proposition 4.4 specifies a condition where no deposit market for fuel G is implemented. If this condition holds, interfuel effects from the mere existence of a second fuel would render a deposit market for one fuel obsolete.

We can further compare quantities and prices for the deposit markets with and without strategic action as shown in Table 4.9. With strategic deposit trade, country M buys less deposits than optimal. This leads to lower deposit and fuel prices.

By putting the above results together, we can now show how the fuel mix of country N differs between the cases of social planner, domestic cap and deposit markets with strategic action and obtain

Proposition 4.5. *If both fuels are perfect substitutes, the fuel mix in country N depends on the scenarios according to*

$$\kappa^G = \frac{x_C^{N,K}}{x_C^{N,G}} > \frac{x_D^{N,K}}{x_D^{N,G}} > \frac{x_{SP}^{N,K}}{x_{SP}^{N,G}}. \tag{4.29}$$

In the cap policy scenario, the ratio of coal production to gas production in country N is characterized by the ratio of cost parameters. In the case of deposit markets with strategic action the fuel mix in country N is cleaner than with a cap policy only, i.e. less coal is produced compared with gas. However, the fuel mix is still dirtier than optimal.

Finally, we compare the domestic welfare of both countries and the climate damage for various scenarios (see Tables 4.3-4.5 in Appendix 4.C for results): In addition to comparing the cases of social planner, domestic cap, and deposit markets with strategic action, we can also determine solutions for deposit markets without strategic action (denoted by subscript $*$), and the case where only deposits of one fuel are traded (with strategic action; denoted by subscript D, K for coal deposit trade only, and D, G for gas deposit trade only). Then, we find

Proposition 4.6. *In the case of perfect substitutability between fuels and strictly positive trade on both deposit markets, the welfare of both countries as well as the resulting climate damage in the different policy scenarios are ranked in the following order:*

$$\begin{aligned} &U^M_{SP} > U^M_D > U^M_{D,K} > U^M_{D,G} > U^M_C > U^M_* \\ &U^N_* > U^N_D > U^N_{D,K} > U^N_{D,G} > U^N_C > U^N_{SP}, \\ &H_C > H_{D,G} > H_{D,K} > H_D > H_{SP} = H_*. \end{aligned} \tag{4.30}$$

If country M would be given a choice over the scenarios, it would prefer the social planner over the deposit policy since it does not need to compensate country N (through the deposit market) for keeping deposits unextracted. Regarding the deposit policy, country M is better off trading deposits of both fuels, and if trade is only possible for one of the fuels, it prefers trading the dirtier fuel. The deposit policy is strictly preferred to the cap policy since it reduces leakage effects. If country M cannot act strategically on the deposit market, however, it prefers the cap policy. Then, even though deposit markets without strategic action are efficient, country M would be better off by only implementing a unilateral cap policy. For country N, the deposit policy without strategic action yields the comparatively best outcome. Here, country N receives a higher compensation compared with a deposit policy where country M acts strategically. This compensation decreases further, if only one fuel is traded on the deposit market, and it vanishes in the cap policy scenario. Finally, country N is better off in the cap policy case compared with the social planner scenario since it does not profit from reduced emissions. Climate damage is largest in the cap policy case and smallest in the social planner case, which is equivalent to the case of undistorted and complete deposit markets in this respect. Climate damage decreases compared to the cap policy case if deposits (of multiple fuels) are traded.

To analyze the political economy of implementing deposit markets in country M, we disaggregate country M's welfare into the surplus of consumers and coal and gas producers, denoted CS^M, PSK^M, and PSG^M, respectively (see Tables 4.6-4.8 in Appendix 4.C for results). Then, we obtain

Proposition 4.7. *In the case of perfect substitutability between fuels and strictly positive trade on both deposit markets, the consumer and producer surplus in country M in the different policy scenarios are ranked as follows:*

$$\begin{aligned} &CS^M_C > CS^M_{D,G} > CS^M_{D,K} > CS^M_D > CS^M_* \\ &PSK^M_* > PSK^M_{D,K} > PSK^M_D > PSK^M_{D,G} > PSK^M_C \\ &PSG^M_* > PSG^M_D > PSG^M_{D,K} > PSG^M_{D,G} > PSG^M_C . \end{aligned} \tag{4.31}$$

Consumers in country M are better off with a cap policy only since any deposit market in place on top of a cap increases fuel prices, thus reducing their consumption level. Comparing the deposit market options, consumers prefer deposit markets for one fuel only over deposit markets covering both fuels. Deposit markets for gas only are preferred to those for coal only, as the latter cut fuel supply more sharply resulting in higher fuel prices. For deposit markets covering both fuels, consumers are better off if country M acts strategically as opposed to the case without distorted deposit markets. Then, country M buys more deposits, fuel supply is cut more sharply, and fuel prices increase more (see also Table 4.9).

Coal and gas producers in country M are best off in the absence of strategic action, where most deposits are purchased and fuel prices are highest. The cap policy option ranks lowest for both of them, since they suffer from carbon leakage more than in any deposit policy scenario. Comparing the scenarios of deposits covering one or both fuels, two effects are at play. First, if country M can only purchase deposits of one fuel it buys more deposits of this fuel than in the scenario where purchasing deposits of both fuels is possible. This effect is more pronounced for the coal deposit only scenario than for the gas deposit only policy, since coal deposits are cheaper and more effective (coal is dirtier than gas). In any case, country M cuts country N's supply of both fuels more sharply and producers in country M can sell more of the respective fuel than with deposit markets covering both fuels. Second, since fuels are perfect substitutes, fuel prices increase if more deposits (of any fuel) are purchased. Therefore, with deposits markets for both fuels, producers in country M can sell at higher prices. For coal producers, the first effect dominates the second so that they prefer deposits on coal only to deposit markets covering both fuels. Further, they only benefit from the fuel price increase in the gas deposit only case, making it their least preferred deposit policy option. Gas producers, on the other hand, prefer deposit markets covering both fuels over deposits for coal only since the first option increases fuel prices more strongly. Further, they benefit more from deposits covering coal only compared with gas only as the second effect dominates the first effect described above. To sum up, while strategic deposit policies covering both fuels are the best policy option for country M's aggregate welfare, consumers and producers may prefer a different policy potentially raising political feasibility concerns.

To further interpret these results from a political economy perspective between both countries, assume each country's government can choose domestic policies to maximize domestic welfare, but that common deposit markets (for one or both fuels) can only be implemented by agreement of both countries, i.e. they need to Pareto-dominate a threat point. This makes sense if one considers a situation without deposit policies as business-as-usual and that implementing a deposit market requires to introduce appropriate and enforceable property rights, market places, and so on. This is not possible unilaterally, but only by agreement of the governments that participate in the market. Then, implementing a deposit market requires a Pareto-improvement. Unilaterally, country M can only choose the cap policy, so that it becomes the threat point. For country N, nothing remains to choose unilaterally. Then Eq. (4.30) shows the following sequence of Pareto improving welfare vectors:

$$(U_C^M, U_C^N) < (U_{D,G}^M, U_{D,G}^N) < (U_{D,K}^M, U_{D,K}^N) < (U_D^M, U_D^N). \tag{4.32}$$

This shows that deposit markets can be implemented in the above sense. Although country N would benefit more if deposit markets do not suffer from strategic action (these gains might be substantial, e.g. Eisenack et al., 2012, Bauer et al., 2016), it cannot garner support from country M to implement ramifications of this market failure easily. As one caveat of this argumentation, note that Pareto dominance does not guarantee that the improvement is large enough to cover the transaction costs from introducing and operating deposit markets. This might be one reason why such markets are not implemented in practice yet. Interestingly, it should be noted that Pareto dominance even holds although deposit markets covering multiple fuels entail more interfuel effects, and thus more distortions from strategic action.

To sum up, in contrast to the setting with a single fuel, the analysis of deposit markets with two fuels that are substitutes in demand reveals novel results: First, due to interfuel effects, we identify conditions where only one deposit market is implemented. Second, the analysis shows that deposit markets covering both fuels alter the fuel mix in countries without emission reduction incentives. Third, consumers and coal and gas producers in country M prefer different policy options. Finally, if deposit markets are implemented for all fuels, both countries prefer such a policy scenario to a unilateral cap policy despite multiple distortions from strategic action channeled through interfuel effects. These results also hold for perfectly segmented fuel markets (see Appendix 4.B).

4.5 Conclusion

Mitigating adverse effects of climate change requires the implementation of demand- or supply-side climate policies. Deposit markets have recently become a research focus in the analysis of the supply-side. Previous studies focusing on a deposit market for a single fuel (e.g. Harstad, 2012, Eichner & Pethig, 2017a) show conditions for efficiency in the presence of carbon leakage and how a deposit market can be distorted by strategic action. We substantially extend this literature by analyzing how – in the presence of multiple fuels – interfuel carbon leakage affects trade on the deposit markets. In contrast to a setting with a single fuel, our analysis allows to identify conditions for which (distorted) deposit markets cannot be implemented due to such interfuel effects. In addition, we find settings in which strategic action with interfuel carbon leakage distorts the outcome towards dirtier or cleaner fuels. To gain insights on the prospects for implementing deposit policies in a world with distorted deposit markets we compare the countries' welfare and consumer and producer surplus between different second-best settings and the first-best.

A hypothesis underlying this paper is that interfuel carbon leakage effects on deposit markets covering multiple fuels compromise efficiency to an extent where their implementation cannot garner support in the first place. This would render deposit policies as a policy alternative obsolete. Our findings show that carbon leakage between both, countries and fuels, affects trade on the deposit markets. More precisely, price manipulations on the deposit markets can be decomposed into interfuel deposit effects, interfuel trade effects and interfuel climate damage effects. Trade with deposits of one fuel can be a substitute or a complement for trade with the other kind of deposits, depending on the shape of the extraction cost functions. If deposits are substitutes, the existence of one deposit market can crowd out a second deposit market. If the fuels are substitutes, countries do not buy deposits of a fuel if its emission intensity is too low compared with the other fuel. Yet, if there is a strictly positive trade of deposits for two fuels in the model, countries selling deposits are induced to produce a cleaner fuel mix. The model also shows that more complete deposit markets then generate more welfare for each country – although interfuel leakage increases the scope for strategic distortions. All countries, even those not effected by climate change, are better off with (multiple) distorted deposit markets than with a cap policy. Considering consumer and producer rents in the country buying deposits, we find that they rank differently between the policy options, which we think has important implications for policymaking.

As usual, the analysis relies on some simplifying assumptions. First, we assume that there are only two (groups of) countries, although one of them can be interpreted as a coalition of countries which acts like a single actor. In our paper, we abstain from considering the stability of this coalition, which is in line with previous literature.[3] Second, as in previous studies, we assume that only countries buying deposits are affected by climate damage. Third, our static partial equilibrium model neglects potential time-consistency and commitment issues. Countries which sell deposits today might re-negotiate the contract in the future or nevertheless extract the deposits. Under uncertainty in global trends, there might be good reasons to terminate contracts (cf. Eisenack & Paschen, 2017). On the flip-side, countries buying deposits may find it in their interest to extract deposits once bought for preservation only despite their climate ambition. Such considerations would be particularly relevant for questions of energy supply

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[3] To our knowledge, only Eichner & Pethig (2017b) examine the stability of the coalition with deposit markets, while a separate strand of literature extensively analyzes coalition stability without considering deposit markets (see e.g. Benchekroun & van Long, 2012, Hagen et al., 2020, for surveys).

security during geopolitical crises, as in the case of the current Russian war in the Ukraine. The political economy perspective of our results can be elaborated, e.g. by going beyond changes in producer and consumer rents (cf. Steinhäuser & Eisenack, 2020) in order to consider the effects of domestic lobby-groups on climate policymaking (cf. Hagen et al., 2021, Schopf & Voss, 2019). If more than one climate coalition forms (e.g. Asheim et al., 2006, Hagen & Eisenack, 2019), these groups could further interact strategically on the deposit markets. The implications of such more complex settings are prima facie not clear. Although beyond the scope of this paper, these issues are relevant for policymaking and could become subject of future research.

To conclude, the analysis has shown that deposit markets bear promise for improving climate policy, even in a world with many fuels of different qualities and with multiple strategic distortions. Yet, it cannot be taken for granted that multiple deposit markets exist in parallel. On the other hand, even in a world where first-best policies are not feasible – a possibility we might, unfortunately, take for real – these markets have the potential to improve the situation for both, countries buying deposits and countries which are reluctant to reduce greenhouse gas emissions.

Appendices

4.A ANALYTICAL RESULTS

Derivation of Eq. (4.21):

Regarding country M's welfare optimization we obtain the first-order conditions by using Eq. (4.7), (4.15), (4.20), and $\frac{dp^K}{dz^{M,f}} = (P_K^K P_f^{z,K} + P_G^K P_f^{z,G})$ and $\frac{dp^G}{dz^{M,f}} = (P_K^G P_f^{z,K} + P_G^G P_f^{z,G})$

$$\begin{aligned}
\forall f : \frac{dU^M}{dz^{M,f}} =& \eta^f H' - p^{z,f} - z^{M,K} \cdot P_f^{z,K} - z^{M,G} \cdot P_f^{z,G} \\
& - (y^{M,K} - x^{M,K} + \eta^K H' \bar{\xi}_K^K) \cdot (P_K^K P_f^{z,K} + P_G^K P_f^{z,G}) \\
& - (y^{M,G} - x^{M,G} + \eta^G H' \bar{\xi}_G^G) \cdot (P_K^G P_f^{z,K} + P_G^G P_f^{z,G}) \\
& + (-C_K^{M,K} + p^K - \eta^K H') \cdot X_f^{M,K} P_f^{z,f} \\
& + (-C_G^{M,G} + p^G - \eta^G H') \cdot X_f^{M,G} P_f^{z,f} \\
& + (B_K^M - p^K) \cdot Y_f^{M,K} P_f^{z,f} + (B_G^M - p^G) \cdot Y_f^{M,G} P_f^{z,f} \\
=& \eta^f H' - p^{z,f} - z^{M,K} \cdot P_f^{z,K} - z^{M,G} \cdot P_f^{z,G} \\
& - (y^{M,K} - x^{M,K} + \eta^K H' \bar{\xi}_K^K) \cdot (P_K^K P_f^{z,K} + P_G^K P_f^{z,G}) \\
& - (y^{M,G} - x^{M,G} + \eta^G H' \bar{\xi}_G^G) \cdot (P_K^G P_f^{z,K} + P_G^G P_f^{z,G}) \\
=& \eta^f H' - p^{z,f} - z^{M,K} \cdot P_f^{z,K} - z^{M,G} \cdot P_f^{z,G} \\
& - (y^{M,K} - x^{M,K} + \eta^K H' \bar{\xi}_K^K) \cdot \frac{dp^K}{dz^{M,f}} \\
& - (y^{M,G} - x^{M,G} + \eta^G H' \bar{\xi}_G^G) \cdot \frac{dp^G}{dz^{M,f}} \overset{!}{=} 0,
\end{aligned} \tag{4.33}$$

where $\forall f, s \in \{K, G\} : P_s^{z,f} = \frac{dP^{z,f}}{dz^{M,s}}$, $\bar{\xi}_f^f = \frac{d\bar{\xi}^f}{dp^f}$, $P_s^f = \frac{dP^f}{dp^{z,s}}$, $X_s^{M,f} = \frac{dX^{M,f}}{dp^{z,s}}$, and $Y_s^{M,f} = \frac{dY^{M,f}}{dp^{z,s}}$.

Proof of Proposition 4.1:

We now derive the signs of the terms $\forall f, s \in \{K, G\} : \bar{\xi}_f^f, P_s^f$, and $P_s^{z,f}$.

First, since $\forall f : \bar{\xi}^f = C_f^{N,f-1}(p^f) =: \bar{\xi}^f(p^f)$ and $\forall f : C_{f,f}^{i,f} > 0$ holds, we obtain that $\forall f : \bar{\xi}_f^f = \frac{d\bar{\xi}^f}{dp^f} = C_{f,f}^{N,f-1}(p^f) > 0$.

Next, we prove that $P_K^G = \frac{dp^G}{dp^{z,K}} > 0$ and $P_K^K = \frac{dp^K}{dp^{z,K}} > 0$, which equivalently holds for the gas deposit price. Similar to Eichner & Pethig (2019), we totally differentiate

$$\begin{aligned} &\forall f : C_f^{N,f}(x^{N,f}) = p^f - p^{z,f}, \\ &\forall f : C_f^{M,f}(x^{M,f}) = p^f - \eta^f H', \\ &\forall i, f : B_f^i(y^{i,K}, y^{i,G}) = p^f, \\ &\forall f : x^{M,f} + x^{N,f} = y^{M,f} + y^{N,f}, \end{aligned} \tag{4.34}$$

and obtain

$$\forall f : C_{f,f}^{N,f}(x^{N,f})dx^{N,f} = dp^f - dp^{z,f}, \tag{4.35}$$

$$\forall f : C_{f,f}^{M,f}(x^{M,f})dx^{M,f} = dp^f - (\eta^f)^2 H'' dx^{M,f}, \tag{4.36}$$

$$\forall i, f : B_{f,K}^i(y^{i,K}, y^{i,G})dy^{i,K} + B_{f,G}^i(y^{i,K}, y^{i,G})dy^{i,G} = dp^f, \tag{4.37}$$

$$\forall f : dx^{M,f} + dx^{N,f} = dy^{M,f} + dy^{N,f}. \tag{4.38}$$

Assuming identical benefit functions for both countries, so that $B := B^M \equiv B^N$, we can solve this equation system for P_K^K and P_K^G, respectively, so that

$$P_K^K = \frac{dp^K}{dp^{z,K}} = \frac{a}{b} \in]0,1[, \tag{4.39}$$

$$P_K^G = \frac{dp^G}{dp^{z,K}} = \frac{c}{b} \in]0,1[, \tag{4.40}$$

where

$$\begin{aligned} a :=&(C_{K,K}^{M,K} + (\eta^K)^2 H'')(-B_{G,G}B_{K,K}(C_{G,G}^{M,G} + (\eta^G)^2 H'' + C_{G,G}^{N,G}) \\ &+ B_{K,G}^2(C_{G,G}^{M,G} + (\eta^G)^2 H'' + C_{G,G}^{N,G}) + 2B_{K,K}C_{G,G}^{N,G}(C_{G,G}^{M,G} + (\eta^G)^2 H'')), \\ b :=&B_{K,G}^2(C_{G,G}^{M,G} + (\eta^G)^2 H'' + C_{G,G}^{N,G})(C_{K,K}^{M,K} + (\eta^K)^2 H'' + C_{K,K}^{N,K}) \\ &- (B_{G,G}(C_{G,G}^{M,G} + (\eta^G)^2 H'' + C_{G,G}^{N,G}) \\ &- 2(C_{G,G}^{M,G} + (\eta^G)^2 H'')C_{G,G}^{N,G})(B_{K,K}(C_{K,K}^{M,K} + (\eta^K)^2 H'' + C_{K,K}^{N,K}) \\ &- 2(C_{K,K}^{M,K} + (\eta^K)^2 H'')C_{K,K}^{N,K}), \\ c :=&2(C_{G,G}^{M,G} + (\eta^G)^2 H'')B_{K,G}(C_{K,K}^{M} + (\eta^K)^2 H'')C_{G,G}^{N,G}, \end{aligned} \tag{4.41}$$

with $b < a < 0$ and $b < c < 0$.

Further, we show that $P_K^{z,K} = \frac{dp^{z,K}}{dz^{M,K}} > 0$. This, again, equivalently holds for the gas deposit price. Following Eichner & Pethig (2019), we totally differentiate

$$\begin{aligned} z^{N,K} &= \bar{\xi}^K(p^K) - x^{N,K}, \\ z^{N,K} &= z^{M,K}, \end{aligned} \tag{4.42}$$

and obtain

$$dz^{N,K} = \bar{\xi}^K_K dp^K - dx^{N,K}, \tag{4.43}$$

$$dz^{N,K} = dz^{M,K}. \tag{4.44}$$

With Eq. (4.35) and $\bar{\xi}^f_f = C^{N,f\,-1}_{f,f}(p^f)$, we insert Eq. (4.43) into Eq. (4.44) and obtain

$$\frac{dp^K}{C^{N,K}_{K,K}(\bar{\xi}^K)} - \frac{dp^K - dp^{z,K}}{C^{N,K}_{K,K}(x^{N,K})} = dz^{M,K}, \tag{4.45}$$

which is equivalent to

$$\underbrace{\left(\frac{P^K_K}{C^{N,K}_{K,K}(\bar{\xi}^K)} - \frac{P^K_K - 1}{C^{N,K}_{K,K}(x^{N,K})}\right)}_{\text{I}} dp^{z,K} = dz^{M,K}, \tag{4.46}$$

where $I > 0$, since $P^K_K \in]0,1[$. Then, we obtain

$$P^{z,K}_K = \frac{dp^{z,K}}{dz^{M,K}} = \frac{1}{\frac{P^K_K}{C^{N,K}_{K,K}(\bar{\xi}^K)} - \frac{P^K_K - 1}{C^{N,K}_{K,K}(x^{N,K})}} > 0. \tag{4.47}$$

Finally, we prove that $P^{z,K}_G = \frac{dp^{z,K}}{dz^{M,G}} \lesseqgtr 0$, which equivalently holds for the gas deposit price. Analogous to Eq. (4.45), we have for gas deposits that

$$\frac{dp^G}{C^{N,G}_{G,G}(\bar{\xi}^G)} - \frac{dp^G - dp^{z,G}}{C^{N,G}_{G,G}(x^{N,G})} = dz^{M,G}. \tag{4.48}$$

Dividing Eq. (4.48) by $dp^{z,K}$, we obtain

$$\frac{dp^G}{dp^{z,K}} \underbrace{\left(\frac{1}{C^{N,G}_{G,G}(\bar{\xi}^G)} - \frac{1}{C^{N,G}_{G,G}(x^{N,G})}\right)}_{=:\ \text{u}} = \frac{dz^{M,G}}{dp^{z,K}}. \tag{4.49}$$

We know from Eq. (4.40) that $\frac{dp^G}{dp^{z,K}} = \frac{c}{b} > 0$. The sign of u depends of the functional form of the cost function. With $C^{N,G}_{G,G}(x^{N,G}) \lesseqgtr C^{N,G}_{G,G}(\bar{\xi}^G)$, we have that $u \lesseqgtr 0$, and therefore, $P^{z,K}_G = \frac{dp^{z,K}}{dz^{M,G}} \lesseqgtr 0$.

Proof of Proposition 4.3:

As a first main step, we establish the ranking of climate damage. We prove that $H_C \geq H_D$ by contradiction. Thus, suppose that $H_D > H_C$. Then, total extraction of fuels is larger in the deposit policy case and the marginal climate damage respects $H'_D \geq H'_C$. The latter implies, however, that country M would extract less in the deposit policy case, since its domestic policy completely considers the marginal climate damage (as it does for the cap policy). Thus, total extraction can only be larger if N extracts more in the presence of a deposit policy. Yet, with a deposit policy, M induces N to extract less (by $z^{M,K}, z^{M,G} \geq 0$) – a contradiction. Similarly, we show $H_D \geq H_{SP}$ by contradiction. In the social planner case, producers internalize climate damage, thereby reducing fuel supply and increasing fuel (shadow) prices compared to a situation without any policies in place. Thus, the marginal loss of surplus (consumer and producer) for M in the social planner case is equal to the marginal reduction of climate damage. Now suppose that $H_D < H_{SP}$ (thus, $H'_D \leq H'_{SP}$). Then country M would need to buy more deposits than in the optimal case without strategic action. However, since we assume that country M is a net importer of both fuels, it would lose more surplus at the margin than if it would further reduce climate damage (note that the assumptions together with Proposition 4.1 guarantee that $P^{z,K}_G, P^{z,G}_K > 0$). This cannot be optimal for M – a contradiction.

In the second main step, we establish the welfare ranking. Note that by introducing a parameter $\mu = 1$, Eq. (4.23) can be equivalently written as

$$\begin{aligned} z^{M,K} = & \mu \cdot H' \cdot \left(\eta^K \cdot (\frac{1}{P^{z,K}_K} - P^K_K \bar{\xi}^K_K) - \eta^G P^G_K \bar{\xi}^G_G \right) \\ & - \frac{p^{z,K}}{P^{z,K}_K} - z^{M,G} \cdot \frac{P^{z,G}_K}{P^{z,K}_K} - (y^{M,K} - x^{M,K}) \cdot P^K_K - (y^{M,G} - x^{M,G}) \cdot P^G_K. \end{aligned} \tag{4.50}$$

We first set $\mu = 0$, essentially assuming a situation without any climate damage. Then our assumption on the extraction costs admits us to use the signs of Eq. (4.39), (4.40), (4.47), and (4.49) from Proposition 4.1. Since country M is an importer of both fuels, the right-hand side of Eq. (4.50) cannot be positive. In the $\mu = 0$ case, we obtain that no deposits are traded, so that $U_{SP}^{M} = U_{D}^{M} = U_{C}^{M}$.

Yet, actually $\mu = 1$. We thus study how welfare changes if μ becomes larger than zero. By employing the envelope theorem to the maximand Eq. (4.5), with H multiplied by μ as a factor, it follows that in equilibrium $\frac{dU_{SP}^{M}}{d\mu} = -H_{SP}$, $\frac{dU_{D}^{M}}{d\mu} = -H_{D}$, and $\frac{dU_{C}^{M}}{d\mu} = -H_{C}$. We can use the ranking of climate damage established in the first part of the proof again, since it holds for any climate damage function, even if it is rescaled by a factor $\mu > 0$. We thus have $0 \geq \frac{dU_{SP}^{M}}{d\mu} \geq \frac{dU_{D}^{M}}{d\mu} \geq \frac{dU_{C}^{M}}{d\mu}$ for any $\mu \in [0,1]$. Thus, also $U_{SP}^{M} \geq U_{D}^{M} \geq U_{C}^{M}$ for $\mu = 1$.

4.B PERFECTLY SEGMENTED FUEL MARKETS

If we assume that fuel markets are perfectly segmented (with $\gamma = 0$), all interfuel effects disappear. Consequently, we can confirm the results from the setting of deposit markets for a single fuel for the case of two fuels. In addition, however, we can analyze how deposit markets covering both fuels affect the fuel mix in the country without emission reduction incentives.

First, we analyze how extraction costs affect country M's deposit choice. For this purpose we vary the cost parameter, so that $\forall f : \kappa^{M,f} \neq \kappa^{N,f}$. For (strictly) positive prices and quantities, it must hold that $\forall f : \delta\eta^{f} < \frac{3\alpha\beta\kappa^{Mf}\kappa^{Nf}+4\alpha\beta\kappa^{Nf^2}+8\alpha\kappa^{Mf}\kappa^{Nf^2}}{2\beta^2\kappa^{Mf}+\beta^2\kappa^{Nf}+5\beta\kappa^{Mf}\kappa^{Nf}+4\beta\kappa^{Nf^2}+8\kappa^{Mf}\kappa^{Nf^2}}$. In this case country M's deposit demand is

$$\forall f : z^{M,f} = \frac{\alpha\beta\kappa^{Mf}(\kappa^{Nf} - \kappa^{Mf}) + \delta\eta^{f}\left(\beta^2\kappa^{Nf} + \beta\kappa^{Mf}(2\kappa^{Mf} + 3\kappa^{Nf}) + 4\kappa^{Mf^2}\kappa^{Nf}\right)}{\beta^2\left(2\kappa^{Mf^2} + 3\kappa^{Mf}\kappa^{Nf} + 2\kappa^{Nf^2}\right) + \beta\kappa^{Mf}\kappa^{Nf}(7\kappa^{Mf} + 8\kappa^{Nf}) + 8\kappa^{Mf^2}\kappa^{Nf^2}}. \tag{4.51}$$

We observe that if $\forall f : \kappa^{M,f} < \kappa^{N,f}$ deposit demand is positive. In other words, country M always purchases deposits, if it is a net exporter of both fuels, because it benefits in two ways: Since country N extracts less, country M is less affected by climate damage. Furthermore, cutting fuel supply of country N results in a fuel price increase, which increases gains for producers in country M. For the opposite case, we find

Proposition 4.8. *If $\forall f : \kappa^{M,f} > \kappa^{N,f}$, so that country M is a net importer of both fuels, there is no trade with deposits unless country M is sufficiently adversely* *affected by climate damage, so that*

$$\forall f : \delta\eta^f > \frac{\alpha\beta{\kappa^{M,f}}^2 - \alpha\beta\kappa^{N,f}\kappa^{M,f}}{\beta^2\kappa^{N,f} + 3\beta\kappa^{N,f}\kappa^{M,f} + 2\beta{\kappa^{M,f}}^2 + 4\kappa^{N,f}{\kappa^{M,f}}^2}. \tag{4.52}$$

For country M, as a net importer of both fuels, to purchase deposits, climate damage from fuel extraction must be sufficiently severe, i.e. it must surpass the above mentioned minimum level. For this case to be an interior solution, the parameter set additionally requires to fulfill that $\forall f : \frac{\beta\kappa^{M,f}}{2\beta+4\kappa^{M,f}} < \kappa^{N,f}$, so that the production costs of country M are small enough to ensure that fuel production is feasible. If country M implements a cap policy without the deposit markets, we obtain an interior solution if $\forall f : \beta < \frac{2\alpha\kappa^{N,f} - 2\delta\eta^f\kappa^{N,f}}{\delta\eta^f}$. In summary, for perfect fuel market segmentation, a fuel importing country M only buys a strictly positive amount of deposits if the climate damage from emissions exceeds a certain threshold.

Further, we can compare country N's fuel mix and both countries' welfare and climate damage for each policy case. For this purpose, we return to our assumptions of $\forall i : \kappa^{i,f} \equiv \kappa^f$ and $\kappa^G > \kappa^K \equiv 1$. For the cases of the social planner, the cap policy, and deposit markets without strategic action we obtain the quantities and prices in Table 4.10 in Appendix 4.C. Regarding the deposit policies, we confirm the qualitative results of Eichner & Pethig (2017a). Prices and quantities for deposit markets with strategic action and deviations from efficiency can be found in Table 4.11 and Table 4.18 in Appendix 4.C.

Even with two perfectly segmented fuel markets, we can determine how the choice of climate policies impacts the fuel mix in country N and obtain

Proposition 4.9. *The fuel mix in country N depends on the policy scenario according to*

$$\frac{x_C^{N,K}}{x_C^{N,G}} > \frac{x_D^{N,K}}{x_D^{N,G}} > \frac{x_{SP}^{N,K}}{x_{SP}^{N,G}}. \tag{4.53}$$

Implementing a cap policy leads to carbon leakage and it makes the fuel mix in country N dirtier. Deposit policies, in contrast, lead to a cleaner fuel mix in country N. We obtain the cleanest fuel mix in the social planner case. With strategic action, country M deviates from the optimal deposit purchase, as shown in Table 4.18. This deviation increases in absolute terms in $\forall f : \delta\eta^f$. Consequently, country M's deviation from the optimum is stronger in its coal deposit purchases compared with those of gas and, accordingly, the fuel mix in country N becomes dirtier than in the efficiency case.

Comparing both countries' welfare and climate damage for each policy case (see Tables 4.12-4.14 in Appendix 4.C for the closed-form results), we find

Proposition 4.10. *In the case of perfectly segmented markets and strictly positive trade on both deposit markets, the welfare of both countries in the different policy scenarios follows exactly the same order as in Eq. (4.30), where fuels are perfect substitutes, i.e.*

$$\begin{aligned} &U^M_{SP} > U^M_D > U^M_{D,K} > U^M_{D,G} > U^M_C > U^M_*, \\ &U^N_* > U^N_D > U^N_{D,K} > U^N_{D,G} > U^N_C > U^N_{SP}. \end{aligned} \tag{4.54}$$

The ranking of climate damage, however, differs, so that we have

$$H_C > \left(H_{D,K} \lesseqgtr H_{D,G}\right) > H_D > H_{SP} = H_*, \tag{4.55}$$

where $H_{D,G} > H_{D,K}$ *iff* $\beta \le \frac{4}{13}\sqrt{{\kappa^G}^2 + 28\kappa^G + 1} + \frac{4(\kappa^G+1)}{13}$.

The last condition shows that climate damage can be bigger in the case of trading gas deposits only than in a scenario where only coal deposits are traded. The underlying condition is that gas is expensive to extract, which leads to high gas deposits prices, low gas deposit demand and consequently higher gas extraction and climate damage.

Finally, studying country M's welfare ranking through a political economy lens, we again rank the surplus of consumers and coal and gas producers to obtain (see Tables 4.15-4.17 in Appendix 4.C for results)

Proposition 4.11. *In the case of perfectly segmented markets and strictly positive trade on both deposit markets, the consumer and producers surplus in country M in the different policy scenarios are ranked as follows:*

$$\begin{aligned} &CS^M_C > \left(CS^M_{D,G} \lesseqgtr CS^M_{D,K}\right) > CS^M_D > CS^M_* \\ &PSK^M_* > PSK^M_{D,K} \equiv PSK^M_D > PSK^M_{D,G} \equiv PSK^M_C \\ &PSG^M_* > PSG^M_D \equiv PSG^M_{D,G} > PSG^M_{D,K} \equiv PSG^M_C. \end{aligned} \tag{4.56}$$

Consumers in country M favor a cap policy over any of the deposit policies as these cut fuel supply in country N, which increases fuel prices. Whether consumers prefer a deposit market for gas or coal only depends on the fuels' emission intensities and extraction cost parameters. Since the consumer surplus is decreasing in both parameters and gas is cleaner but more expensive to extract than coal, it is ambiguous which option consumers prefer (see derivatives of consumer surplus with respect to gas emission intensity and cost parameter as an example in Eq. (4.57) in Appendix 4.C). Deposit markets for one fuel only are strictly preferred to deposit markets covering both fuels, and consumers are worst off in the case of undistorted deposit markets where most deposits are purchased.

Coal and gas producers in country M prefer deposit markets without strategic action, as more deposits are purchased than in any other policy option and fuel prices are highest. Since markets are perfectly segmented, producers of either of the fuels are indifferent between deposit markets covering both fuels or only the fuel they extract. They strictly prefer those policy options to a scenario where deposit markets only cover the fuel they do not extract, which results in the same producer surplus as a cap policy.

4.C Parametric results

Applying the parametric functions Eq. (4.25)-(4.27) in section 4.4 to the general model for the different policy scenarios in section 4.3, we obtain the equilibrium prices and quantities when fuels are perfect substitutes as shown in Tables 4.1 and 4.2. For prices and quantities to be (strictly) positive in all policy scenarios, the parameters require to fulfill $\eta^K \leq \frac{7\eta^G}{5}$ and $\delta < \frac{2\alpha\kappa^G}{\beta\eta^K\kappa^G+2\beta\eta^K-\beta\eta^G+2\eta^K\kappa^G}$. For (strictly) positive prices and deposit markets covering gas deposits only, it must additionally hold that $\beta \leq \frac{2}{5}$.

Inserting these prices and quantities into the parametric functions yields benefits, costs, and climate damage (see Table 4.5) for the various policy scenarios. Further, inserting these results into the welfare functions in Eq. (4.1) and (4.2), as well as Eq. (4.5) and (4.6) for deposit markets, we obtain both countries' welfare when fuels are perfect substitutes as stated in Tables 4.3 and 4.4.

Country M's welfare can be disaggregated into the surplus of consumers and coal and gas producers as in Tables 4.6-4.8.

Table 4.1: Quantities and prices in the case of social planner, cap policy, and deposit markets case without strategic action, when fuels are perfect substitutes.

	Social planner	Cap policy	Deposit markets without strategic action
$\forall i : y^{i,K}$	$\frac{\kappa^G(\alpha-\delta\eta^K)+\beta\delta(\eta^G-\eta^K)}{\beta\kappa^G+\beta+\kappa^G}$	$\frac{\kappa^G(2\alpha-\delta\eta^K)+\beta\delta(\eta^G-\eta^K)}{2(\beta\kappa^G+\beta+\kappa^G)}$	$\frac{\kappa^G(\alpha-\delta\eta^K)+\beta\delta(\eta^G-\eta^K)}{\beta\kappa^G+\beta+\kappa^G}$
$\forall i : y^{i,G}$	$\frac{\alpha+\beta\delta\eta^K-(\beta+1)\delta\eta^G}{\beta\kappa^G+\beta+\kappa^G}$	$\frac{2\alpha+\beta\delta\eta^K-(\beta+1)\delta\eta^G}{2(\beta\kappa^G+\beta+\kappa^G)}$	$\frac{\alpha+\beta\delta\eta^K-(\beta+1)\delta\eta^G}{\beta\kappa^G+\beta+\kappa^G}$
$x^{M,K}$	$\frac{\kappa^G(\alpha-\delta\eta^K)+\beta\delta(\eta^G-\eta^K)}{\beta\kappa^G+\beta+\kappa^G}$	$\frac{2\kappa^G(\alpha-\delta\eta^K)+\beta\delta(\eta^G-\eta^K(\kappa^G+2))}{2(\beta\kappa^G+\beta+\kappa^G)}$	$\frac{\kappa^G(\alpha-\delta\eta^K)+\beta\delta(\eta^G-\eta^K)}{\beta\kappa^G+\beta+\kappa^G}$
$x^{M,G}$	$\frac{\alpha+\beta\delta\eta^K-(\beta+1)\delta\eta^G}{\beta\kappa^G+\beta+\kappa^G}$	$\frac{\frac{2\alpha\kappa^G+\beta\delta(\eta^K\kappa^G+\eta^G)}{2(\beta\kappa^G+\beta+\kappa^G)}-\delta\eta^G}{\kappa^G}$	$\frac{\alpha+\beta\delta\eta^K-(\beta+1)\delta\eta^G}{\beta\kappa^G+\beta+\kappa^G}$
$x^{N,K}$	$\frac{\kappa^G(\alpha-\delta\eta^K)+\beta\delta(\eta^G-\eta^K)}{\beta\kappa^G+\beta+\kappa^G}$	$\frac{2\alpha\kappa^G+\beta\delta(\eta^K\kappa^G+\eta^G)}{2(\beta\kappa^G+\beta+\kappa^G)}$	$\frac{\kappa^G(\alpha-\delta\eta^K)+\beta\delta(\eta^G-\eta^K)}{\beta\kappa^G+\beta+\kappa^G}$
$x^{N,G}$	$\frac{\alpha+\beta\delta\eta^K-(\beta+1)\delta\eta^G}{\beta\kappa^G+\beta+\kappa^G}$	$\frac{2\alpha\kappa^G+\beta\delta(\eta^K\kappa^G+\eta^G)}{2\kappa^G(\beta\kappa^G+\beta+\kappa^G)}$	$\frac{\alpha+\beta\delta\eta^K-(\beta+1)\delta\eta^G}{\beta\kappa^G+\beta+\kappa^G}$
$\forall f : p^f$	-	$\frac{2\alpha\kappa^G+\beta\delta(\eta^K\kappa^G+\eta^G)}{2(\beta\kappa^G+\beta+\kappa^G)}$	$\frac{\alpha\kappa^G+\beta\delta(\eta^K\kappa^G+\eta^G)}{\beta\kappa^G+\beta+\kappa^G}$
$\forall i : z^{i,K}$	-	-	$\delta\eta^K$
$\forall i : z^{i,G}$	-	-	$\frac{\delta\eta^G}{\kappa^G}$
$\forall f : p^{z,f}$	-	-	$\delta\eta^f$

Table 4.2: Quantities and prices on deposit markets, when fuels are perfect substitutes.

$\forall i : y^{i,K}$	$\frac{\beta\kappa^G(28\alpha(\kappa^G+1)-\delta\eta^K(16\kappa^G+45)+29\delta\eta^G)+8{\kappa^G}^2(4\alpha-3\delta\eta^K)-21\beta^2\delta(\kappa^G+1)(\eta^K-\eta^G)}{4(\beta\kappa^G+\beta+\kappa^G)(7\beta(\kappa^G+1)+8\kappa^G)}$
$\forall i : y^{i,G}$	$\frac{4\alpha+\frac{\delta\left(21\beta^2(\kappa^G+1)(\eta^K-\eta^G)+29\beta\eta^K\kappa^G-\beta\eta^G(45\kappa^G+16)-24\eta^G\kappa^G\right)}{7\beta(\kappa^G+1)+8\kappa^G}}{4(\beta\kappa^G+\beta+\kappa^G)}$
$x^{M,K}$	$\frac{\beta\kappa^G(7\alpha(\kappa^G+1)-3\delta\eta^K(3\kappa^G+5)+6\delta\eta^G)+8{\kappa^G}^2(\alpha-\delta\eta^K)+\beta^2(-\delta)(\kappa^G+1)(\eta^K(3\kappa^G+7)-4\eta^G)}{(\beta\kappa^G+\beta+\kappa^G)(7\beta(\kappa^G+1)+8\kappa^G)}$
$x^{M,G}$	$\frac{\beta\kappa^G(7\alpha(\kappa^G+1)+6\delta\eta^K\kappa^G-3\delta\eta^G(5\kappa^G+3))+8{\kappa^G}^2(\alpha-\delta\eta^G)+\beta^2\delta(\kappa^G+1)(4\eta^K\kappa^G-\eta^G(7\kappa^G+3))}{\kappa^G(\beta\kappa^G+\beta+\kappa^G)(7\beta(\kappa^G+1)+8\kappa^G)}$
$x^{N,K}$	$\frac{\beta\kappa^G(14\alpha(\kappa^G+1)+\delta\eta^K(2\kappa^G-15)+17\delta\eta^G)+8{\kappa^G}^2(2\alpha-\delta\eta^K)+\beta^2\delta(\kappa^G+1)(\eta^K(6\kappa^G-7)+13\eta^G)}{2(\beta\kappa^G+\beta+\kappa^G)(7\beta(\kappa^G+1)+8\kappa^G)}$
$x^{N,G}$	$\frac{\beta\kappa^G(14\alpha(\kappa^G+1)+17\delta\eta^K\kappa^G+\delta\eta^G(2-15\kappa^G))+8{\kappa^G}^2(2\alpha-\delta\eta^G)+\beta^2\delta(\kappa^G+1)(13\eta^K\kappa^G+\eta^G(6-7\kappa^G))}{2\kappa^G(\beta\kappa^G+\beta+\kappa^G)(7\beta(\kappa^G+1)+8\kappa^G)}$
$x^{M,K}-y^{M,K}$	$-\frac{\delta(\beta\eta^K(12\kappa^G+7)+5\beta\eta^G+8\eta^K\kappa^G)}{4(7\beta(\kappa^G+1)+8\kappa^G)} < 0$
$x^{M,G}-y^{M,G}$	$-\frac{\delta(5\beta\eta^K\kappa^G+\beta\eta^G(7\kappa^G+12)+8\eta^G\kappa^G)}{4\kappa^G(7\beta(\kappa^G+1)+8\kappa^G)} < 0$
$\forall i : z^{i,K}$	$\frac{\delta(\beta\eta^K(2\kappa^G+7)-5\beta\eta^G+8\eta^K\kappa^G)}{2(7\beta(\kappa^G+1)+8\kappa^G)}$
$\forall i : z^{i,G}$	$\frac{\delta(-5\beta\eta^K\kappa^G+\beta\eta^G(7\kappa^G+2)+8\eta^G\kappa^G)}{2\kappa^G(7\beta(\kappa^G+1)+8\kappa^G)}$
$\forall f : p^f$	$\frac{\beta\kappa^G(7\alpha(\kappa^G+1)+6\delta(\eta^K\kappa^G+\eta^G))+8\alpha{\kappa^G}^2+4\beta^2\delta(\kappa^G+1)(\eta^K\kappa^G+\eta^G)}{(\beta\kappa^G+\beta+\kappa^G)(7\beta(\kappa^G+1)+8\kappa^G)}$
$p^{z,K}$	$\frac{\delta(\beta\eta^K(2\kappa^G+7)-5\beta\eta^G+8\eta^K\kappa^G)}{2(7\beta(\kappa^G+1)+8\kappa^G)}$
$p^{z,G}$	$\frac{\delta(-5\beta\eta^K\kappa^G+\beta\eta^G(7\kappa^G+2)+8\eta^G\kappa^G)}{2(7\beta(\kappa^G+1)+8\kappa^G)}$

Table 4.3: Welfare of country M in different scenarios, when fuels are perfect substitutes.

Scenario	U^M
Social planner	$\frac{\alpha^2(\kappa^G+1)-4\alpha\delta(\eta^K\kappa^G+\eta^G)+3\delta^2\left(\beta(\eta^K-\eta^G)^2+{\eta^K}^2\kappa^G+{\eta^G}^2\right)}{2(\beta\kappa^G+\beta+\kappa^G)}$
Cap	$\frac{4\kappa^G\left(\alpha^2(\kappa^G+1)-4\alpha\delta(\eta^K\kappa^G+\eta^G)+\delta^2\left({\eta^K}^2\kappa^G+{\eta^G}^2\right)\right)+\beta\delta^2\left({\eta^K}^2(4-3\kappa^G)\kappa^G-14\eta^K\eta^G\kappa^G+{\eta^G}^2(4\kappa^G-3)\right)}{8\kappa^G(\beta\kappa^G+\beta+\kappa^G)}$
Deposit	$\frac{\beta\kappa^G\left(14\alpha^2(\kappa^G+1)^2-56\alpha\delta(\kappa^G+1)(\eta^K\kappa^G+\eta^G)+3\delta^2\left({\eta^K}^2\kappa^G(2\kappa^G+15)-26\eta^K\eta^G\kappa^G+{\eta^G}^2(15\kappa^G+2)\right)\right)}{4\kappa^G(\beta\kappa^G+\beta+\kappa^G)(7\beta(\kappa^G+1)+8\kappa^G)}$ $+\frac{8{\kappa^G}^2\left(2\alpha^2(\kappa^G+1)-8\alpha\delta(\eta^K\kappa^G+\eta^G)+3\delta^2\left({\eta^K}^2\kappa^G+{\eta^G}^2\right)\right)+\beta^2\delta^2(\kappa^G+1)\left({\eta^K}^2(21-10\kappa^G)\kappa^G-62\eta^K\eta^G\kappa^G+{\eta^G}^2(21\kappa^G-10)\right)}{4\kappa^G(\beta\kappa^G+\beta+\kappa^G)(7\beta(\kappa^G+1)+8\kappa^G)}$
Efficiency	$\frac{\kappa^G\left(\alpha^2(\kappa^G+1)-4\alpha\delta(\eta^K\kappa^G+\eta^G)+\delta^2\left({\eta^K}^2\kappa^G+{\eta^G}^2\right)\right)+\beta\delta^2\left({\eta^K}^2(1-2\kappa^G)\kappa^G-6\eta^K\eta^G\kappa^G+{\eta^G}^2(\kappa^G-2)\right)}{2\kappa^G(\beta\kappa^G+\beta+\kappa^G)}$
Coal deposits	$\frac{\beta\kappa^G\left(\alpha^2\left(7{\kappa^G}^2+15\kappa^G+8\right)-4\alpha\delta(7\kappa^G+8)(\eta^K\kappa^G+\eta^G)+\delta^2\left(3{\eta^K}^2\kappa^G(\kappa^G+8)-34\eta^K\eta^G\kappa^G+{\eta^G}^2(15\kappa^G+2)\right)\right)}{2\kappa^G(\beta\kappa^G+\beta+\kappa^G)(\beta(7\kappa^G+8)+8\kappa^G)}$ $+\frac{4{\kappa^G}^2\left(2\alpha^2(\kappa^G+1)-8\alpha\delta(\eta^K\kappa^G+\eta^G)+\delta^2\left(3{\eta^K}^2\kappa^G+2{\eta^G}^2\right)\right)+\beta^2\delta^2\left({\eta^K}^2\kappa^G\left(-5{\kappa^G}^2+3\kappa^G+12\right)-2\eta^K\eta^G\kappa^G(13\kappa^G+17)+{\eta^G}^2\left(7{\kappa^G}^2+4\kappa^G-6\right)\right)}{2\kappa^G(\beta\kappa^G+\beta+\kappa^G)(\beta(7\kappa^G+8)+8\kappa^G)}$
Gas deposits	$\frac{\beta\kappa^G\left(\alpha^2\left(8{\kappa^G}^2+15\kappa^G+7\right)-4\alpha\delta(8\kappa^G+7)(\eta^K\kappa^G+\eta^G)+\delta^2\left({\eta^K}^2\kappa^G(2\kappa^G+15)-34\eta^K\eta^G\kappa^G+3{\eta^G}^2(8\kappa^G+1)\right)\right)}{2\kappa^G(\beta\kappa^G+\beta+\kappa^G)(\beta(8\kappa^G+7)+8\kappa^G)}$ $+\frac{4{\kappa^G}^2\left(2\alpha^2(\kappa^G+1)-8\alpha\delta(\eta^K\kappa^G+\eta^G)+\delta^2\left(2{\eta^K}^2\kappa^G+3{\eta^G}^2\right)\right)+\beta^2\delta^2\left({\eta^K}^2\kappa^G\left(-6{\kappa^G}^2+4\kappa^G+7\right)-2\eta^K\eta^G\kappa^G(17\kappa^G+13)+{\eta^G}^2\left(12{\kappa^G}^2+3\kappa^G-5\right)\right)}{2\kappa^G(\beta\kappa^G+\beta+\kappa^G)(\beta(8\kappa^G+7)+8\kappa^G)}$

Table 4.4: Welfare of country N in different scenarios, when fuels are perfect substitutes.

Scenario	U^N
Social planner	$\frac{\alpha^2(\kappa^G+1)-\delta^2\left(\beta(\eta^K-\eta^G)^2+{\eta^K}^2\kappa^G+{\eta^G}^2\right)}{2(\beta\kappa^G+\beta+\kappa^G)}$
Cap	$\frac{4\alpha^2\kappa^G(\kappa^G+1)+\beta\delta^2(\eta^K\kappa^G+\eta^G)^2}{8\kappa^G(\beta\kappa^G+\beta+\kappa^G)}$
Deposit	$\frac{\beta^2\kappa^G(\kappa^G+1)\left(196\alpha^2(\kappa^G+1)^2+\delta^2\left({\eta^K}^2\kappa^G(228\kappa^G+161)+134\eta^K\eta^G\kappa^G+{\eta^G}^2(161\kappa^G+228)\right)\right)}{8\kappa^G(\beta\kappa^G+\beta+\kappa^G)(7\beta(\kappa^G+1)+8\kappa^G)^2}$ $+\frac{16\beta{\kappa^G}^2\left(28\alpha^2(\kappa^G+1)^2+\delta^2\left({\eta^K}^2\kappa^G(15\kappa^G+11)+8\eta^K\eta^G\kappa^G+{\eta^G}^2(11\kappa^G+15)\right)\right)}{8\kappa^G(\beta\kappa^G+\beta+\kappa^G)(7\beta(\kappa^G+1)+8\kappa^G)^2}$ $+\frac{64{\kappa^G}^3\left(4\alpha^2(\kappa^G+1)+\delta^2\left({\eta^K}^2\kappa^G+{\eta^G}^2\right)\right)+\beta^3\delta^2(\kappa^G+1)^2\left({\eta^K}^2\kappa^G(68\kappa^G+49)+38\eta^K\eta^G\kappa^G+{\eta^G}^2(49\kappa^G+68)\right)}{8\kappa^G(\beta\kappa^G+\beta+\kappa^G)(7\beta(\kappa^G+1)+8\kappa^G)^2}$
Efficiency	$\frac{\kappa^G\left(\alpha^2(\kappa^G+1)+\delta^2\left({\eta^K}^2\kappa^G+{\eta^G}^2\right)\right)+\beta\delta^2\left({\eta^K}^2\kappa^G(2\kappa^G+1)+2\eta^K\eta^G\kappa^G+{\eta^G}^2(\kappa^G+2)\right)}{2\kappa^G(\beta\kappa^G+\beta+\kappa^G)}$
Coal deposits	$\frac{\beta^2\kappa^G\left(\alpha^2(\kappa^G+1)(7\kappa^G+8)^2+\delta^2\left(3{\eta^K}^2\kappa^G\left(19{\kappa^G}^2+40\kappa^G+16\right)+2\eta^K\eta^G\kappa^G(29\kappa^G+40)+{\eta^G}^2(25\kappa^G+32)\right)\right)}{2\kappa^G(\beta\kappa^G+\beta+\kappa^G)(\beta(7\kappa^G+8)+8\kappa^G)^2}$ $+\frac{4\beta{\kappa^G}^2\left(4\alpha^2\left(7{\kappa^G}^2+15\kappa^G+8\right)+\delta^2\left(3{\eta^K}^2\kappa^G(5\kappa^G+4)+10\eta^K\eta^G\kappa^G+4{\eta^G}^2\right)\right)}{2\kappa^G(\beta\kappa^G+\beta+\kappa^G)(\beta(7\kappa^G+8)+8\kappa^G)^2}$ $+\frac{16{\kappa^G}^3\left(4\alpha^2(\kappa^G+1)+\delta^2{\eta^K}^2\kappa^G\right)+\beta^3\delta^2\left({\eta^K}^2\kappa^G\left(17{\kappa^G}^3+57{\kappa^G}^2+60\kappa^G+16\right)+2\eta^K\eta^G\kappa^G\left(11{\kappa^G}^2+29\kappa^G+20\right)+{\eta^G}^2\left(10{\kappa^G}^2+25\kappa^G+16\right)\right)}{2\kappa^G(\beta\kappa^G+\beta+\kappa^G)(\beta(7\kappa^G+8)+8\kappa^G)^2}$
Gas deposits	$\frac{\beta^2\kappa^G\left(\alpha^2(\kappa^G+1)(8\kappa^G+7)^2+\delta^2\left({\eta^K}^2{\kappa^G}^2(32\kappa^G+25)+2\eta^K\eta^G\kappa^G(40\kappa^G+29)+3{\eta^G}^2\left(16{\kappa^G}^2+40\kappa^G+19\right)\right)\right)}{2\kappa^G(\beta\kappa^G+\beta+\kappa^G)(\beta(8\kappa^G+7)+8\kappa^G)^2}$ $+\frac{4\beta{\kappa^G}^2\left(4\alpha^2\left(8{\kappa^G}^2+15\kappa^G+7\right)+\delta^2\left(4{\eta^K}^2{\kappa^G}^2+10\eta^K\eta^G\kappa^G+3{\eta^G}^2(4\kappa^G+5)\right)\right)}{2\kappa^G(\beta\kappa^G+\beta+\kappa^G)(\beta(8\kappa^G+7)+8\kappa^G)^2}$ $+\frac{16{\kappa^G}^3\left(4\alpha^2(\kappa^G+1)+\delta^2{\eta^G}^2\right)+\beta^3\delta^2\left({\eta^K}^2{\kappa^G}^2\left(16{\kappa^G}^2+25\kappa^G+10\right)+2\eta^K\eta^G\kappa^G\left(20{\kappa^G}^2+29\kappa^G+11\right)+{\eta^G}^2\left(16{\kappa^G}^3+60{\kappa^G}^2+57\kappa^G+17\right)\right)}{2\kappa^G(\beta\kappa^G+\beta+\kappa^G)(\beta(8\kappa^G+7)+8\kappa^G)^2}$

Table 4.5: Climate damage in different scenarios, when fuels are perfect substitutes.

Scenario	H
Social planner	$-\frac{2\delta(-\alpha(\eta^{K}\kappa^{G}+\eta^{G})+\beta\delta(\eta^{K}-\eta^{G})^{2}+\delta(\eta^{K\,2}\kappa^{G}+\eta^{G\,2}))}{\beta\kappa^{G}+\beta+\kappa^{G}}$
Cap	$-\frac{\delta(-2\alpha(\eta^{K}\kappa^{G}+\eta^{G})+\beta\delta(\eta^{K}-\eta^{G})^{2}+\delta(\eta^{K\,2}\kappa^{G}+\eta^{G\,2}))}{\beta\kappa^{G}+\beta+\kappa^{G}}$
Deposit	$-\frac{\delta(-28\alpha\beta(\kappa^{G}+1)(\eta^{K}\kappa^{G}+\eta^{G})-32\alpha\kappa^{G}(\eta^{K}\kappa^{G}+\eta^{G})+21\beta^{2}\delta(\kappa^{G}+1)(\eta^{K}-\eta^{G})^{2})}{2(\beta\kappa^{G}+\beta+\kappa^{G})(7\beta(\kappa^{G}+1)+8\kappa^{G})}$
	$-\frac{\delta(\beta\delta(\eta^{K\,2}\kappa^{G}(16\kappa^{G}+45)-58\eta^{K}\eta^{G}\kappa^{G}+\eta^{G\,2}(45\kappa^{G}+16))+24\delta\kappa^{G}(\eta^{K\,2}\kappa^{G}+\eta^{G\,2}))}{2(\beta\kappa^{G}+\beta+\kappa^{G})(7\beta(\kappa^{G}+1)+8\kappa^{G})}$
Efficiency	$-\frac{2\delta(-\alpha(\eta^{K}\kappa^{G}+\eta^{G})+\beta\delta(\eta^{K}-\eta^{G})^{2}+\delta(\eta^{K\,2}\kappa^{G}+\eta^{G\,2}))}{\beta\kappa^{G}+\beta+\kappa^{G}}$
Coal deposits	$-\frac{\delta(\beta(\delta(8\eta^{K\,2}\kappa^{G}(\kappa^{G}+3)-21\eta^{K}\eta^{G}\kappa^{G}+\eta^{G\,2}(15\kappa^{G}+8))-2\alpha(7\kappa^{G}+8)(\eta^{K}\kappa^{G}+\eta^{G}))))}{(\beta\kappa^{G}+\beta+\kappa^{G})(\beta(7\kappa^{G}+8)+8\kappa^{G})}$
	$-\frac{\delta(4\kappa^{G}(\delta(3\eta^{K\,2}\kappa^{G}+2\eta^{G\,2})-4\alpha(\eta^{K}\kappa^{G}+\eta^{G}))+\beta^{2}\delta(\eta^{K}-\eta^{G})(4\eta^{K}(2\kappa^{G}+3)-\eta^{G}(7\kappa^{G}+9)))}{(\beta\kappa^{G}+\beta+\kappa^{G})(\beta(7\kappa^{G}+8)+8\kappa^{G})}$
Gas deposits	$-\frac{\delta(\beta(\delta(\eta^{K\,2}\kappa^{G}(8\kappa^{G}+15)-21\eta^{K}\eta^{G}\kappa^{G}+8\eta^{G\,2}(3\kappa^{G}+1))-2\alpha(8\kappa^{G}+7)(\eta^{K}\kappa^{G}+\eta^{G})))}{(\beta\kappa^{G}+\beta+\kappa^{G})(\beta(8\kappa^{G}+7)+8\kappa^{G})}$
	$-\frac{\delta(4\kappa^{G}(\delta(2\eta^{K\,2}\kappa^{G}+3\eta^{G\,2})-4\alpha(\eta^{K}\kappa^{G}+\eta^{G}))+\beta^{2}\delta(\eta^{K}-\eta^{G})(\eta^{K}(9\kappa^{G}+7)-4\eta^{G}(3\kappa^{G}+2))}{(\beta\kappa^{G}+\beta+\kappa^{G})(\beta(8\kappa^{G}+7)+8\kappa^{G})}$

Table 4.9 shows the difference in quantities and prices for the deposit markets with and without strategic action.

Following the same steps as in the case, where fuels are substitutes, we can calculate prices and quantities for the various policy scenarios, when fuel markets are perfectly segmented and obtain the results in Tables 4.10 and 4.11. For prices and quantities to be (strictly) positive in all policy scenarios, the parameters require to fulfill $\delta < \frac{2\alpha}{\beta\eta^{G}+2\eta^{G}}$ and $\eta^{K} < \frac{2\alpha}{\beta\delta+2\delta}$.

Further, we can compute benefits, costs, and climate damage (see Table 4.14) for the various policy scenarios. By inserting these results into the welfare functions in Eq. (4.1), (4.2), (4.5), and (4.6), we obtain both countries' welfare in the various policy scenarios when fuel markets are perfectly segmented as stated in Tables 4.12 and 4.13.

Country M's welfare can be disaggregated into the surplus of consumers and coal and gas producers as in Tables 4.15-4.17.

Table 4.6: Consumer surplus in different scenarios, when fuels are perfect substitutes.

Scenario	CS^M
Cap	$\frac{\beta(\delta(\eta^K\kappa^G+\eta^G)-2\alpha(\kappa^G+1))^2}{8(\beta\kappa^G+\beta+\kappa^G)^2}$
Deposit	$\frac{\beta(\alpha(\kappa^G+1)(7\beta(\kappa^G+1)+8\kappa^G)-2\delta(2\beta(\kappa^G+1)+3\kappa^G)(\eta^K\kappa^G+\eta^G))^2}{2(\beta\kappa^G+\beta+\kappa^G)^2(7\beta(\kappa^G+1)+8\kappa^G)^2}$
Efficiency	$\frac{\beta(\alpha(\kappa^G+1)-\delta(\eta^K\kappa^G+\eta^G))^2}{2(\beta\kappa^G+\beta+\kappa^G)^2}$
Coal deposits	$\frac{\beta(\alpha(\kappa^G+1)(\beta(7\kappa^G+8)+8\kappa^G)-\delta(2\beta\eta^K\kappa^G(2\kappa^G+3)+\beta\eta^G(3\kappa^G+4)+2\kappa^G(3\eta^K\kappa^G+2\eta^G)))^2}{2(\beta\kappa^G+\beta+\kappa^G)^2(\beta(7\kappa^G+8)+8\kappa^G)^2}$
Gas deposits	$\frac{\beta(\alpha(\kappa^G+1)(\beta(8\kappa^G+7)+8\kappa^G)-\delta(\beta\eta^K\kappa^G(4\kappa^G+3)+\beta\eta^G(6\kappa^G+4)+2\kappa^G(2\eta^K\kappa^G+3\eta^G)))^2}{2(\beta\kappa^G+\beta+\kappa^G)^2(\beta(8\kappa^G+7)+8\kappa^G)^2}$

Table 4.7: Coal producer surplus in different scenarios, when fuels are perfect substitutes.

Scenario	PSK^M
Cap	$-\frac{(\beta\delta(\eta^K(\kappa^G+2)-\eta^G)-2\kappa^G(\alpha-\delta\eta^K))(2\kappa^G(\alpha+\delta\eta^K)+\beta\delta(\eta^K(3\kappa^G+2)+\eta^G))}{8(\beta\kappa^G+\beta+\kappa^G)^2}$
Deposit	$-\frac{\left(\beta\kappa^G(-7\alpha(\kappa^G+1)+3\delta\eta^K(3\kappa^G+5)-6\delta\eta^G)-8{\kappa^G}^2(\alpha-\delta\eta^K)+\beta^2\delta(\kappa^G+1)(\eta^K(3\kappa^G+7)-4\eta^G)\right)}{2(\beta\kappa^G+\beta+\kappa^G)^2(7\beta(\kappa^G+1)+8\kappa^G)^2}$ $\cdot\frac{\left(\beta\kappa^G(7\alpha(\kappa^G+1)+3\delta\eta^K(7\kappa^G+5)+6\delta\eta^G)+8{\kappa^G}^2(\alpha+\delta\eta^K)+\beta^2\delta(\kappa^G+1)(\eta^K(11\kappa^G+7)+4\eta^G)\right)}{2(\beta\kappa^G+\beta+\kappa^G)^2(7\beta(\kappa^G+1)+8\kappa^G)^2}$
Efficiency	$-\frac{(-\alpha\kappa^G+\beta\delta(\eta^K-\eta^G)+\delta\eta^K\kappa^G)(\kappa^G(\alpha+\delta\eta^K)+\beta\delta(2\eta^K\kappa^G+\eta^K+\eta^G))}{2(\beta\kappa^G+\beta+\kappa^G)^2}$
Coal deposits	$\frac{1}{8}\left(\frac{\left(2\alpha\kappa^G+\frac{\beta\delta\kappa^G(\beta\eta^K(\kappa^G+4)-\beta\eta^G+4\eta^K\kappa^G)}{\beta(7\kappa^G+8)+8\kappa^G}+\beta\delta(\eta^K\kappa^G+\eta^G)\right)^2}{(\beta\kappa^G+\beta+\kappa^G)^2}-4\delta^2{\eta^K}^2\right)$
Gas deposits	$\frac{1}{8}\left(\frac{\left(2\alpha\kappa^G+\beta\delta(\eta^K\kappa^G+\eta^G)+\frac{\beta\delta(\beta(-\eta^K\kappa^G+4\eta^G\kappa^G+\eta^G)+4\eta^G\kappa^G)}{\beta(8\kappa^G+7)+8\kappa^G}\right)^2}{(\beta\kappa^G+\beta+\kappa^G)^2}-4\delta^2{\eta^K}^2\right)$

Table 4.8: Gas producer surplus in different scenarios, when fuels are perfect substitutes.

Scenario	PSG^M
Cap	$-\frac{(\beta\delta(-\eta^K\kappa^G+2\eta^G\kappa^G+\eta^G)-2\kappa^G(\alpha-\delta\eta^G))(2\kappa^G(\alpha+\delta\eta^G)+\beta\delta(\eta^K\kappa^G+\eta^G(2\kappa^G+3)))}{8\kappa^G(\beta\kappa^G+\beta+\kappa^G)^2}$
Deposit	$-\frac{\left(\beta\kappa^G(-7\alpha(\kappa^G+1)-6\delta\eta^K\kappa^G+3\delta\eta^G(5\kappa^G+3))-8{\kappa^G}^2(\alpha-\delta\eta^G)+\beta^2\delta(\kappa^G+1)(\eta^G(7\kappa^G+3)-4\eta^K\kappa^G)\right)}{2\kappa^G(\beta\kappa^G+\beta+\kappa^G)^2(7\beta(\kappa^G+1)+8\kappa^G)^2}$ $\cdot\frac{\left(\beta\kappa^G(7\alpha(\kappa^G+1)+6\delta\eta^K\kappa^G+3\delta\eta^G(5\kappa^G+7))+8{\kappa^G}^2(\alpha+\delta\eta^G)+\beta^2\delta(\kappa^G+1)(4\eta^K\kappa^G+\eta^G(7\kappa^G+11))\right)}{2\kappa^G(\beta\kappa^G+\beta+\kappa^G)^2(7\beta(\kappa^G+1)+8\kappa^G)^2}$
Efficiency	$\frac{(\alpha+\beta\delta\eta^K-(\beta+1)\delta\eta^G)(\kappa^G(\alpha+\delta\eta^G)+\beta\delta(\eta^K\kappa^G+\eta^G(\kappa^G+2)))}{2(\beta\kappa^G+\beta+\kappa^G)^2}$
Coal deposits	$\frac{\frac{\left(\beta\kappa^G\left(-2\alpha+\frac{\delta(\beta\eta^K(\kappa^G+4)-\beta\eta^G+4\eta^K\kappa^G)}{\beta(7\kappa^G+8)+8\kappa^G}+\delta\eta^K\right)+\beta(2\alpha\kappa^G+\delta\eta^G)+2\alpha\kappa^G\right)^2}{(\beta\kappa^G+\beta+\kappa^G)^2}-4\delta^2{\eta^G}^2}{8\kappa^G}$
Gas deposits	$\frac{\frac{\left(2\alpha\kappa^G+\frac{\beta\delta(\beta(-\eta^K\kappa^G+4\eta^G\kappa^G+\eta^G)+4\eta^G\kappa^G)}{\beta(8\kappa^G+7)+8\kappa^G}+\beta\delta\eta^K\kappa^G+\beta\delta\eta^G\right)^2}{(\beta\kappa^G+\beta+\kappa^G)^2}-4\delta^2{\eta^G}^2}{8\kappa^G}$

Table 4.9: Strategic deposit policy: deviation from efficiency, when fuels are perfect substitutes.

	Deviations from efficiency
$\forall i : z^{i,K} - z_*^{i,K}$	$-\frac{\delta(\beta\eta^K(12\kappa^G+7)+5\beta\eta^G+8\eta^K\kappa^G)}{2(7\beta(\kappa^G+1)+8\kappa^G)} < 0$
$\forall i : z^{i,G} - z_*^{i,G}$	$-\frac{\delta(5\beta\eta^K\kappa^G+\beta\eta^G(7\kappa^G+12)+8\eta^G\kappa^G)}{2\kappa^G(7\beta(\kappa^G+1)+8\kappa^G)} < 0$
$\forall f : p^f - p_*^f$	$-\frac{\beta\delta(3\beta(\kappa^G+1)+2\kappa^G)(\eta^K\kappa^G+\eta^G)}{(\beta\kappa^G+\beta+\kappa^G)(7\beta(\kappa^G+1)+8\kappa^G)} < 0$
$p^{z,K} - p_*^{z,K}$	$-\frac{\delta(\beta\eta^K(12\kappa^G+7)+5\beta\eta^G+8\eta^K\kappa^G)}{2(7\beta(\kappa^G+1)+8\kappa^G)} < 0$
$p^{z,G} - p_*^{z,G}$	$-\frac{\delta(5\beta\eta^K\kappa^G+\beta\eta^G(7\kappa^G+12)+8\eta^G\kappa^G)}{2(7\beta(\kappa^G+1)+8\kappa^G)} < 0$

Table 4.10: Quantities and prices in the case of social planner, cap policy, and deposit markets case without strategic action, when markets are perfectly segmented.

	Social planner	Cap policy	Deposit markets without strategic action
$\forall i : y^{i,K}$	$\frac{\alpha-\delta\eta^K}{\beta+1}$	$\frac{2\alpha-\delta\eta^K}{2\beta+2}$	$\frac{\alpha-\delta\eta^K}{\beta+1}$
$\forall i : y^{i,G}$	$\frac{\alpha-\delta\eta^G}{\beta+\kappa^G}$	$\frac{2\alpha-\delta\eta^G}{2(\beta+\kappa^G)}$	$\frac{\alpha-\delta\eta^G}{\beta+\kappa^G}$
$x^{M,K}$	$\frac{\alpha-\delta\eta^K}{\beta+1}$	$\frac{2\alpha-(\beta+2)\delta\eta^K}{2(\beta+1)}$	$\frac{\alpha-\delta\eta^K}{\beta+1}$
$x^{M,G}$	$\frac{\alpha-\delta\eta^G}{\beta+\kappa^G}$	$-\frac{-2\alpha\kappa^G+\beta\delta\eta^G+2\delta\eta^G\kappa^G}{2\beta\kappa^G+2{\kappa^G}^2}$	$\frac{\alpha-\delta\eta^G}{\beta+\kappa^G}$
$x^{N,K}$	$\frac{\alpha-\delta\eta^K}{\beta+1}$	$\frac{2\alpha+\beta\delta\eta^K}{2\beta+2}$	$\frac{\alpha-\delta\eta^K}{\beta+1}$
$x^{N,G}$	$\frac{\alpha-\delta\eta^G}{\beta+\kappa^G}$	$\frac{2\alpha\kappa^G+\beta\delta\eta^G}{2\beta\kappa^G+2{\kappa^G}^2}$	$\frac{\alpha-\delta\eta^G}{\beta+\kappa^G}$
p^K	-	$\frac{2\alpha+\beta\delta\eta^K}{2\beta+2}$	$\frac{\alpha+\beta\delta\eta^K}{\beta+1}$
p^G	-	$\frac{2\alpha\kappa^G+\beta\delta\eta^G}{2(\beta+\kappa^G)}$	$\frac{\alpha\kappa^G+\beta\delta\eta^G}{\beta+\kappa^G}$
$\forall i : z^{i,K}$	-	-	$\delta\eta^K$
$\forall i : z^{i,G}$	-	-	$\frac{\delta\eta^G}{\kappa^G}$
$\forall f : p^{z,f}$	-	-	$\delta\eta^f$

Table 4.11: Quantities and prices on deposit markets, when markets are perfectly segmented.

$\forall i : y^{i,K}$	$\frac{\alpha(7\beta+8)-2(2\beta+3)\delta\eta^K}{(\beta+1)(7\beta+8)}$
$\forall i : y^{i,G}$	$\frac{7\alpha\beta+8\alpha\kappa^G-4\beta\delta\eta^G-6\delta\eta^G\kappa^G}{(\beta+\kappa^G)(7\beta+8\kappa^G)}$
$x^{M,K}$	$\frac{\alpha(7\beta+8)-\left(3\beta^2+9\beta+8\right)\delta\eta^K}{(\beta+1)(7\beta+8)}$
$x^{M,G}$	$\frac{\beta\kappa^G(7\alpha-9\delta\eta^G)+8\kappa^{G^2}(\alpha-\delta\eta^G)-3\beta^2\delta\eta^G}{\kappa^G(\beta+\kappa^G)(7\beta+8\kappa^G)}$
$x^{N,K}$	$\frac{\alpha(7\beta+8)+\left(3\beta^2+\beta-4\right)\delta\eta^K}{(\beta+1)(7\beta+8)}$
$x^{N,G}$	$\frac{\beta\kappa^G(7\alpha+\delta\eta^G)+4\kappa^{G^2}(2\alpha-\delta\eta^G)+3\beta^2\delta\eta^G}{\kappa^G(\beta+\kappa^G)(7\beta+8\kappa^G)}$
$x^{M,K} - y^{M,K}$	$-\frac{(3\beta+2)\delta\eta^K}{7\beta+8} < 0$
$x^{M,G} - y^{M,G}$	$-\frac{\delta\eta^G(3\beta+2\kappa^G)}{\kappa^G(7\beta+8\kappa^G)} < 0$
$\forall i : z^{i,K}$	$\frac{(\beta+4)\delta\eta^K}{7\beta+8}$
$\forall i : z^{i,G}$	$\frac{\delta\eta^G(\beta+4\kappa^G)}{\kappa^G(7\beta+8\kappa^G)}$
p^K	$\frac{\alpha(7\beta+8)+2\beta(2\beta+3)\delta\eta^K}{(\beta+1)(7\beta+8)}$
p^G	$\frac{\beta\kappa^G(7\alpha+6\delta\eta^G)+8\alpha\kappa^{G^2}+4\beta^2\delta\eta^G}{(\beta+\kappa^G)(7\beta+8\kappa^G)}$
$p^{z,K}$	$\frac{(\beta+4)\delta\eta^K}{7\beta+8}$
$p^{z,G}$	$\frac{\delta\eta^G(\beta+4\kappa^G)}{7\beta+8\kappa^G}$

Table 4.12: Welfare of country M in different scenarios, when markets are perfectly segmented.

Scenario	U^M
Social planner	$\frac{\alpha^2(2\beta+\kappa^G+1)-4\alpha\delta(\beta(\eta^K+\eta^G)+\eta^K\kappa^G+\eta^G)+3\delta^2\left(\beta\left(\eta^{K\,2}+\eta^{G\,2}\right)+\eta^{K\,2}\kappa^G+\eta^{G\,2}\right)}{2(\beta+1)(\beta+\kappa^G)}$
Cap	$\frac{\beta\left(8\alpha^2\kappa^G-16\alpha\delta\kappa^G(\eta^K+\eta^G)+\delta^2\left(\eta^{K\,2}(4-3\kappa^G)\kappa^G+\eta^{G\,2}(4\kappa^G-3)\right)\right)+4\kappa^G\left(\alpha^2(\kappa^G+1)-4\alpha\delta(\eta^K\kappa^G+\eta^G)+\delta^2\left(\eta^{K\,2}\kappa^G+\eta^{G\,2}\right)\right)-3\beta^2\delta^2\left(\eta^{K\,2}\kappa^G+\eta^{G\,2}\right)}{8(\beta+1)\kappa^G(\beta+\kappa^G)}$
Deposit	$\frac{\beta^3\left(98\alpha^2\kappa^G-196\alpha\delta\kappa^G(\eta^K+\eta^G)+3\delta^2\left(\eta^{K\,2}(7-25\kappa^G)\kappa^G+\eta^{G\,2}(7\kappa^G-25)\right)\right)+32\kappa^{G\,2}\left(2\alpha^2(\kappa^G+1)-8\alpha\delta(\eta^K\kappa^G+\eta^G)+3\delta^2\left(\eta^{K\,2}\kappa^G+\eta^{G\,2}\right)\right)-35\beta^4\delta^2\left(\eta^{K\,2}\kappa^G+\eta^{G\,2}\right)}{2(\beta+1)(7\beta+8)\kappa^G(\beta+\kappa^G)(7\beta+8\kappa^G)}$ $+\frac{\beta^2\left(161\alpha^2\kappa^G(\kappa^G+1)-28\alpha\delta\kappa^G(\eta^K(15\kappa^G+8)+\eta^G(8\kappa^G+15))+\delta^2\left(\eta^{K\,2}\kappa^G\left(-40\kappa^{G\,2}+45\kappa^G+84\right)+\eta^{G\,2}\left(84\kappa^{G\,2}+45\kappa^G-40\right)\right)\right)}{2(\beta+1)(7\beta+8)\kappa^G(\beta+\kappa^G)(7\beta+8\kappa^G)}$ $+\frac{4\beta\kappa^G\left(2\alpha^2\left(7\kappa^{G\,2}+30\kappa^G+7\right)-8\alpha\delta(\eta^K\kappa^G(7\kappa^G+15)+\eta^G(15\kappa^G+7))+3\delta^2\left(\eta^{K\,2}\kappa^G(2\kappa^G+15)+\eta^{G\,2}(15\kappa^G+2)\right)\right)}{2(\beta+1)(7\beta+8)\kappa^G(\beta+\kappa^G)(7\beta+8\kappa^G)}$
Efficiency	$\frac{\beta\left(2\alpha^2\kappa^G-4\alpha\delta\kappa^G(\eta^K+\eta^G)+\delta^2\left(\eta^{K\,2}(1-2\kappa^G)\kappa^G+\eta^{G\,2}(\kappa^G-2)\right)\right)+\kappa^G\left(\alpha^2(\kappa^G+1)-4\alpha\delta(\eta^K\kappa^G+\eta^G)+\delta^2\left(\eta^{K\,2}\kappa^G+\eta^{G\,2}\right)\right)-2\beta^2\delta^2\left(\eta^{K\,2}\kappa^G+\eta^{G\,2}\right)}{2(\beta+1)\kappa^G(\beta+\kappa^G)}$
Coal deposits	$\frac{\beta^2\left(56\alpha^2\kappa^G-112\alpha\delta\kappa^G(\eta^K+\eta^G)+\delta^2\left(4\eta^{K\,2}(3-5\kappa^G)\kappa^G+\eta^{G\,2}(28\kappa^G-45)\right)\right)+4\beta\left(\alpha^2\kappa^G(7\kappa^G+23)-4\alpha\delta\kappa^G(\eta^K(7\kappa^G+8)+15\eta^G)+3\delta^2\left(\eta^{K\,2}\kappa^G(\kappa^G+4)+\eta^{G\,2}(5\kappa^G-2)\right)\right)}{8(\beta+1)(7\beta+8)\kappa^G(\beta+\kappa^G)}$ $+\frac{16\kappa^G\left(2\alpha^2(\kappa^G+1)-8\alpha\delta(\eta^K\kappa^G+\eta^G)+\delta^2\left(3\eta^{K\,2}\kappa^G+2\eta^{G\,2}\right)\right)+\beta^3\left(-\delta^2\right)\left(20\eta^{K\,2}\kappa^G+21\eta^{G\,2}\right)}{8(\beta+1)(7\beta+8)\kappa^G(\beta+\kappa^G)}$
Gas deposits	$\frac{\beta^2\left(56\alpha^2\kappa^G-112\alpha\delta\kappa^G(\eta^K+\eta^G)+\delta^2\left(\eta^{K\,2}(28-45\kappa^G)\kappa^G+4\eta^{G\,2}(3\kappa^G-5)\right)\right)+4\beta\kappa^G\left(\alpha^2(23\kappa^G+7)-4\alpha\delta(15\eta^K\kappa^G+\eta^G(8\kappa^G+7))+3\delta^2\left(\eta^{K\,2}(5-2\kappa^G)\kappa^G+\eta^{G\,2}(4\kappa^G+1)\right)\right)}{8(\beta+1)\kappa^G(\beta+\kappa^G)(7\beta+8\kappa^G)}$ $+\frac{16\kappa^{G\,2}\left(2\alpha^2(\kappa^G+1)-8\alpha\delta(\eta^K\kappa^G+\eta^G)+\delta^2\left(2\eta^{K\,2}\kappa^G+3\eta^{G\,2}\right)\right)+\beta^3\left(-\delta^2\right)\left(21\eta^{K\,2}\kappa^G+20\eta^{G\,2}\right)}{8(\beta+1)\kappa^G(\beta+\kappa^G)(7\beta+8\kappa^G)}$

Table 4.13: Welfare of country N in different scenarios, when markets are perfectly segmented.

Scenario	U^N
Social planner	$\frac{\alpha^2(2\beta+\kappa^G+1)-\delta^2\left(\beta\left({\eta^K}^2+{\eta^G}^2\right)+{\eta^K}^2\kappa^G+{\eta^G}^2\right)}{2(\beta+1)(\beta+\kappa^G)}$
Cap	$\frac{8\alpha^2\beta\kappa^G+4\alpha^2\kappa^G(\kappa^G+1)+\beta^2\delta^2\left({\eta^K}^2\kappa^G+{\eta^G}^2\right)+\beta\delta^2\left({\eta^K}^2{\kappa^G}^2+{\eta^G}^2\right)}{8(\beta+1)\kappa^G(\beta+\kappa^G)}$
Deposit	$\frac{7\beta^5\left(686\alpha^2\kappa^G+\delta^2\left({\eta^K}^2\kappa^G(391\kappa^G+399)+{\eta^G}^2(399\kappa^G+391)\right)\right)+\beta^4\left(13377\alpha^2\kappa^G(\kappa^G+1)+\delta^2\left({\eta^K}^2\kappa^G\left(2992{\kappa^G}^2+9177\kappa^G+2940\right)+{\eta^G}^2\left(2940{\kappa^G}^2+9177\kappa^G+2992\right)\right)\right)}{2(\beta+1)(7\beta+8)^2\kappa^G(\beta+\kappa^G)(7\beta+8\kappa^G)^2}$ $+\frac{4\beta^3\left(196\alpha^2\kappa^G\left(15{\kappa^G}^2+46\kappa^G+15\right)+\delta^2\left({\eta^K}^2\kappa^G\left(272{\kappa^G}^3+2508{\kappa^G}^2+2415\kappa^G+196\right)+{\eta^G}^2\left(196{\kappa^G}^3+2415{\kappa^G}^2+2508\kappa^G+272\right)\right)\right)}{2(\beta+1)(7\beta+8)^2\kappa^G(\beta+\kappa^G)(7\beta+8\kappa^G)^2}$ $+\frac{16\beta^2\kappa^G\left(28\alpha^2\left(7{\kappa^G}^3+67{\kappa^G}^2+67\kappa^G+7\right)+\delta^2\left({\eta^K}^2\kappa^G\left(228{\kappa^G}^2+660\kappa^G+161\right)+{\eta^G}^2\left(161{\kappa^G}^2+660\kappa^G+228\right)\right)\right)}{2(\beta+1)(7\beta+8)^2\kappa^G(\beta+\kappa^G)(7\beta+8\kappa^G)^2}$ $+\frac{256\beta{\kappa^G}^2\left(4\alpha^2\left(7{\kappa^G}^2+22\kappa^G+7\right)+\delta^2\left({\eta^K}^2\kappa^G(15\kappa^G+11)+{\eta^G}^2(11\kappa^G+15)\right)\right)+1024{\kappa^G}^3\left(4\alpha^2(\kappa^G+1)+\delta^2\left({\eta^K}^2\kappa^G+{\eta^G}^2\right)\right)+833\beta^6\delta^2\left({\eta^K}^2\kappa^G+{\eta^G}^2\right)}{2(\beta+1)(7\beta+8)^2\kappa^G(\beta+\kappa^G)(7\beta+8\kappa^G)^2}$
Efficiency	$\frac{2\alpha^2\beta\kappa^G+\alpha^2\kappa^G(\kappa^G+1)+2\beta^2\delta^2\left({\eta^K}^2\kappa^G+{\eta^G}^2\right)+\beta\delta^2\left({\eta^K}^2\kappa^G(2\kappa^G+1)+{\eta^G}^2(\kappa^G+2)\right)+\delta^2\kappa^G\left({\eta^K}^2\kappa^G+{\eta^G}^2\right)}{2(\beta+1)\kappa^G(\beta+\kappa^G)}$
Coal deposits	$\frac{\beta^3\left(392\alpha^2\kappa^G+\delta^2\left(4{\eta^K}^2\kappa^G(17\kappa^G+57)+161{\eta^G}^2\right)\right)+4\beta^2\left(7\alpha^2\kappa^G(7\kappa^G+39)+\delta^2\left(3{\eta^K}^2\kappa^G(19\kappa^G+20)+44{\eta^G}^2\right)\right)}{8(\beta+1)(7\beta+8)^2\kappa^G(\beta+\kappa^G)}$ $+\frac{16\beta\left(4\alpha^2\kappa^G(7\kappa^G+15)+\delta^2\left({\eta^K}^2\kappa^G(15\kappa^G+4)+4{\eta^G}^2\right)\right)+64\kappa^G\left(4\alpha^2(\kappa^G+1)+\delta^2{\eta^K}^2\kappa^G\right)+\beta^4\delta^2\left(68{\eta^K}^2\kappa^G+49{\eta^G}^2\right)}{8(\beta+1)(7\beta+8)^2\kappa^G(\beta+\kappa^G)}$
Gas deposits	$\frac{\beta^3\left(392\alpha^2\kappa^G+\delta^2\left(161{\eta^K}^2{\kappa^G}^2+4{\eta^G}^2(57\kappa^G+17)\right)\right)+4\beta^2\kappa^G\left(7\alpha^2(39\kappa^G+7)+\delta^2\left(44{\eta^K}^2{\kappa^G}^2+{\eta^G}^2(60\kappa^G+57)\right)\right)}{8(\beta+1)\kappa^G(\beta+\kappa^G)(7\beta+8\kappa^G)^2}$ $+\frac{16\beta{\kappa^G}^2\left(4\alpha^2(15\kappa^G+7)+\delta^2\left(4{\eta^K}^2{\kappa^G}^2+{\eta^G}^2(4\kappa^G+15)\right)\right)+64{\kappa^G}^3\left(4\alpha^2(\kappa^G+1)+\delta^2{\eta^G}^2\right)+\beta^4\delta^2\left(49{\eta^K}^2\kappa^G+68{\eta^G}^2\right)}{8(\beta+1)\kappa^G(\beta+\kappa^G)(7\beta+8\kappa^G)^2}$

Table 4.14: Climate damage in different scenarios, when markets are perfectly segmented.

Scenario	H
Social planner	$-\frac{2\delta\left(\delta\left(\beta\left(\eta^{K\,2}+\eta^{G\,2}\right)+\eta^{K\,2}\kappa^{G}+\eta^{G\,2}\right)-\alpha(\beta(\eta^{K}+\eta^{G})+\eta^{K}\kappa^{G}+\eta^{G})\right)}{(\beta+1)(\beta+\kappa^{G})}$
Cap	$-\frac{\delta\left(\delta\left(\beta\left(\eta^{K\,2}+\eta^{G\,2}\right)+\eta^{K\,2}\kappa^{G}+\eta^{G\,2}\right)-2\alpha(\beta(\eta^{K}+\eta^{G})+\eta^{K}\kappa^{G}+\eta^{G})\right)}{(\beta+1)(\beta+\kappa^{G})}$
Deposit	$\frac{2\delta\left(\alpha(\beta(\eta^{K}+\eta^{G})+\eta^{K}\kappa^{G}+\eta^{G})-\frac{2\delta\left(14\beta^{3}\left(\eta^{K\,2}+\eta^{G\,2}\right)+3\beta^{2}\left(\eta^{K\,2}(10\kappa^{G}+7)+\eta^{G\,2}(7\kappa^{G}+10)\right)+\beta\left(\eta^{K\,2}\kappa^{G}(16\kappa^{G}+45)+\eta^{G\,2}(45\kappa^{G}+16)\right)+24\kappa^{G}\left(\eta^{K\,2}\kappa^{G}+\eta^{G\,2}\right)\right)}{(7\beta+8)(7\beta+8\kappa^{G})}\right)}{(\beta+1)(\beta+\kappa^{G})}$
Efficiency	$-\frac{2\delta\left(\delta\left(\beta\left(\eta^{K\,2}+\eta^{G\,2}\right)+\eta^{K\,2}\kappa^{G}+\eta^{G\,2}\right)-\alpha(\beta(\eta^{K}+\eta^{G})+\eta^{K}\kappa^{G}+\eta^{G})\right)}{(\beta+1)(\beta+\kappa^{G})}$
Coal deposits	$-\frac{\delta\left(\delta\left(\beta^{2}\left(8\eta^{K\,2}+7\eta^{G\,2}\right)+4\beta\eta^{K\,2}(2\kappa^{G}+3)+15\beta\eta^{G\,2}+12\eta^{K\,2}\kappa^{G}+8\eta^{G\,2}\right)-2\alpha(7\beta+8)(\beta(\eta^{K}+\eta^{G})+\eta^{K}\kappa^{G}+\eta^{G})\right)}{(\beta+1)(7\beta+8)(\beta+\kappa^{G})}$
Gas deposits	$-\frac{\delta\left(\delta\left(\beta^{2}\left(7\eta^{K\,2}+8\eta^{G\,2}\right)+15\beta\eta^{K\,2}\kappa^{G}+4\beta\eta^{G\,2}(3\kappa^{G}+2)+4\kappa^{G}\left(2\eta^{K\,2}\kappa^{G}+3\eta^{G\,2}\right)\right)-2\alpha(7\beta+8\kappa^{G})(\beta(\eta^{K}+\eta^{G})+\eta^{K}\kappa^{G}+\eta^{G})\right)}{(\beta+1)(\beta+\kappa^{G})(7\beta+8\kappa^{G})}$

Table 4.15: Consumer surplus in different scenarios, when markets are perfectly segmented.

Scenario	CS^M
Cap	$\frac{\beta\left(4\alpha^2\left(2\beta^2+2\beta(\kappa^G+1)+\kappa^{G2}+1\right)-4\alpha\delta\left(\beta^2(\eta^K+\eta^G)+2\beta(\eta^K\kappa^G+\eta^G)+\eta^K\kappa^{G2}+\eta^G\right)+\delta^2\left(\beta^2\left(\eta^{K2}+\eta^{G2}\right)+2\beta\left(\eta^{K2}\kappa^G+\eta^{G2}\right)+\eta^{K2}\kappa^{G2}+\eta^{G2}\right)\right)}{8(\beta+1)^2(\beta+\kappa^G)^2}$
Deposit	$\frac{\beta\left(\alpha^2(7\beta+8)^2(7\beta+8\kappa^G)^2\left(2\beta^2+2\beta(\kappa^G+1)+\kappa^{G2}+1\right)+4\delta^2\left(48\beta\left(\eta^{K2}(16\kappa^G+45)\kappa^{G3}+\eta^{G2}(45\kappa^G+16)\kappa^G\right)+576\kappa^{G2}\left(\eta^{K2}\kappa^{G2}+\eta^{G2}\right)\right)\right)}{2(\beta+1)^2(7\beta+8)^2(\beta+\kappa^G)^2(7\beta+8\kappa^G)^2}$ $-\frac{\beta\left(4\alpha(7\beta+8)\delta(7\beta+8\kappa^G)\left(14\beta^4(\eta^K+\eta^G)+\beta^3(\eta^K(44\kappa^G+21)+\eta^G(21\kappa^G+44))+\beta^2(2\eta^K\kappa^G(23\kappa^G+33)+\eta^G(66\kappa^G+46))\right)\right)}{2(\beta+1)^2(7\beta+8)^2(\beta+\kappa^G)^2(7\beta+8\kappa^G)^2}$ $+\frac{\beta\left(4\delta^2\left(196\beta^6\left(\eta^{K2}+\eta^{G2}\right)+84\beta^5\left(\eta^{K2}(10\kappa^G+7)+\eta^{G2}(7\kappa^G+10)\right)+\beta^4\left(\eta^{K2}\left(1348\kappa^{G2}+2520\kappa^G+441\right)+\eta^{G2}\left(441\kappa^{G2}+2520\kappa^G+1348\right)\right)\right)\right)}{2(\beta+1)^2(7\beta+8)^2(\beta+\kappa^G)^2(7\beta+8\kappa^G)^2}$ $+\frac{\beta\left(4\delta^2\left(6\beta^3\left(\eta^{K2}\kappa^G\left(160\kappa^{G2}+674\kappa^G+315\right)+\eta^{G2}\left(315\kappa^{G2}+674\kappa^G+160\right)\right)+\beta^2\left(\eta^{K2}\kappa^{G2}\left(256\kappa^{G2}+2880\kappa^G+3033\right)+\eta^{G2}\left(3033\kappa^{G2}+2880\kappa^G+256\right)\right)\right)\right)}{2(\beta+1)^2(7\beta+8)^2(\beta+\kappa^G)^2(7\beta+8\kappa^G)^2}$ $-\frac{\beta\left(4\alpha(7\beta+8)\delta(7\beta+8\kappa^G)\left(\beta\left(\eta^K(16\kappa^G+69)\kappa^{G2}+\eta^G(69\kappa^G+16)\right)+24\kappa^G\left(\eta^K\kappa^{G2}+\eta^G\right)\right)\right)}{2(\beta+1)^2(7\beta+8)^2(\beta+\kappa^G)^2(7\beta+8\kappa^G)^2}$
Efficiency	$\frac{\beta\left(\alpha^2\left(2\beta^2+2\beta(\kappa^G+1)+\kappa^{G2}+1\right)-2\alpha\delta\left(\beta^2(\eta^K+\eta^G)+2\beta(\eta^K\kappa^G+\eta^G)+\eta^K\kappa^{G2}+\eta^G\right)+\delta^2\left(\beta^2\left(\eta^{K2}+\eta^{G2}\right)+2\beta\left(\eta^{K2}\kappa^G+\eta^{G2}\right)+\eta^{K2}\kappa^{G2}+\eta^{G2}\right)\right)}{2(\beta+1)^2(\beta+\kappa^G)^2}$
Coal deposits	$\frac{\beta\left(4\alpha^2(7\beta+8)^2\left(2\beta^2+2\beta(\kappa^G+1)+\kappa^{G2}+1\right)-4\alpha(7\beta+8)\delta\left(\beta^3(8\eta^K+7\eta^G)+2\beta^2(\eta^K(8\kappa^G+6)+11\eta^G)+\beta(8\eta^K\kappa^G(\kappa^G+3)+23\eta^G)+12\eta^K\kappa^{G2}+8\eta^G\right)\right)}{8(\beta+1)^2(7\beta+8)^2(\beta+\kappa^G)^2}$ $+\frac{\beta\left(\delta^2\left(\beta^4\left(64\eta^{K2}+49\eta^{G2}\right)+2\beta^3\left(32\eta^{K2}(2\kappa^G+3)+105\eta^{G2}\right)+\beta^2\left(16\eta^{K2}\left(4\kappa^{G2}+24\kappa^G+9\right)+337\eta^{G2}\right)+48\beta\left(2\eta^{K2}\kappa^G(2\kappa^G+3)+5\eta^{G2}\right)+16\left(9\eta^{K2}\kappa^{G2}+4\eta^{G2}\right)\right)\right)}{8(\beta+1)^2(7\beta+8)^2(\beta+\kappa^G)^2}$
Gas deposits	$\frac{\beta\left(4\alpha^2(7\beta+8\kappa^G)^2\left(2\beta^2+2\beta(\kappa^G+1)+\kappa^{G2}+1\right)-4\alpha\delta(7\beta+8\kappa^G)\left(\beta^3(7\eta^K+8\eta^G)+2\beta^2(11\eta^K\kappa^G+\eta^G(6\kappa^G+8))+\beta\left(23\eta^K\kappa^{G2}+8\eta^G(3\kappa^G+1)\right)+8\eta^K\kappa^{G3}+12\eta^G\kappa^G\right)\right)}{8(\beta+1)^2(\beta+\kappa^G)^2(7\beta+8\kappa^G)^2}$ $+\frac{\beta\left(\delta^2\left(\beta^4\left(49\eta^{K2}+64\eta^{G2}\right)+2\beta^3\left(105\eta^{K2}\kappa^G+32\eta^{G2}(3\kappa^G+2)\right)+\beta^2\left(337\eta^{K2}\kappa^{G2}+16\eta^{G2}\left(9\kappa^{G2}+24\kappa^G+4\right)\right)+48\beta\left(5\eta^{K2}\kappa^{G3}+\eta^{G2}(6\kappa^G+4)\kappa^G\right)+16\kappa^{G2}\left(4\eta^{K2}\kappa^{G2}+9\eta^{G2}\right)\right)\right)}{8(\beta+1)^2(\beta+\kappa^G)^2(7\beta+8\kappa^G)^2}$

Table 4.16: Coal producer surplus in different scenarios, when markets are perfectly segmented.

Scenario	PSK^M
Cap ≡ Gas deposits	$\frac{(2\alpha-(\beta+2)\delta\eta^K)(2\alpha+(3\beta+2)\delta\eta^K)}{8(\beta+1)^2}$
Deposit ≡ Coal deposits	$\frac{\left(\alpha(7\beta+8)-\left(3\beta^2+9\beta+8\right)\delta\eta^K\right)\left(\alpha(7\beta+8)+\left(11\beta^2+21\beta+8\right)\delta\eta^K\right)}{2(\beta+1)^2(7\beta+8)^2}$
Efficiency	$\frac{(\alpha-\delta\eta^K)(\alpha+(2\beta+1)\delta\eta^K)}{2(\beta+1)^2}$

We compute the deviations from efficiency by subtracting the results in the efficiency scenario from those in the deposit policy scenario with strategic action and obtain the results in Table 4.18.

Derivatives of consumer surplus in Proposition 4.11:

The derivatives of the consumer surplus with respect to gas emission intensity and cost parameter when markets are perfectly segmented and deposits are implemented for gas only are:

$$\begin{aligned}
\frac{dCS^M_{D,G}}{d\eta^G} =& \frac{2\beta\delta(2\beta+3\kappa^G)(-7\alpha\beta-8\alpha\kappa^G+4\beta\delta\eta^G+6\delta\eta^G\kappa^G)}{(\beta+\kappa^G)^2(7\beta+8\kappa^G)^2} < 0, \\
\frac{dCS^M_{D,G}}{d\kappa^G} =& -\frac{\beta(7\alpha\beta+8\alpha\kappa^G-4\beta\delta\eta^G-6\delta\eta^G\kappa^G)}{(\beta+\kappa^G)^3(7\beta+8\kappa^G)^3} \\
&\cdot \frac{\left(\alpha(7\beta+8\kappa^G)^2-2\delta\eta^G\left(9\beta^2+32\beta\kappa^G+24\kappa^{G^2}\right)\right)}{(\beta+\kappa^G)^3(7\beta+8\kappa^G)^3} < 0.
\end{aligned} \tag{4.57}$$

Table 4.17: Gas producer surplus in different scenarios, when markets are perfectly segmented.

Scenario	PSG^M
Cap ≡ Coal deposits	$-\frac{(-2\alpha\kappa^G+\beta\delta\eta^G+2\delta\eta^G\kappa^G)(2\kappa^G(\alpha+\delta\eta^G)+3\beta\delta\eta^G)}{8\kappa^G(\beta+\kappa^G)^2}$
Deposit ≡ Gas deposits	$-\frac{\left(7\beta\kappa^G(\alpha+3\delta\eta^G)+8{\kappa^G}^2(\alpha+\delta\eta^G)+11\beta^2\delta\eta^G\right)}{2\kappa^G(\beta+\kappa^G)^2(7\beta+8\kappa^G)^2} \cdot \frac{\left(\beta(9\delta\eta^G\kappa^G-7\alpha\kappa^G)-8{\kappa^G}^2(\alpha-\delta\eta^G)+3\beta^2\delta\eta^G\right)}{2\kappa^G(\beta+\kappa^G)^2(7\beta+8\kappa^G)^2}$
Efficiency	$\frac{(\alpha-\delta\eta^G)(\kappa^G(\alpha+\delta\eta^G)+2\beta\delta\eta^G)}{2(\beta+\kappa^G)^2}$

Table 4.18: Strategic deposit policy: deviations from efficiency, when markets are perfectly segmented.

$\forall i : z^{i,K} - z^{i,K}_*$	$-\frac{2(3\beta+2)\delta\eta^K}{7\beta+8} < 0$
$\forall i : z^{i,G} - z^{i,G}_*$	$-\frac{2\delta\eta^G(3\beta+2\kappa^G)}{\kappa^G(7\beta+8\kappa^G)} < 0$
$p^K - p^K_*$	$-\frac{\beta(3\beta+2)\delta\eta^K}{(\beta+1)(7\beta+8)} < 0$
$p^G - p^G_*$	$\beta\delta\eta^G\left(\frac{1}{\beta+\kappa^G} - \frac{10}{7\beta+8\kappa^G}\right) < 0$
$p^{z,K} - p^{z,K}_*$	$-\frac{2(3\beta+2)\delta\eta^K}{7\beta+8} < 0$
$p^{z,G} - p^{z,G}_*$	$-\frac{2\delta\eta^G(3\beta+2\kappa^G)}{7\beta+8\kappa^G} < 0$

5

Disentangling the exposure of asset owners to power sector stranded assets across the globe

Abstract

Many fossil fuel-related assets become stranded due to climate policies. Assessment of the owners and distribution of stranded assets is essential to anticipate policy resistance. We employ novel data suitable for assessing stranded assets at the asset owner level and analyze owners and incidence of asset stranding in the power sector globally. We show that Asia-Pacific, Europe, and the US are highly exposed to stranded assets, especially coal power plants. Stranded assets are highly concentrated in a few asset owners in some countries (e.g. India). Even if owners are more equally exposed (e.g. in the US) they can vary considerably in the timing of asset stranding due to differences in plant fleets' age profile. European, US, and Chinese asset owners own large shares of stranded coal plants abroad. Listed asset owners may face stranded assets of almost 78 % of their share price or more than 80 % of their equity. Asset owners' exposure to asset stranding positively correlates with ownership of alternative energy assets. India stands out with high asset stranding exposure and little ownership of alternative energy assets.

Reference: von Dulong, A. (2023). Disentangling the exposure of asset owners to power sector stranded assets across the globe, 'revise and resubmit' in *Nature Communications*.

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5.1 INTRODUCTION

REACHING THE 2 °C CLIMATE GOAL requires the implementation of stringent policies to transform the energy sector. This includes leaving fossil fuels unextracted (McGlade & Ekins, 2015, Eisenack et al., 2021, Welsby et al., 2021) and prematurely retiring fossil fuel-burning energy infrastructure (Tong et al., 2019), also referred to as "asset stranding" (Van der Ploeg & Rezai, 2020).[1] The success of such policies potentially hinges upon their interaction with stranded assets (von Dulong et al., 2023a). Fierce opposition to policies has been shown to be formed by adversely affected asset owners (Cheon & Urpelainen, 2013, Douenne & Fabre, 2022). Accounting for such resistance is crucial for producing realistic policy advice and for proposing feasible policies (Dixit, 1996, Acemoglu & Robinson, 2013).

To assess potential sources of resistance to climate policies and to gain a better understanding of who has high stakes in national policy formation and international climate negotiations we ask: Who are the owners of power sector stranded assets across the globe and how are stranded assets distributed between them? Further, resistance to climate policies may be moderated if affected asset owners are also invested in alternative energy assets – potentially even benefiting from these policies. Thus, we ask whether asset owners' ownership of alternative energy assets correlates with asset stranding exposure.

The extant literature on power sector asset stranding focuses mostly on the global or country level (Fisch-Romito et al., 2021), while this paper primarily targets the asset owner level. To reach the 1.5 °C Paris goals, coal power plants must retire decades earlier than historically (Cui et al., 2019, Fofrich et al., 2020). Put differently, globally, only 42 -49 % of (operating and pipeline) power plant generators can be utilized until the end of their economic lifetime (Pfeiffer et al., 2018), and 300 GW of coal-fired capacity commissioned between 2011 and 2014 must be stranded to reach the 2 °C climate change target (Farfan & Breyer, 2017). Depending on the policy stringency and the time horizon global stranded assets in coal capacity range between US$150 billion and US$1.4 trillion (Johnson et al., 2015, Edwards et al., 2022). While these papers are important contributions to understanding the extent and associated costs of asset stranding in the power

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[1] Assets may also strand due to climate impacts or transition risks, which are not directly linked to climate policies such as changing social preferences (cf. Caldecott et al., 2021).

sector, they do not reveal information on affected stakeholders below the country level, especially how costs are distributed between the direct owners of assets and owners higher up the ownership tree. This, however, is crucial for anticipating resistance to policies and providing realistic policy recommendations.

To the best of our knowledge, only a few papers analyze asset stranding at a more fine-grained level. In the power sector, Breitenstein et al. (2022) quantify stranded assets of German power companies due to the country's coal phase-out. They show that individual companies may suffer absolute losses as high as €4.8 billion and more than €7 per share outstanding if the coal phase-out is implemented in 2030 as opposed to 2038. The asset owner-level exposure to asset stranding has further been studied outside the power sector. For instance, regarding the upstream fossil fuel producing sector, Semieniuk et al. (2022) trace global stranded assets from the oil and gas sector to the ultimate owner and find that predominantly non-listed investors headquartered in countries of the Organisation for Economic Co-operation and Development (OECD) are exposed to stranded assets. Although these studies provide key findings for asset stranding at the asset owner level, they focus either on German companies solely or on the upstream fossil fuel producing sector. This paper aims at filling this literature gap by assessing power sector asset stranding at the asset owner level globally.

In this study, stranded assets are computed using a unique combination of two data sets. The first data set covers assets around the globe linked to their direct owner and the entire ownership tree of asset owners owning the direct owner (Asset Resolution, 2022). We use a subset of the data, which focuses on the power sector and includes, among others, information on power plant operating capacity, age, location, and ownership structure. We match this data set with data from the International Energy Agency's (IEA) World Energy Outlook 2021 (IEA, 2021b). The IEA data provides a scenario on regional fossil fuel power capacities, which allows for a sustainable development in line with the 2 °C goal ("Sustainable Development Scenario"). If this climate-compatible capacity is exceeded by the operating capacity as given by the first data set, we successively identify power plants as stranded (oldest plants first) until the climate-compatible and operating capacity are in line. Then, we compute stranded assets as power plants' overnight capital costs (OCC), which are not recovered due to premature decommissioning.[2]

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[2] OCC cover a power plant's pre-construction, construction, and contingency costs but exclude interest during its construction – as if the plant was built overnight (IEA & NEA, 2020). OCC are used to evaluate and assess different power plant project options (Koomey & Hultman, 2007).

Finally, we aggregate these stranded assets at the asset owner level.

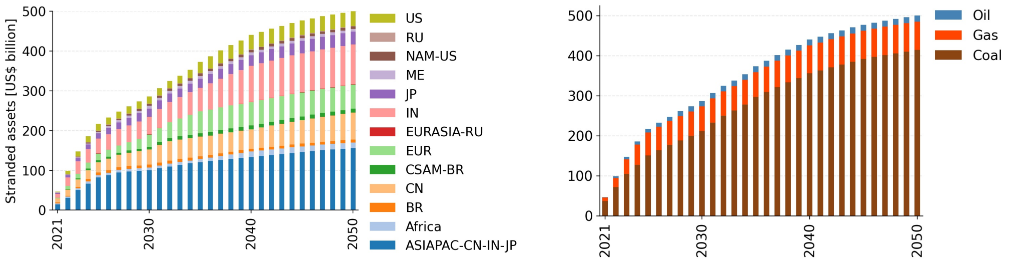
Our results suggest that prematurely decommissioned power plants are predominantly located in Asia-Pacific countries, Europe, and the US, and they mostly use coal as energy input. In contrast to the US, however, Asia-Pacific and European countries' announced climate pledges largely fall short of those required for a sustainable development. Thus, compared to a asset stranding in line with announced pledges a considerable amount of additional assets – especially coal power plants – must be stranded to reach a sustainable development in those countries. We show that the distribution of stranded assets across asset owners varies strongly between countries. For instance, in India one single asset owner owns the majority of stranded assets, which is in stark contrast to the US, where stranded assets are much more equally distributed across asset owners. Zooming in on the US, we find that even if asset owners are equally exposed to stranded assets, they can differ considerably in the timing of asset stranding due to differences in the age profile of power plant fleets. Often, the location of stranded power plants is quite different from the location of asset owners ultimately owning these plants. For instance, European, US, and Chinese asset owners own a large share of stranded coal power plants located in foreign countries. Among the top most exposed entities are listed asset owners with stranded assets of almost 78 % of their share price. Listed asset owners in OECD countries are more able to buffer their exposure to stranded assets with their total equity compared to non-OECD asset owners. Finally, there is a positive correlation (Spearman's $r = 0.69$) between asset owners' ownership of alternative energy assets and asset stranding exposure. However, only a small share of asset owners most exposed to asset stranding own alternative energy assets. Across regions, China and India stand out: Both are highly exposed to asset stranding but compared to China, India shows relatively little ownership of alternative energy assets.

5.2 Results

5.2.1 Stranded assets across regions and fuels

In total, almost 2.8 TW of fossil power plant capacity must be stranded globally between 2021 and 2050 to be in line with IEA's Sustainable Development Scenario. Employing our method of assessing the monetary losses of prematurely decommissioning these plants, this translates into stranded assets worth more than US$

500 billion.[3] Figure 5.1 presents stranded assets across regions and fuels. Regions most affected are Asia-Pacific, Europe, and the US.[4] Predominantly power plants using coal as energy input are stranded. Thus, these regions may face social repercussions and policy resistance, in particular resulting from the implementation of coal power plant shut-downs – this, however, requires further research.



(a) Across regions.

(b) Across fossil fuels.

Figure 5.1: Cumulative stranded assets between 2021 and 2050 across regions and fuels. Region abbreviations in the legend are as follows: United States (US), Russia (RU), North America excluding the US (NAM-US), Middle East (ME), Japan (JP), India (IN), Eurasia excluding Russia (EURASIA-RU), Europe (EUR), Central and South America excluding Brazil (CSAM-BR), China (CN), Brazil (BR), and Asia-Pacific excluding China, India, and Japan (ASIAPAC-CN-IN-JP).

Opposition to climate policies fostering a sustainable development may be particularly strong if such policies result in more stranded assets than those currently announced. To quantify stranded assets in line with policies currently announced, we employ the IEA's Announced Pledges Scenario, which assumes implementation of all recently announced 2030 climate targets and longer term net zero pledges.[5] We define the stranded assets ambition gap as the difference between stranded assets in the Sustainable Development Scenario and those in the Announced Pledges Scenario. Quantifying asset stranding due to current announced climate pledges results in stranded assets worth US$212 billion. Thus, there is an ambition gap between the two scenarios equivalent to stranded assets worth almost US$300 billion. Figure 5.2 shows the distribution of this stranded assets ambition gap across regions and fossil fuels. Asia-Pacific countries excluding China, India, and

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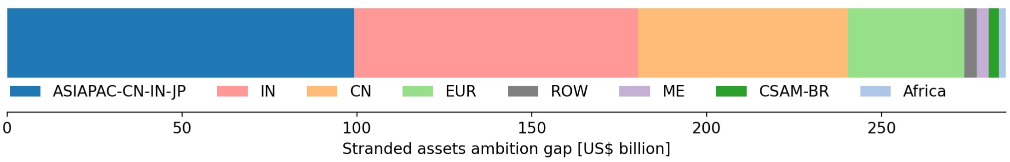
[3] For a sensitivity analysis of this result with respect to assumptions on interest rates and power plant standard lifetimes please see Table 5.5 in Appendix 5.C. All stranded asset figures are discounted to 2021. They do not include stranded capacities owned by unknown asset owners (see Appendix 5.B).

[4] For the spatial distribution of stranded assets at the plant level please see Figure 5.10 in Appendix 5.C.

[5] For more details on the IEA's Announced Pledges Scenario, see Appendix 5.A.

(a) Across regions



(b) Across fossil fuels

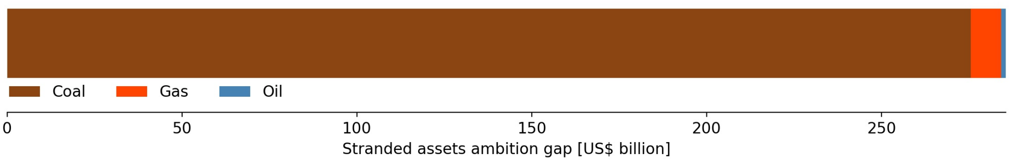


Figure 5.2: Stranded assets ambition gap. Region abbreviations in the legend are as described in Figure 5.1.

Japan alone make up around US$100 billion of the stranded assets ambition gap. Announced pledges from India, China, and European countries largely fall short of targets required for a sustainable development resulting in an ambition gap of stranded assets worth around US$80, 60, and 33 billion, respectively. In contrast, there is no ambition gap in the US as announced pledges are already in line with a sustainable development. Thus, future research could analyze whether resistance to policies is less strong in the US compared to Asia-Pacific and European countries, which are yet to raise the stringency of their climate targets. Across fossil fuels, the ambition gap is largely driven by insufficiently stringent pledges targeting the phase-out of coal power plants. Globally, coal power plants worth more than US$275 billion would need to be stranded in addition to pledged shut-downs to be in line a sustainable development.

5.2.2 DISTRIBUTION OF STRANDED ASSETS ACROSS DIRECT AND PARENT OWNERS

At the country-level, opposition to climate policies may be shaped by the distribution of stranded assets across owners.[6] For instance, if stranded assets are concentrated in a few asset owners coordination of resistance may be easier compared to a situation, where many owners are relatively equally exposed to asset strand-

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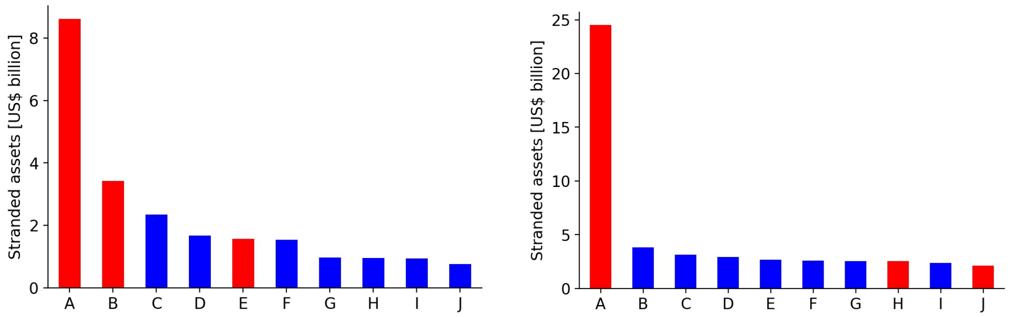
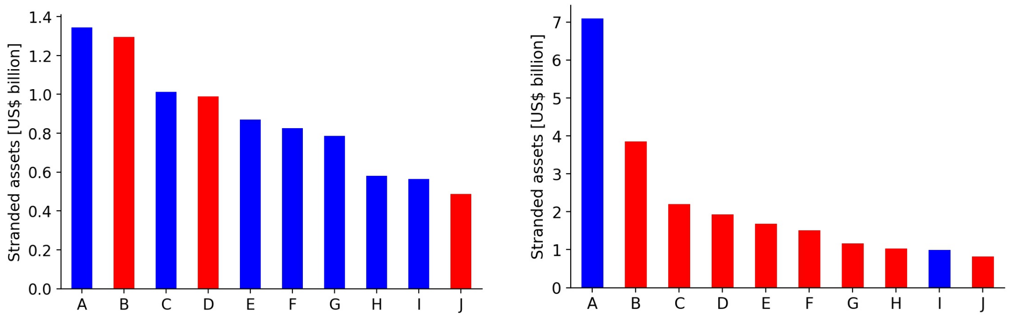
[6] Hereinafter, stranded assets are those quantified using the IEA's Sustainable Development Scenario.

ing. Using the ownership information in the Asset Resolution data, we aggregate stranded assets for each power plant at the direct owner level. Figure 5.3 shows the top 10 direct owners most exposed to stranded assets in selected countries. The distribution of stranded assets across direct owners varies greatly between countries. In both China and India, a single direct owner is heavily exposed to asset stranding, while other direct owners headquartered in these countries suffer much less. On the other hand, in the US, stranded assets are much more equally distributed between direct owners. Japan presents a mixed case, with two direct owners being more exposed to asset stranding than the rest.



(a) China (b) India



(c) US (d) Japan

Figure 5.3: Stranded assets of the top 10 most exposed non-listed (blue) and listed (red) direct owners headquartered in the respective countries. Each bar represents total stranded assets of a direct owner, which are located in the same country as the direct owner's headquarter. For names of the direct owners represented by capital letters for conciseness, see Table 5.6 in Appendix 5.C.

Direct owners may be (partially) owned by parent owners, who are at the top of an ownership tree.[7] These parent owners can be invested in a magnitude of direct owners amplifying their stranded assets exposure. If highly exposed parent

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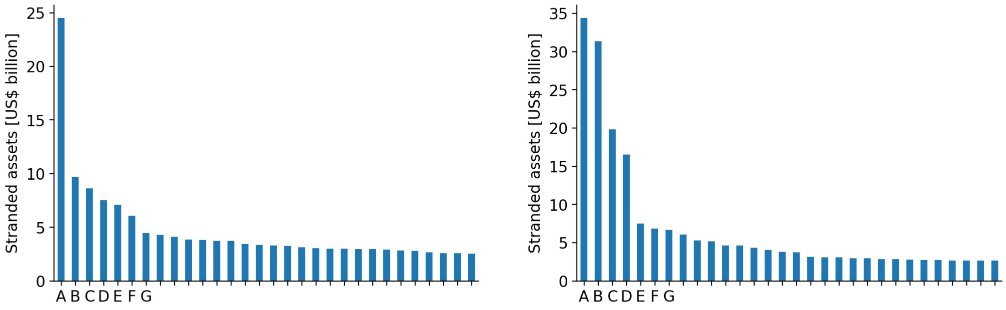
[7] For details, see Appendix 5.A

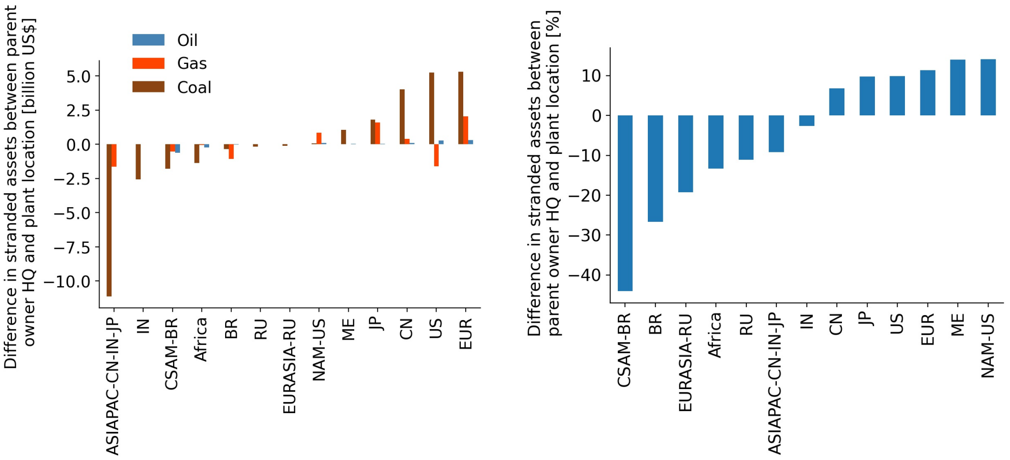
owners are nation states, resistance to policies may then not only be formed at the country level but instead shape international climate coordination. Figure 5.4 contrasts the distribution of stranded assets across direct and parent owners globally. Apart from one outlier, namely NTPC Limited headquartered in India, stranded assets are relatively equally distributed across direct owners at the global level. Aggregated at the parent owner level, a great share of stranded assets is concentrated in four owners, all of which are nation states: The People's Republic of China, the Republic of India, the Republic of Korea, and the Republic of Indonesia, respectively. These parent owners may have high stakes at international negotiations on climate policies.



(a) Across direct owners (b) Across parent owners

Figure 5.4: Stranded assets distribution of direct and parent owners globally. Panel (a): As in Figure 5.3, each bar represents total stranded assets of a direct owner, which are located in the same country as the direct owner's headquarter. Panel (b): Each bar represents total stranded assets of a parent owner, which may not be located in the same country as the parent owner's headquarter. For names of the direct and parent owners represented by capital letters for conciseness, see Table 5.6 in Appendix 5.C.

Parent owners can be invested in direct owners in various countries, exposing them to energy transitions globally. Then, opposition to policies may not be limited to the domestic country. Figure 5.5 depicts the difference in total stranded assets faced by parent owners headquartered in a region and total stranded assets from prematurely retired power plants in the same region. Panel (a) shows that parent owners in Europe, the US, China, Japan, and the Middle East own coal power plant stranded assets located in regions outside their headquarters. On the flip-side, regions such as Asia-Pacific excluding China, India, and Japan do not own coal power plant stranded assets worth more than US$10 billion located in this region. Panel (b) aggregates stranded assets of all fossil fuels and demonstrates

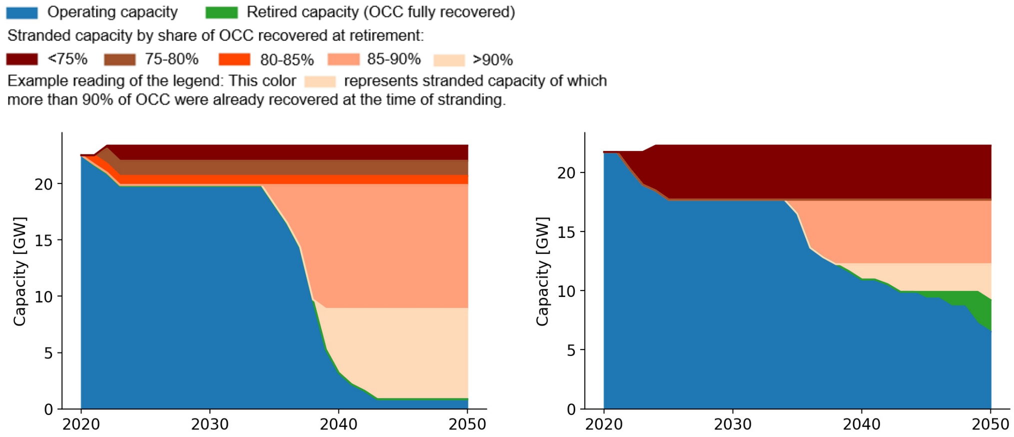


(a) Across fossil fuels [US$ billion] (b) Aggregated over fossil fuels [%]

Figure 5.5: Difference in total stranded assets faced by parent owners headquartered in a region and total stranded assets from power plants located in the same region.

that North America excluding the US and the Middle East are highly exposed to stranded assets from other regions, while more than 40 % of stranded assets located in Central and South America excluding Brazil are owned by foreign parent owners.

Finally, the distribution of stranded assets across time can be crucial to anticipate policy resistance. As an example, Figure 5.6 shows the gas power plant capacities of two US headquartered parent owners, Vistra Corporation and Duke Energy Corporation, between 2020 and 2050. Both parent owners follow climate targets set for the US and they are similarly exposed to gas stranded assets: Vistra Corporation and Duke Energy Corporation face losses as high as US$1.6 and US$1.5 billion, respectively. However, their distribution of stranded assets varies across time as their gas power plant fleets differ in age profile. Vistra Corporation in Panel (a) finds most of its gas capacity stranded between 2035 and 2045. A major share of Vistra Corporation's stranded capacity has more than 85 % of OCC recovered by the time of stranding. This is in stark contrast to the stranded capacity of Duke Energy Corporation in Panel (b). Almost half of its capacity is still operating or retired with fully recovered OCC by 2050. Major stranded assets occur around 2025 when capacities with less than 75 % of OCC recovered are stranded. This example demonstrates that parent owners with similar initial fossil capacities headquartered in the same country may differ considerably in the



(a) Vistra Corporation

(b) Duke Energy Corporation

Figure 5.6: Gas power plant capacities of two US headquartered parent owners between 2020 and 2050.

timing of their asset stranding exposure due to the age structure of their respective power plant fleet.

5.2.3 Stranded assets owned by listed parent owners

As depicted in Figure 5.3, listed asset owners in various countries are among the top most exposed entities. These owners may oppose climate policies if resulting stranded assets depress their share prices. Figure 5.7 shows stranded assets of the top 30 most exposed listed parent owners by means of stranded assets per share outstanding and as a percentage in share price.[8] Listed parent owners may suffer from stranded assets as high as US$24 per share outstanding or almost 78 % of their share price. Listed asset owners in OECD countries predominantly rank among the top 30 most exposed entities according to both measures. While two thirds of stranded assets are owned by parent owners headquartered in non-OECD countries, this pictures shifts for parent owners listed on stock exchanges. Listed parent owners headquartered in OECD countries own stranded assets worth US$124 billion as opposed to non-OECD headquartered listed parent owners with stranded assets worth US$40 billion. Thus, even if parent owners

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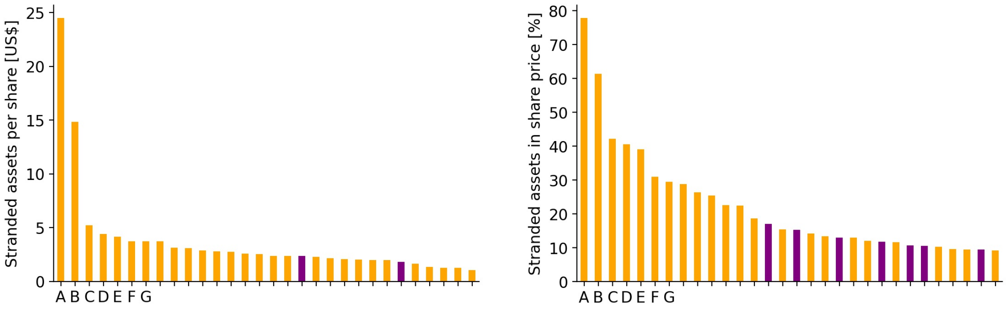
[8] Estimations of stranded assets per share outstanding and as a percentage in share price depend on an asset owner's debt ratio. Debt ratios differ considerably across industries, countries, and time (Remmers et al., 1974). Given that our sample of asset owners spans many industries and countries, we assume a debt ratio of 0.6. Higher debt ratios would decrease the estimations by the exact same proportion.



(a) Per share outstanding [US$] (b) In share price [%]

Figure 5.7: Stranded assets of the top 30 most exposed listed parent owners in OECD (orange) and non-OECD (purple) countries. Each bar represents stranded assets per share outstanding or as a percentage in share price that accrue to a listed parent owner. For names of the parent owners represented by capital letters for conciseness, see Table 5.6 in Appendix 5.C.

in non-OECD countries show stronger exposure to stranded assets, shareholders may find stranded assets owned by listed parent owners headquartered in OECD countries more concerning.[9]

Asset owners may also resist climate policies if they are unable to cushion the resulting stranded assets with their equity. Figure 5.8 shows listed parent owners' ratio of stranded assets to total equity. Stranded assets may eat up more than 80 %

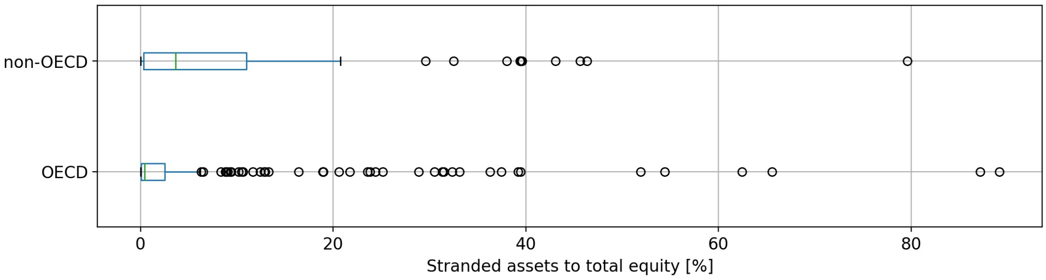


Figure 5.8: Ratio of stranded assets to total equity for listed parent owners headquartered in OECD and non-OECD countries. Listed parent owners with negative total equity or stranded assets larger than their total equity are ignored.

of listed parent owners' equity. On average, listed parent owners headquartered in non-OECD countries show higher levels of stranded assets to equity. Thus, they are less able to buffer their stranded assets exposure with the equity they own.

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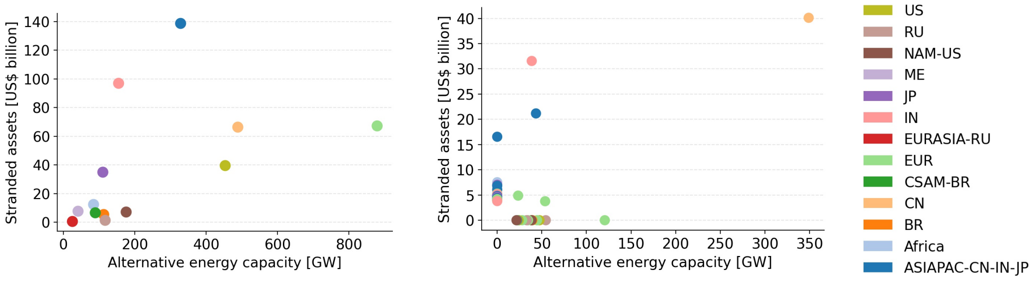
[9] For additional results on shareholder engagement with listed asset owners exposed to stranded assets see Appendix 5.C.

This result is driven by the difference in total equity, which parent owners own on average. While listed parent owners in OECD and non-OECD countries are about equally exposed to stranded assets, those headquartered in OECD countries show higher levels of total equity (see Figure 5.11 in Appendix 5.C).

5.2.4 Stranded assets and alternative energy assets

While the energy transition leaves fossil power plants stranded, it also requires a massive ramp up of alternative energy assets, i.e. renewable and nuclear energy power plants. Investments in alternative energy assets may help regions and asset owners balance or mitigate their exposure to stranded assets. This could in turn reduce resistance to climate policies. Figure 5.9 shows ownership of stranded assets and alternative energy capacity by regions and selected parent owners across the globe. The regions in Panel (a) of Figure 5.9 can be roughly summarized as three clusters. The first cluster consists of regions that are moderately exposed to stranded assets and own large shares of alternative energy capacity. It includes the US, China, and Europe. A second cluster is made up of India and Asia-Pacific excluding China, India, and Japan, characterized by high levels of stranded assets exposure and moderate to low degrees of ownership over alternative energy capacity. The third cluster includes all remaining regions owning relatively little stranded assets and alternative energy capacity. At the regional level, the first cluster may be best suited to balance exposure to stranded assets with alternative energy assets. In contrast, India and Asia-Pacific excluding China, India, and



(a) Across regions (b) Across parent owners

Figure 5.9: Stranded assets and alternative energy capacity owned by regions and selected parent owners. Panel (b) shows the 20 parent owners most exposed to asset stranding and the 20 parent owners owning the largest share of alternative energy capacity. Asset owners in both categories may overlap. Region abbreviations in the legend are as described in Figure 5.1.

Japan may strongly resist the implementation of climate policies or the announcement of stringent climate pledges – an avenue for future research with high policy relevance.

Panel (b) in Figure 5.9 disaggregates regional stranded and alternative energy assets and focuses on parent owners. For conciseness only the top 20 asset owners most exposed to asset stranding and the top 20 asset owners owning the largest share of alternative energy assets are plotted. The People's Republic of China stands out being highly exposed to stranded assets and owning large alternative energy capacities. Further, two parent owners in India and Asia-Pacific excluding China, India, and Japan show strong exposure to stranded assets and moderate ownership of alternative energy assets. Two European parent owners own relatively little of both stranded assets and alternative energy capacity. The majority of these parent owners is either exposed to asset stranding with no ownership of alternative energy assets or vice versa. Across the whole sample, however, parent owners, which are exposed to asset stranding show a positive correlation (Spearman's $r = 0.69$) with ownership of alternative energy assets.

5.3 DISCUSSION

There are some limitations to this analysis. First, the IEA scenario assumptions on climate policies, prices, technological progress, behavior, etc. are crucial for the valuation of stranded assets. For instance, the stringency and the design of policies can affect the distribution and absolute value of stranded assets. Energy efficiency improvements at the plant level, advances in carbon capture, utilization, and storage (CCUS) retrofitability and net-negative emission technologies could reduce stranded assets. On the flip-side, changes in preferences and the diffusion of low-carbon technologies may increase stranded assets (cf. Mercure et al., 2018). Second, this study assesses stranded assets as sunk costs. Stranded assets in terms of lost profits may be a lot higher with important implications for the feasibility of climate policies.

This study focuses on asset owner-level asset stranding in the power sector but the Asset Resolution data likewise allow analyzing other sectors, which lack research despite their exposure to transition risks (Fisch-Romito et al., 2021). For instance, future studies could adapt the methodology employed in this analysis to assess asset owners' exposure to stranded assets in the transport sector (automobile, shipping, and aviation) and the industry sector (steel and cement). Such insights are highly relevant for policymakers: By analyzing the extant and distribution of power sector stranded assets at the asset owner level, the results in this paper can support anticipation of opposition to climate policies including lobbying efforts. This is crucial for the successful implementation of climate policies.

Appendices

5.A METHODS

Methodology. In our baseline analysis, we identify fossil fuel power plants across the globe that must be stranded between 2021 and 2050 to achieve the 2 °C Paris goal. This requires comparing the capacity, which is consistent with the 2 °C Paris goal, with the operating capacity in a given year and region, i.e. a country or group of countries. If the climate-compatible capacity is exceeded, we identify the oldest power plant as ”stranded” and deduct its capacity from the operating capacity (cf. Edwards et al., 2022). We repeat this step successively until the operating capacity is in line with the climate-compatible capacity in a given year and region. For simplicity we assume that power plants are always stranded entirely, so that a plant’s capacity cannot be partially reduced. The operating capacity in the analysis’ base year of 2020 is composed of all active power plants in 2020 and it includes pipeline capacities for the years thereafter. In an additional analysis, we identify power plants to be stranded if all major national climate pledges are to be fulfilled. Since these pledges are not sufficient to achieve the 2 °C Paris goal (Climate Analytics et al., 2022), this analysis facilitates assessing an ambition gap in terms of stranded assets.

Once we have identified power plants to be stranded, we compute the monetary losses that accrue to the asset owners of these power plants. There are different definitions and measures of stranded assets’ monetary value in the literature. One option is to compute lost profits, i.e. the difference in profits between scenarios (cf. Breitenstein et al., 2022, Semieniuk et al., 2022). This measure covers many aspects of stranded assets’ monetary value relevant to their owners. At the same time, however, it requires a number of assumptions including the development of prices, demand, and behavior, input substitution between energy sources, as well as changes in costs, policies, and technological progress. Further, lost profits are highly dependent on the policy design (Eisenack et al., 2021). For a global analysis, individual assumptions for every power plant, country or region might be necessary for this measure. Another option is to solely consider unrecovered overnight capital costs (OCC) associated with stranding assets prematurely to their plant lifetime (cf. Johnson et al., 2015, Kefford et al., 2018, Edwards et al., 2022), so that stranded assets are computed as

$$Stranded\ assets = \frac{(L-R)}{L} \cdot OCC \cdot K, \tag{5.1}$$

where L is a power plant's standard lifetime, R is a power plant's retirement age, OCC is measured in US$ per MW and K represents power plant capacity in MW.[10] In computing stranded assets, we only consider plants with $L \geq R$, otherwise we define stranded assets to be zero. This approach focuses on sunk costs. It is a narrower definition of stranded assets and could thus result in a lower bound of a stranded assets estimation. We implement this approach since it requires a reduced set of assumptions and thereby facilitates an analysis of stranded assets globally. Our approach may lead to conservative estimates of stranded assets since we strand old plants with high levels of recovered capital costs first, while in reality, e.g. for geopolitical reasons, younger plants might be stranded instead. We discount stranded assets to 2021 at an interest rate of 5 % (cf. Johnson et al., 2015). Assumptions on power plants' standard lifetimes and OCC are provided in Appendix 5.B. In a sensitivity analysis, we alter the interest rate and power plants' standard lifetimes (see Table 5.5 in Appendix 5.C).

Data. We employ a unique combination of three data sources. First, to obtain power plants' operating capacity and a mapping from physical assets to their owners, we employ a novel data set from Asset Resolution (Asset Resolution, 2022). The Asset Resolution data include multiple sectors covering more than 75 % of global emissions, namely energy (fossil fuel production and power), transport (automotive, aviation, and shipping), and industry (cement and steel). 300,000 assets in these sectors are matched with 65,000 asset owners. The asset-level data contain information on technology type (e.g. energy source for power plants), asset status (e.g. active, under construction, start year), location, production, capacity, financial metrics (e.g. capital expenditures), and emission metrics (e.g. emission intensity). The ownership data allows to identify the direct owner of an asset (called "direct owner" henceforth) and its ownership tree of asset owners owning the direct owner. Along this ownership tree, each link between an asset and a direct owner is characterized by an ownership share, since an asset can be owned by multiple direct owners. Further, each link between two asset owners is characterized by an equity share. If asset owner A owns a listed asset owner B, which issues equity securities, asset owner A's equity share is the ratio of its owned shares to asset owner B's total shares outstanding. If asset owner A owns a non-listed asset owner B the equity share is one. To simplify interpretation of

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[10] We thus assume that over the power plant's lifetime productivity is constant and capital costs are recovered linearly.

the results, we focus on three levels of the ownership tree, namely assets, direct owners, and the asset owners at the top of each ownership tree, called ”parent owner” henceforth. A parent owner may represent a (non-)listed company, a nation state or an individual shareholder. When aggregating the value of assets at the parent owner level, all ownership and equity shares along the ownership tree are accounted for.

Since this analysis focuses on power sector asset stranding, we only use the Asset Resolution data subset on the power sector. The power plant level data set covers capacity plans (operating and pipeline) from 1897 to 2075 of over 135,000 unique power plants across the globe. Regarding fossil fuel power plants, the Asset Resolution data covers over 32,800 unique power plants using coal, oil, gas or a mix of two fuels as input. The analysis requires imputing some missing information in the Asset Resolution data set (see Appendix 5.B). Table 5.2 in Appendix 5.B shows the fossil fuel power plant descriptive statistics after imputing missing values.

Second, we use data from IEA’s World Energy Outlook 2021 (IEA, 2021b), which provides the climate-compatible power plant capacity and the capacity following current national climate pledges. IEA uses the World Energy Model, a large-scale simulation tool, to outline development scenarios of energy demand and supply until 2050. This model covers the whole global energy system and provides projections on a sector-by-sector and region-by-region level using 2020 as a base year.

For our baseline analysis, we employ the Sustainable Development Scenario (SDS), which outlines how the global energy system can evolve in order to meet the the United Nation’s energy-related Sustainable Development Goals (SDG) in a cost-effective, realistic way. These goals are universal access to energy (SDG 7), reduction of severe health impacts from air pollution (part of SDG 3), and tackling climate change (SDG 13). The SDS is consistent with the 2 °C Paris goal with a 50 % probability without relying on global net-negative CO_2 emissions. Some assumptions of SDS are of particular relevance for our analysis. First, the SDS assumes CO_2 pricing differentiated between (groups of) countries. For instance, carbon prices in advanced economies with net-zero pledges start converging from 2025 on and reach US\$160/t CO_2 in 2050. Selected developing countries establish a CO_2 price that reaches US\$95/t CO_2 in 2050. Second, regarding power sector policies, CCUS is assumed to play a crucial role: 850 (5000) Mt of CO_2 emissions are captured in 2030 (2050), of which one-third is captured by the power sector, mainly in China and the US. For each region, the power capacity employing CCUS is not differentiated between fuels. To approximate how much coal and gas capacity with CCUS each region runs in each year, we multiply the share of each fuel's capacity in a region and year by its total fossil CCUS capacity.

In an additional analysis, we use the Announced Pledges Scenario (APS), which assumes that all countries implement their recently announced 2030 climate targets and longer term net zero pledges fully and on time. Importantly, net zero pledges can be reached by offsetting some remaining emissions from the energy sector, e.g. by absorbing emissions from forestry and land use. In comparison the the SDS, the APS highlights the ambition gap between reaching the 2 °C Paris goal and recently announced pledges. For instance, in 2050 CO_2 emissions from the energy sector and industrial processes reach more than 20 Gt in the APS compared to less than 10 Gt in the SDS.

Third, we retrieve data from Yahoo (2022) on 338 listed parent owners' financial information. These include data on shares outstanding, market capitalization, and total equity as of December 30th 2021. Currencies are converted to US$ using 2021 annual average exchange rates from OECD National Accounts Statistics (2022) and Deutsche Bundesbank (2022). For descriptive statistics of these variables, please refer to Table 5.4 in Appendix 5.B.

5.B Supplementary methods

Power plant standard lifetime assumptions. We assume that coal, gas, and oil plants have a standard lifetime of 50, 40, and 40 years, respectively (Cui et al., 2019, Tong et al., 2019). Power plants' OCC may recover over shorter periods, in which case we could overestimate stranded assets. Thus, we alter power plant standard lifetimes in a sensitivity analysis (see Table 5.5 in Appendix 5.C).

OCC assumptions. OCC for the US, EU, China, and India are taken from the IEA (2021b). OCC for Australia, Canada, Japan, Korea, Mexico, and Brazil are taken from the IEA & NEA (2020).[11] OCC of other OECD countries are the average of OCC from the OECD countries mentioned and the EU. Likewise, OCC

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[11] If multiple OCC estimations are provided for a country, we take their average. We exclude OCC of plants with carbon capture, utilization, and storage in this calculation as they greatly exceed OCC of conventional power plants and would distort the estimations upwards. For the OCC estimations of gas power plants in Australia, Canada, and Brazil, we consider both combined- and open-cycle gas turbine plants.

of other non-OECD countries are averages of OCC of China, India, and Brazil. All OCC used in the analysis are shown in Table 5.1.

Table 5.1: Overnight capital costs per technology and country.

	Overnight capital costs [US$/kW]	
Country	Coal power plants	Gas/oil power plants
Australia	3095	812
Canada	-	906
EU	2000	1000
Japan	2419	1109
Korea	1151	973
Mexico	-	601
US	2100	1000
Other OECD countries	2153	914
Brazil	2189	847
China	800	560
India	1200	700
Other non-OECD countries	1396	702

Asset Resolution data imputation. For power plants with missing installation year ($n = 26$), we use their decommissioning year and impute their installation year assuming the power plant lifetimes above. For power plants with missing information on both installation and decommissioning year (14 % of all plants), we assume the median installation year of power plants with the same technology located in the same country. For 64 plants, this imputation is not possible, since no other plant of the same technology exists in the same country. In such cases, we impute the installation year using the median installation year of power plants with the same technology located in OECD and non-OECD countries, respectively. We then proceed by imputing the decommissioning years of the power plants assuming the lifetimes above. Table 5.2 shows the fossil fuel power plant descriptive statistics after imputing missing values.

In the base year of the analysis, namely 2020, the Asset Resolution data covers only between 62 % and 86 % of the global fossil power plant capacity outlined in the IEA data depending on the fuel type and region (see Table 5.3).

To avoid underestimating asset stranding to due this data gap, we impute the

Table 5.2: Fossil fuel power plant descriptive statistics.

	mean	std	min	25 %	50 %	75 %	max
Installation year	2001	8	1924	1996	2000	2005	2036
Decommissioning year	2041	9	2020	2036	2039	2045	2085
Capacity [MW]	72.35	194.59	0.01	1.80	2.80	18.00	6000.00

capacity that is missing in the base year. More precisely, we construct power plants for each region and fuel type with the median age and capacity of the respective region and fuel type. For the constructed power plants, we assume the lifetimes above. We fill the data gap in the Asset Resolution data for 2020 with these constructed power plants. For instance, for Brazil, we construct 8 coal power plants with a capacity of 131 MW aged 10 years. Since the lifetime of a coal power plant is assumed to be 50 years in the baseline analysis, these constructed power plants retire in our imputed Asset Resolution data in 2050. We assign constructed power plants to an unknown asset owner. In our stranding method, we strand power plants owned by such an unknown asset owner first if it has the same age as a power plant owned by a known owner. Constructing these power plants is thus important to identify and strand plants, which are above the median age (for a given region and technology) and would not be stranded otherwise due to the data gap.

Finally, if the equity share between direct and parent owner is missing ($n = 9$), we manually search for the parent owner, which may be the major shareholder, on the direct owner's website and assume an equity share equal to one. If the equity shares of a direct owner do not add up to one ($n = 138$ or 2 % of direct owners owning stranded assets and $n = 194$ or 1 % of direct owners owning alternative energy assets), we scale up the equity shares provided in the data proportionately so that they sum up to one. For 504 direct and parent owners, we impute missing information on headquarter location by manually searching through their respective websites.

Yahoo Finance data.

The table below shows descriptive statistics of the variables retrieved from Yahoo (2022):

Table 5.3: Shares of power plant capacity in IEA data covered by Asset Resolution data. Region abbreviations are as described in Figure 5.1.

Region	Coal	Gas	Oil
ASIAPAC-CN-IN-JP	1.00	0.98	0.73
Africa	0.97	0.86	0.81
BR	0.75	1.06	0.90
CN	0.78	0.72	0.49
CSAM-BR	1.06	0.98	0.74
EUR	0.83	0.83	0.42
EURASIA-RU	0.77	0.78	0.09
IN	1.01	1.08	0.54
JP	0.86	0.81	0.37
ME	1.06	0.91	0.85
NAM-US	0.99	1.02	0.45
RU	0.50	0.53	0.16
US	0.88	0.88	0.32
World	0.84	0.86	0.62

Table 5.4: Descriptive statistics of parent owner financial variables.

	mean	std	min	25 %	50 %	75 %	max
Shares outstanding [Mio.]	$7.7 \cdot 10^3$	$1.0 \cdot 10^5$	1.3	130.0	415.6	$1.3 \cdot 10^3$	$1.9 \cdot 10^6$
Market capitalization [Mio. US$]	$2.9 \cdot 10^4$	$6.1 \cdot 10^4$	5.6	$2.3 \cdot 10^3$	$8.4 \cdot 10^3$	$3.0 \cdot 10^4$	$6.8 \cdot 10^5$
Total equity [bn. US$]	17.8	38.7	-2.0	1.9	6.2	17.8	514.9

5.C SUPPLEMENTARY RESULTS

The aggregation of stranded assets at the regional level potentially covers up within-region heterogeneity. Figure 5.10 shows stranded assets globally using the geolocation of prematurely retired power plants.

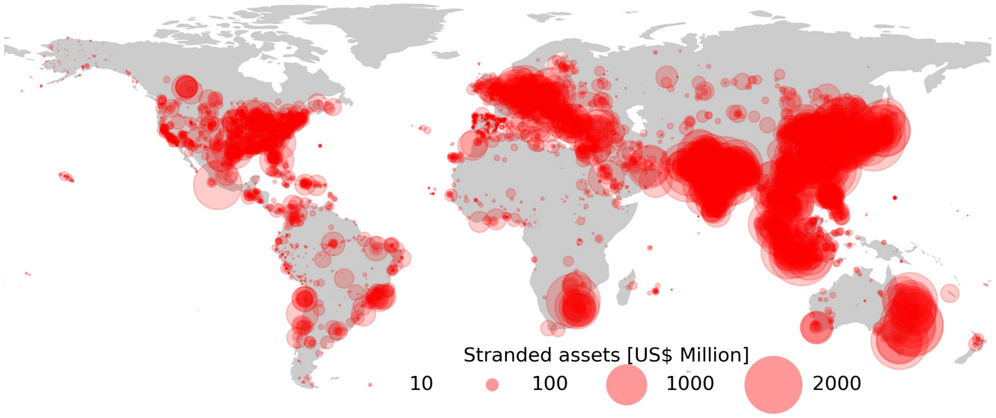

Figure 5.10: Spatial distribution of stranded assets between 2021 and 2050.

The quantification of stranded assets depends on assumptions on interest rates and power plant lifetimes as shown in Table 5.5. Higher interest rates and lower power plant lifetimes decrease stranded assets.

Table 5.5: Global stranded assets [US$ billion] for different interest rates and power plant standard lifetimes.

	Interest rate [%]		
Plant standard lifetime [years]	5	3	7
Coal: 50; oil/gas: 40	500	601	427
Coal: 25; oil/gas: 20	75	92	61

Shareholders may engage with listed asset owners exposed to stranded assets, e.g. via climate initiatives, which support asset owners aiming at climate targets. For instance, ”Climate Action 100+” is an investor-led initiative with the goal to assist asset owners in their transition to net-zero emissions by active engagement (Climate Action 100+, 2022). ”Science Based Targets initiative” shows asset owners how quickly they need to reduce their emissions to reach net-zero targets and provides technical assistance in this process (Science Based Targets initiative, 2022). A small subset of listed parent owners are members in these climate initiatives and together they own 8.5 % of stranded assets.

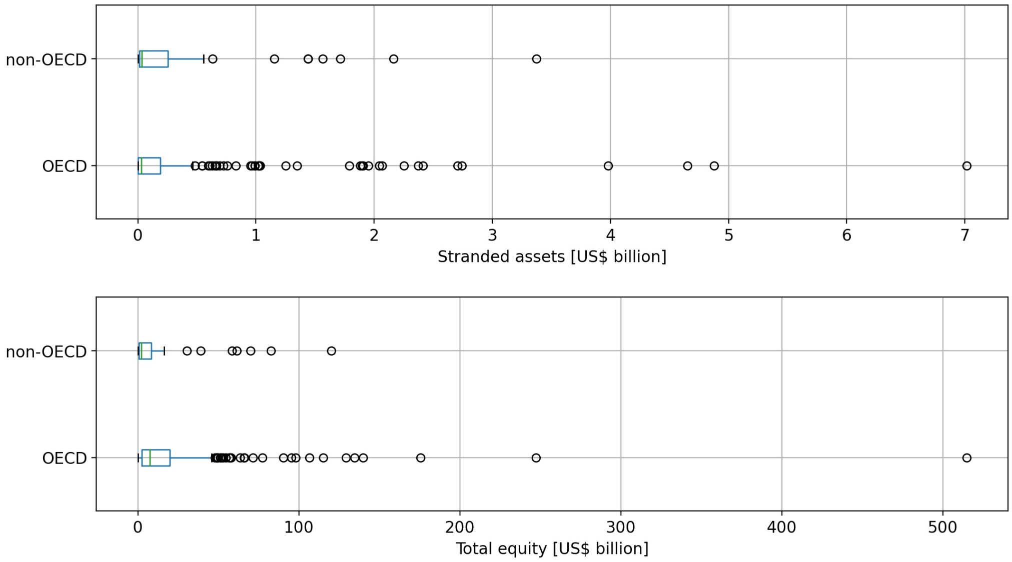

Figure 5.11: Stranded asset and total equity of listed parent owners headquartered in OECD and non-OECD countries. Listed parent owners with negative total equity or stranded assets larger than their total equity are ignored.

Table 5.6: Asset owner names of placeholders in Fig. 5.3, 5.4, and 5.7.

Fig.	Placeholder	Asset owner name
5.3 (a)	A	Huaneng Power International Inc
	B	Datang International Power Generation
	C	China Energy Investment Corp Ltd
	D	China Huaneng Group Co Ltd
	E	Huadian Power International Co
	F	China Datang Corp
	G	Shanghai Waigaoqiao Power Generation Co Ltd
	H	Zhejiang Beilun Power Generation Co Ltd
	I	Guangdong Energy Group Co Ltd
	J	China Huadian Corp Ltd
5.3 (b)	A	NTPC Ltd
	B	Mahagenco
	C	Rajasthan Rajya Vidyut Utpadan Nigam Ltd
	D	Damodar Valley Corp
	E	Uttar Pradesh Rajya Vidyut Utpadan Nigam Ltd

Table 5.6 – continued from previous page

Fig.	Placeholder	Asset owner name
	F	Tamil Nadu Generation & Distribution Corp Ltd
	G	Telangana State Power Generation Corp Ltd
	H	Adani Power Ltd
	I	The West Bengal Power Development Corp Ltd
	J	The Tata Power Co Ltd
5.3 (c)	A	Luminant Holding Co LLC
	B	Vistra Corp
	C	Calpine Corp
	D	NRG Energy Inc
	E	Duke Energy Carolinas LLC
	F	Florida Power & Light Co
	G	Santee Cooper
	H	Alabama Power Co
	I	Duke Energy Florida LLC
	J	Xcel Energy Inc
5.3 (d)	A	JERA Co Inc
	B	Tohoku Electric Power Co Inc
	C	Kyushu Electric Power Co Inc
	D	Hokuriku Electric Power Co
	E	Chugoku Electric Power Co Inc
	F	The Kansai Electric Power Co Inc
	G	Electric Power Development Co
	H	Hokkaido Electric Power Co Inc
	I	Kobelco Power Kobe Inc
	J	Nippon Steel Corp
5.4 (a)	A	NTPC Ltd
	B	Perusahaan Perseroan Persero PT
	C	Huaneng Power International Inc
	D	Eskom Holdings SOC Ltd
	E	JERA Co Inc
	F	Taiwan Power Co
	G	Korea South-East Power Co Ltd
5.4 (b)	A	People’s Republic Of China
	B	Republic Of India
	C	Republic Of Korea
	D	Republic Of Indonesia
	E	Republic Of South Africa
	F	Socialist Republic Of Vietnam
	G	Chubu Electric Power Co Inc

Table 5.6 – continued from previous page

Fig.	Placeholder	Asset owner name
5.7 (a)	A	Samchully Co Ltd
	B	SGC eTEC E & C Co Ltd
	C	POSCO
	D	Daelim Industrial Co Ltd
	E	Electric Power Development Co
	F	Hokuriku Electric Power Co
	G	Tohoku Electric Power Co Inc
5.7 (b)	A	Hokuriku Electric Power Co
	B	Tohoku Electric Power Co Inc
	C	Hokkaido Electric Power Co Inc
	D	AGL Energy Ltd
	E	Envipco Holding NV
	F	Tauron Polska Energia SA
	G	Okinawa Electric Power Co Inc

6

Endogenous climate policy, systemic risks, and asset stranding

Abstract

A regulator sets a carbon tax under stochastic climate change. Severe climate change demands high carbon taxes. The resulting downward pressure on fossil-related asset prices may precipitate a systemic financial crisis. We identify two equilibria: one is associated with carbon-intense investments and low carbon taxes, the other with a rapid fossil fuel phase-out and high taxes. We propose instruments which eliminate the carbon-intense equilibrium: (1) increasing the equity buffer of the banking system, and (2) increasing the wedge between the cost of funding fossil versus renewable assets. We argue that financial supervision cannot ignore climate concerns.

Keywords: Climate policy, Stranded assets, Systemic risk, Investor expectations, Financial regulation

Reference: von Dulong, A., Hagen, A. & Jaakkola, N. (2023). Endogenous climate policy, systemic risks, and asset stranding, Working paper.

Preliminary versions of this paper were presented at EAERE Annual Conference 2021 (virtual), EEA Annual Congress 2021 (virtual), AERE Summer Conference 2021 (virtual), VfS Annual Conference 2021 in Regensburg, and SURED Conference 2022 in Ascona.

6.1 INTRODUCTION

In 2015, Mark Carney, the governor of the Bank of England, warned that financial markets could be destabilised by ’transition risk’—ambitious climate policy reducing the value of capital related to fossil fuels, and the financial assets backing these (Carney, 2015). We know all too well how financial destabilisation (also called a systemic crisis) can have major costs for the real economy. Isabel Schnabel, of the Executive Board of the European Central Bank (ECB), has said the ECB should take into account risks associated with the transition to a low-carbon economy, given its role as the supervisor of eurozone banks (Schnabel, 2020). Further, she argued the ECB should also consider adjusting the benchmark allocation of asset purchase programmes to reflect the carbon intensity of the associated bonds.

Other policymakers are more cautious. Weidmann (2021) emphasises the Tinbergen rule: of having specialised policy instruments, one for each policy goal. He also underlines the primacy of carbon pricing as the instrument for emission reductions, and the democratic legitimacy conferred on climate policy when conducted by parliaments and governments.[1]

In this paper, we show that transition risk ties financial regulation and climate policy together. We construct the policy instrument which allows central bankers to focus on managing overall risks to the financial system. However, our results also demonstrate that, should the political decisionmakers fail to use the instrument, then the financial stability mandate may require the central banker to act instead: to conduct climate policy, of sorts, *in order* to maintain financial stability.

We identify multiple equilibria when climate policymaking is endogenous under systemic transition risk. One features high carbon-intensive investment and a high likelihood of transition risk; the other rapid disinvestment away from fossil-related capital and, consequently, little transition risk. A financial regulator—often the central bank—with a mandate to ensure financial stability thus has a basis, and maybe a responsibility, to ensure the latter equilibrium obtains.[2]

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[1] From the speech: “Banking regulation should retain its risk-oriented focus. It should not be used as an instrument to promote other policy objectives. (...) Many believe that not enough climate action is being taken at the political level. Some go further, claiming that central banks therefore need to step in. As tempting as this idea might sound, it’s not up to independent central banks to correct or replace political decisions. We are not granted independence to make the decisions that politicians are unwilling to make.”

[2] We discuss the roles of financial regulators and governments in implementing policies further in our conclusion.

The mechanism operates as follows. We assume systemic crises happen when financial assets suffer losses which exceed some fraction of aggregate capital buffers. The severity of climate change impacts is stochastic, and the government sets Pigovian taxes after observing this. Thus, taxes ought to be high if climate change turns out to be severe. But high carbon taxes lower the rate of return on fossil-related capital, so that investors' return is less than expected. If there is a lot of fossil-related capital, a high carbon tax may cause a systemic crisis, leading to deadweight losses. The government optimally lowers carbon taxes below the social cost of carbon, in order to mitigate or eliminate transition risk losses. Knowing this, firms heavy investment in fossil-intensive assets turns out to be rational. On the other hand, a move away from such assets reduces transition risk, so that high future carbon taxes are expected. This lowers the expected profitability of the assets, again confirming the investors' decisions.

The regulator can use various instruments, such as those proposed by Schnabel (2020), to guide the economy to the latter, more desirable outcome. It is sufficient to use the instruments only to the degree that the less desirable fossil-intensive equilibrium is eliminated. However, this expectations management involves efficiency losses.

We consider two instruments for the regulator. One is to increase the robustness of the banking system. However, the fact that the system is not perfectly robust implies that there are costs associated with such policies, and increasing robustness further will likely prove increasingly costly. The second option is to increase the wedge between the cost of funding fossil versus renewable assets, for example by the central bank penalising carbon-intensive investments when these are offered as collateral. But this is also costly: the wedge implies that too few carbon-intensive investments are made in the renewable equilibrium.

Our contribution to the literature is manifold: First, we contribute to the burgeoning literature on climate policies and asset stranding (cf. von Dulong et al., 2023a). There are a few studies analyzing how climate policies or investment-based instruments lead to asset stranding (Bertram et al., 2015, Fæhn et al., 2017, van der Ploeg & Rezai, 2018, Rozenberg et al., 2020). Closely related are studies focusing on the interaction between climate policies and firms' financial constraints as well as sustainable finance policies that promote low carbon sector investments (Fuest & Meier, 2022, Heider & Inderst, 2022). The economic models in these studies all assume that governments implement policies to reach a Benthamite utilitarian optimum (or a second best that comes as close as possible to that optimum). Moreover, the environment is deterministic, so that some stranding of irreversible assets is optimal and foreseen.

In reality there is uncertainty about climate policies. Bretschger & Soretz (2022) analyze the effects of uncertain climate policies on capital valuation, economic growth, and the environment. In their model, climate policies follow a stochastic process. Similar exogenous climate policy shocks are considered by Diluiso et al. (2021). In our paper climate policies are optimally chosen by a regulator, a social-welfare maximiser constrained by the fragility of the financial system and investor expectations.

Further, we contribute to studies analyzing how complementarities create the possibility of multiple equilibria (Van der Ploeg & Venables, 2022). The study by Kalkuhl et al. (2020) is closely related to our paper. They model the interaction between a carbon tax and stranded assets in a setting where the government cannot commit to the climate policy due to political economy incentives. They show that the government chooses the carbon tax to be either prohibitively high, preventing fossil fuel investments altogether, or to be zero. Between these two extreme outcomes, however, no intermediate cases of policies and investments can arise. The study by Biais & Landier (2022) also features multiple equilibria resulting from a government's limited commitment to climate policies. In their model firms make decisions on investments in green technologies under the expectation of an emission cap. Spillover effects from green investments lower firms' emission reduction costs, thereby allowing the government to implement the – otherwise too costly – emission cap. In contrast to the above studies, policy decisions in our paper are driven by the threat of a financial systemic crisis. More importantly, our approach allows investment to respond to expectations more flexibly. In particular, in our framework, policies are associated with deadweight losses. We also obtain our results under rational expectations.

Our second contribution is to the literature on macroprudential policy. The contribution by Jeanne & Korinek (2020) is closest to ours, in terms of model structure. They develop a model of liquidity provision and financial crises which has similar elements as the present paper. However, we are interested in climate policy and the interaction of the fossil energy sector with the financial sector. The study by Oehmke & Opp (2022) focuses on bank capital requirements and climate policies to address transition and physical risks. They show that capital requirements for carbon-intensive loans can effectively mitigate financial risks related to carbon emissions and increase the credibility of higher carbon taxes. Further, Döttling & Rola-Janicka (2022) study carbon taxes and financial regulation in a model featuring financial frictions as well as transition and physical risks. They show that the interaction between the carbon tax and financial constraints depends on the two climate-related risks and that the mix of a carbon tax and a leverage regulation can improve welfare. In contrast to the above studies, our central emphasis is on the possibility of multiple equilibria, whereas they primarily consider macroprudential policy when the equilibrium is unique. To the extent that financial crises are often the result of policies (housing market regulation comes to mind), our contributions may be relevant for future work in macroprudential policy more generally.

We also contribute tangentially to the literature on systemic risk. The existing studies on systemic risks largely focus on the banking sector, and specifically on potential contagion via the impact of asset exposures and default cascades, and/or liquidity shocks and funding runs (Glasserman & Young, 2016). Chen et al. (2014) analyze financial systemic risk due to asset price contagion and Acharya (2009) studies the effect of diversification by financial firms on exposure to common shocks. Although such effects might amplify the impacts that climate policy-related devaluations of assets might have on the financial sector, the key difference to these studies is that the systemic shock in our context is endogenous and determined by policies. Regarding asset stranding, however, the policymaker's incentives to cause a shock (or not) will be shaped by market outcomes, which themselves depend on expectations of the policymaker's actions.

The remainder of the paper is structured as follows: In section 6.2, we present the model. We then obtain the solution in section 6.3, before discussing the policy instruments in section 6.4. We discuss some implications of our results and prospects for future work in section 6.5.

6.2 Model set-up

In this section, we set up a partial equilibrium model of the carbon economy. We focus on systemic risk and asset stranding, with the key interaction being that between the regulator's decisions and the expectations of the investors. The model has three different types of agents taking actions: investors, production firms, and a regulator. Uncertainty is represented by nature moving. There are also implicitly consumers who consume the surplus from the sector, and who suffer any climate damages and costs of a systemic crisis. Finally, there is a financial sector channelling invested funds to capital.

We illustrate the timing of the game in Figure 6.1. We gather here also the problems solved by these agents, and the variables resolved at each stage by optimality or equilibrium conditions. In this section, we assume the regulator takes actions only after investors and nature have moved.

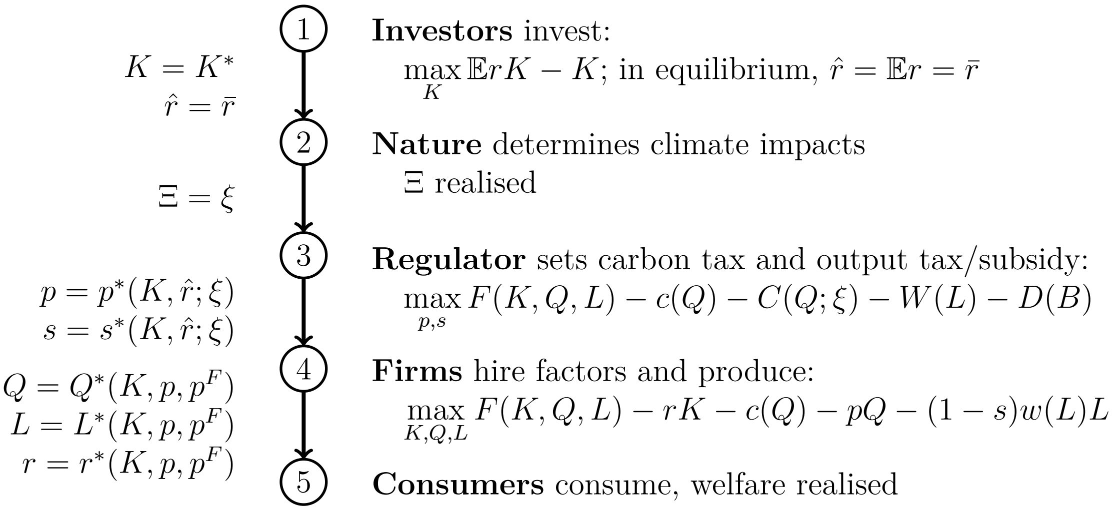

Figure 6.1: Timing of the game

We now explain in more detail our assumptions regarding factors driving the behaviour of the various agents.

Investors. There is a competitive fringe of investors. The investors choose how much to invest in fossil-related capital K, based on the expected return. There is an outside option, the rate of return on capital which is exogenous and denoted by $\bar{r}$ (which implicitly accounts for any discounting). Thus their problem is to solve

$$\max_K (\hat{r} - \bar{r})K$$

where $\hat{r}$ is the expected gross return. We implicitly assume the overall quantity of investment in the economy is exogenously fixed, and that the return on non-fossil investments is deterministic and independent of the fossil economy.

Financial sector. Investments are channelled via a financial sector. To keep the analysis tractable, we abstract from a detailed representation and instead use a reduced-form model of the financial system. The key assumption is that the book value of firms in the financial sector depends on the expected rate of return $\hat{r}$, so that if realised profits fall below this, the book value is written down, generating an accounting loss B (for 'bad debt'). The financial sector can absorb a moderate accounting loss $B < \bar{B}$ without problems. However, a large accounting loss $B > \bar{B}$ will lead to defaults, and these will generate deadweight losses.

The loss threshold $\bar{B} > 0$ represents the financial system's ability to absorb losses; the total sum of equity buffers, adjusted for amplification effects due to default cascades in the financial network. It is an exogenous parameter; in particular it does not depend on fossil investments K. This could be because the financial sector's overall loss-absorbing capacity depends on investment in the outside sector, relative to which the fossil sector is 'small'.

More specifically, the fossil investments are held on the representative financial firm's balance sheet as assets, with a book value equal to the expected gross return. If the realised gross return $1+rK$ falls short of the book value $1+\hat{r}K$, the resulting write-off of bad investments $B = (\hat{r} - r)K$ will eat into the equity buffer $\bar{B}$. If equity falls below zero, the representative financial firm goes into default. This results in a deadweight loss $D(B)$. The social loss function is given by

$$D([\hat{r} - r]K) = \begin{cases} 0 & \text{if } [\hat{r} - r]K \leq \bar{B} \\ \delta([\hat{r} - r]K - \bar{B}) & \text{otherwise,} \end{cases}$$

where $\delta > 0$ is a factor scaling the firms' financial loss to the social loss. Note that the loss function has a kink where financial firms default.[3] The social losses are also proportional to the total quantity of investment. This set-up can be derived from e.g. the specification used by Malherbe (2020) to consider bank equity requirements, and with the stylised models explored by Glasserman & Young (2016) for recovery from individual defaulting banks. The parameter δ implicitly embeds the amplifying effect of the network connecting financial firms. If there is very little fossil investment, so that K is small, then there is no risk of a systemic crisis, as the losses are capped by $\hat{r}K$.

Our reduced-form description could, for example, reflect a financial sector consisting of banks, with a limited supply of bank equity, exogenously given equity buffers and interconnections between banks (Malherbe, 2020). Thus, a high carbon tax can trigger defaults among banks, and the interconnections can lead to

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[3] This kink is not central; the buffer $\bar{B}$ before the crisis is triggered is. There could also be a jump due to the rent extraction contest, as suggested by Glasserman & Young (2016).

a contagious default cascade, amplifying the losses (Glasserman & Young, 2016). Alternatively, the financial system could consist of mutual funds with potential contagion due to fire sales of common asset holdings (Delpini et al., 2019). The deadweight losses thus result, for example, from a rent extraction contest over the liquidated assets; from inefficiently premature liquidation of assets; from delays in payments, leading to inefficient delays in investment; or from inefficiencies associated with the taxation required to pay for a bailout (Glasserman & Young, 2016, Malherbe, 2020).

Production firms. The competitive fossil-related production firms employ capital, labour and fossil fuel to maximise profits. The problem of the representative firm is to solve

$$\max_{K,Q,L} F(K,Q,L) - c(Q) - pQ - rK - (1-s)w(L)L.$$

The production function is strictly concave and has constant returns to scale. The private cost of extracting fossil fuel is denoted $c(Q)$; p and s are the carbon price and output subsidy, respectively, set by the regulator and taken as given by the firms; r is the cost of renting capital on the market; $w(L)$ is the wage required to attract labour away from the outside sector; and s is a proportional wage subsidy. Fossil fuel extraction and amount of labour hired are determined by the firms; as the capital supply is given by past investment, the rental rate r will adjust to ensure that the capital market clears.

We immediately make some simplifying assumptions, to avoid undue technical complications.

Assumption 6.1. *The production function is Cobb-Douglas and the private and external costs of using carbon are linear:*

$$F(K,Q,L) = AK^{\alpha}Q^{\beta}L^{1-\alpha-\beta}, \qquad c(Q) = \zeta Q, \qquad C(Q;\xi) = \xi Q,$$

with A>0, $1 > \alpha > 0$*,* $1-\alpha > \beta > 0$*,* $\zeta > 0$*,* $\xi > 0$*.*

Thus, A is the total-factor productivity, α is the output elasticity of K and β is the output elasticity of Q; ζ is a constant marginal fuel extraction cost; and ξ is the social cost of carbon.

Assumption 6.2. *Labour is supplied to the fossil sector with an elasticity that is* *weakly falling with the size of the sector:*

$$\eta(L) \equiv \frac{w(L)}{w'(L)L}, \quad \eta'(L) \leq 0. \tag{6.1}$$

Furthermore, there is $\bar{L}$ *such that* $\lim_{L\uparrow\bar{L}} \eta(L) = 0$.

In words, as more and more labour is pulled into the fossil sector, it becomes more difficult to attract additional labour with a marginal wage increase. The total labour force is $\bar{L}$, and the marginal product of labour in the outside sector grows without bound as labour employed in the outside sector $\bar{L} - L$ vanishes.

Regulator. The benevolent regulator seeks to maximise (linear) utility from output, less extraction costs; the externality cost due to climate change $C(Q;\Xi)$; plus the surplus from using labour in the outside sector $W(\bar{L}-L)$, where aggregate labour supply $\bar{L}$ is assumed to be large enough so that the fossil sector never employs all labour; and any deadweight losses due to a systemic crisis:

$$\max_{p,s} F(K,Q,L) - c(Q) - C(Q;\Xi) + W(\bar{L}-L) - D([\hat{r}-r]K). \tag{6.2}$$

Climate damages (both total and marginal) are increasing in the random variable Ξ.

Assumption 6.3. *The climate damage parameter* Ξ *is distributed according to an atomless probability density function* $f(\xi)$*, with domain* $\xi \in [\xi_{min}, \xi_{max}]$.

The true value of ξ, is realised after investors have made the fossil investments, but before the government sets the carbon price. The cost of moving labour to fossil-related production from the outside sector is $W(L)$ and satisfies $w(L) = -W'(\bar{L}-L)$.[4] We are thus implicitly assuming that the tax revenues are recycled without distortions.

6.3 SOLVING THE MODEL

The game in Figure 6.1 is solved by backward induction; we walk through these in reverse order.

Stage 5: Consumption. The last stage is just book-keeping, with utility computed depending on consumption (fossil production, net of opportunity costs

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[4] This could come, for example, from some production function of a representative firm employing workers qualified to also work in the fossil sector.

of labour brought in from the outside sector, of fuel extraction costs, and of deadweight losses associated with the financial crisis) and on climate impacts.

Stage 4: Production. Solving the firms' problem in the fourth stage, the first-order conditions are

$$F_K(K,Q,L) = r, \tag{6.3}$$

$$F_L(K,Q,L) = (1-s)w(L), \tag{6.4}$$

$$F_Q(K,Q,L) = c'(Q) + p. \tag{6.5}$$

These conditions recursively define

$$(Q^*, L^*) = h(K,p,s), \qquad r^* = r^*(K,p,s),$$

where the function $r^*(\cdot)$ implicitly incorporates the fact that (Q^*, L^*) are given by the vector-values function $h(K,p,s)$. Given K, p, and s, the total value of asset writedowns is given by $B(p,s;K,\hat{r}) = [\hat{r} - r^*(K,p,s)]K$.

We want to know the effects of the policies on fossil fuel use, and on the rate of return to fossil capital. We define the elasticity of the marginal private benefit to fossil fuel as

$$\eta_p(K,Q,L) \equiv \frac{\partial(F_Q - c'(Q))}{\partial Q}\frac{Q}{F_Q - c'(Q)} < 0.$$

Omitting the arguments of η_p for clarity, and understanding that the factor inputs are evaluated at their equilibrium values, we then get the elasticities

$$\epsilon_{Q,p} \equiv \frac{\partial Q^*}{\partial p}\frac{p}{Q^*} = \frac{\eta(L^*)^{-1} + \alpha + \beta}{\eta(L^*)^{-1} + \alpha/(1-\beta)}\eta_p^{-1} < \eta_p^{-1} \leq 0, \tag{6.6}$$

$$\epsilon_{L,p} \equiv \frac{\partial L^*}{\partial p}\frac{p}{L^*} = \frac{\beta}{\eta(L^*)^{-1} + \alpha + \beta}\epsilon_{Q,p} \leq 0, \tag{6.7}$$

$$\epsilon_{r,p} \equiv \frac{\partial r^*}{\partial p}\frac{p}{r^*} = \beta\frac{\eta(L^*)^{-1} + 1}{\eta(L^*)^{-1} + \alpha + \beta}\epsilon_{Q,p} \leq 0, \tag{6.8}$$

$$\epsilon_{Q,s} \equiv \frac{\partial Q^*}{\partial s}\frac{s}{Q^*} = \frac{s}{1-s}\frac{1-\alpha-\beta}{(1-\beta)\eta(L^*)^{-1} + \alpha} \geq 0, \tag{6.9}$$

$$\epsilon_{L,s} \equiv \frac{\partial L^*}{\partial s}\frac{s}{L^*} = \frac{s}{1-s}\frac{1-\beta}{\alpha + (1-\beta)\eta(L^*)^{-1}} \geq 0, \tag{6.10}$$

$$\epsilon_{r,s} \equiv \frac{\partial r^*}{\partial s}\frac{s}{r^*} = \frac{\partial F_K}{\partial Q}\frac{Q^*}{F_K}\epsilon_{Q,s} + \frac{\partial F_K}{\partial L}\frac{L^*}{F_K}\epsilon_{L,s} \geq 0. \tag{6.11}$$

We have used here Assumptions 6.1 and 6.2. In equation (6.6), the fraction featuring the labour supply elasticity $\eta(L^*)$ involves the feedback between fossil use and labour supply, which acts as an 'amplifier' on the direct effects of the carbon tax on fossil fuel extraction: carbon taxes reduce fossil fuel use, which pushes labour out, which further reduces the fossil fuel input, and so on. This amplification appears directly in equation (6.7). Of course an inelastic labour supply ($\eta(L^*) = 0$) shuts off these amplification mechanisms. An elastic labour supply also increases the response of the rate of return on capital, as is clear from equation (6.8). The effect of the wage subsidy, given by equations (6.9)–(6.11), is clearly zero if the labour supply elasticity is zero; otherwise, wage subsidies have strictly positive impacts of the fossil input, labour input, and the capital return.

Stage 3: Carbon taxes. In the third stage, the regulator takes the fossil capital stock K, the realisation of climate damages ξ, and the expected return $\hat{r}$ (on which the financial firms' book value is based) as given. It also understands the firms' optimal choices $Q^*(\cdot)$ and $L^*(\cdot)$ and how they depend on p and s, and then sets the optimal carbon tax and wage subsidies

$$p^* = p^*(K, \xi, \hat{r}), \qquad s^* = s^*(K, \xi, \hat{r}).$$

The first-order conditions for the regulator, assuming that the optimal solution implies B being bounded away from $\bar{B}$, are, for $X \in \{p, s\}$ and evaluated at $p = p^*$, $s = s^*$, $L = L^*(K, p^*, s^*)$, $Q = Q^*(K, p^*, s^*)$

$$\begin{aligned}(F_Q - \zeta - \xi + KD'(B)F_{KQ}) \frac{\partial Q^*}{\partial X} \\ + (F_L - w(L) + KD'(B)F_{KL}) \frac{\partial L^*}{\partial X} = 0.\end{aligned}$$

Using equations (6.6), (6.7), (6.9) and (6.10) it is easy to show that both of these equations can only hold if

$$\xi - p^* = KD'(B)F_{KQ}, \tag{6.12}$$

$$s^* w(L) = KD'(B)F_{KL}, \tag{6.13}$$

where we have also used the firm's first-order conditions.

The interpretation is straightforward. The left-hand side of equation (6.12) gives the uninternalised component of the external cost of a marginal unit of emissions. The right-hand side is the marginal benefit of emissions on reducing the deadweight loss associated with a financial crisis: higher fuel supply increases the *ex post* rate of return on investments, which is useful in a crisis as it reduces the bad debts and thus the social cost of the crisis. Conversely, the left-hand side of equation (6.13) is the cost of the production inefficiency associated with the distorting wage subsidy, while the right-hand side is again the benefit of reducing the deadweight loss of the financial crisis (boosting labour supply also increases the rate of return to investments).

To continue the analysis further, it is useful to consider the set of policies which just trigger the financial crisis.

Definition 6.1. *The set of crisis-triggering policies* $\bar{P} = \tilde{h}(K, \hat{r}) \in [0, \infty) \times [0, 1]$*, with element* $(\bar{p}, \bar{s})$*, are defined by the equation* $(\hat{r} - r^*(K, \bar{p}, \bar{s}))K = \bar{B}$.

Note that for a fixed $\hat{r}$, the crisis-triggering policies are monotonic in the capital stock K: $\partial\bar{p}/\partial K < 0$, $\partial\bar{s}/\partial K > 0$. With more assets at risk, the realised rate of return sufficient to trigger the crisis is higher. Diminishing returns tend to push the realised rate of return lower, so that the carbon taxes must be lower to stay on the crisis threshold, and/or the wage subsidies must be higher.

We can now give the optimal policies.

Lemma 6.1. *The optimal policies are given by: (i)* $p^* = \xi$, $s^* = 0$*, if* $(\hat{r} - r^*(K, \xi, 0))K \leq \bar{B}$*; (ii)* $p^* = p^{**}(\xi) \equiv (\xi - \alpha\delta\zeta)/(1 + \alpha\delta)$, $s^* = s^{**} \equiv \alpha\delta/(1 + \alpha\delta)$*, if* $(\hat{r} - r^*(K, p^{**}, s^{**}))K > \bar{B}$*; (iii)* $p^* = \xi - (\xi + \zeta)s^*$, $(\hat{r} - r^*(K, p^*, s^*))K = \bar{B}$*, otherwise.*

In words: the policies are a weakly convex combination of $(\xi, 0)$ and (p^{**}, s^{**}). The first case is straightforward. If $B < \bar{B}$, the right-hand sides of equations (6.12) and (6.13) are equal to zero. In this case, the optimal carbon tax is Pigovian and there is no wage subsidy. This happens if the marginal climate damage ξ is sufficiently small, so that setting $p = \xi$ and $s = 0$ implies that there is no crisis, i.e. $B < \bar{B}$.

The second case arises if the regulator finds it optimal to let the crisis happen. If $B > \bar{B}$, the right-hand side of both equations is positive, the tax is below the Pigovian level ($p^* < \xi$) and the wage subsidy is strictly positive. In other words, the regulator reduces the carbon tax, to account for the marginal deadweight loss associated with the crisis; and imposes a wage subsidy for the same reason. Given

Assumption 6.1, the optimal carbon tax is a weighted sum of the external cost ξ and the negative of the extraction cost $-\zeta$, or $p^* = p^{**}$, and the wage subsidy is $s^* = s^{**}$, as long as these yield $B > \bar{B}$. This occurs for high values of climate damage ξ: the regulator is sufficiently concerned about the climate impacts that she prefers to let the crisis take place.

The third case is an intermediate case. Note that the right-hand side of equations (6.12) and (6.13) is discontinuous at $B = \overline{B}$. There is an intermediate range of climate damages for which the regulator sets policies just exactly to go to the brink of the crisis, without going over it. In this case, both policies are distorted away from the Pigovian levels: carbon taxes are lowered below the marginal climate damage ξ, and to avoid distorting the labour-fossil fuel margin, a wage subsidy is imposed to satisfy $(\xi - p^*)/s^* = \xi + \zeta$. Note that, in this case, $p^*/s^* = p^{**}/s^{**}$, which ensures an efficient labour-fossil fuel margin.

Stage 2: Nature. After investments have been made, but before the carbon tax is set, nature selects the state of the world, in terms of the severity of the carbon taxes. That is, the random variable Ξ takes on a particular value ξ.

Stage 1: Investment. Investors understand the behaviour of the regulator. However, they behave competitively, and thus take the carbon prices as given, independent of their own investment choice. The equilibrium conditions are then

$$\hat{r}^* = \bar{r}, \qquad \hat{r}^* = \mathbb{E}r^*(K^*, p^*(K^*, \Xi, \hat{r}^*), s^*(K^*, \Xi, \hat{r}^*)). \tag{6.14}$$

The former condition in equation (6.14) just says that firms will only invest in positive quantities if they expect to recoup the opportunity cost, in expectation. The second condition expresses rational expectations regarding the expected gross return, in which the expected value is taken with respect to Ξ.

Equilibrium. To summarise, we can gather the conditions which define an equilibrium of the economy:

Definition 6.2. *The equilibrium in this economy is a tuple* $\{Q^*, L^*, r^*, p^*, \hat{r}^*, K^*\}$ *such that production firms' first-order conditions hold (equations* (6.3)-(6.5)*), the government maximises social welfare (Lemma 6.1), and investment is in equilibrium (equation* (6.14)*).*

The central feature of the equilibrium is the fixed-point condition for $\hat{r}^*$ given by equation (6.14). Note that

$$\frac{\mathrm{d}}{\mathrm{d}K}\mathbb{E}r^* = \mathbb{E}\left[\frac{\partial r^*}{\partial K} + \frac{\partial r^*}{\partial p}\frac{\partial p^*}{\partial K} + \frac{\partial r^*}{\partial s}\frac{\partial s^*}{\partial K}\right].$$

The first term in the expectation is negative. The second two terms are both either zero (for climate impacts ξ such that $B \neq \bar{B}$) or positive (for ξ such that $B = \bar{B}$). Recall that the expectation is taken over the climate impacts. Thus, for levels of K such that the regulator optimally only just prevents the crisis from occurring for a large enough probability mass of the climate impact parameter, the expected rate of return to fossil capital may be upward sloping. This implies there may be multiple equilibria.

Proposition 6.1. *There exist parameterisations of the model which admit multiple equilibria.*

We can show the existence of multiple equilibria for parameter values for the US electricity sector from Fullerton & Ta (2019) who calibrate a Cobb-Douglas model to fit a large detailed dynamic computable general equilibrium model of the US economy.[5]

6.4 POLICY INSTRUMENTS

We will now discuss policies instruments a regulator could implement to guide the economy away from the equilibrium under which financial stability is threatened.

Credible expectations management. If a policymaker today can credibly manage investor expectations in the direction of low investment, and high future carbon taxation, then this can potentially select the low-investment equilibrium without the need for further action. However, the regulator's communication prior to the beginning of the game is cheap talk, in the sense that if the investors believe a high-investment equilibrium will be played despite the communication, then the regulator's announcement has no effect on the outcome. Purely cheap talk-driven expectations management is thus a risky instrument for bringing about the low-investment equilibrium.

Higher capital requirements. Suppose the policymaker is able to increase the loss-bearing equity buffer $\bar{B}$. This could be done, for example, by increasing

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[5] We find that with this parameterisation multiple equilibria exist even with a $\bar{B}$ of 10% of capital in the sector.

the equity banks are required to hold per unit of capital. It is straightforward that this will eliminate the equilibrium under which transition risk threatens the financial system.

Note that higher capital requirements are unlikely to be costless from the perspective of a period-0 regulator. Whether there will also be deadweight losses associated with the policy depends on whether the costs reflect real costs to society, or political costs to the regulator.

Note that capital requirements are typically the fief of the supervisor of the financial system, which typically is the central bank. Thus, this policy instrument conflates climate mitigation and financial stability as policy goals.

Raising the cost of fossil investments. Alternatively, the cost of investing in fossil technologies could be increased, so that investors' opportunity cost of funds would be $1 + \kappa$, for some $\kappa > 0$. Such a policy could be implemented by a government, in terms of taxing investments which were particularly complementary to carbon emissions. Alternatively, it could be implemented by central banks by giving low-carbon investment preferential treatment when posted as collateral.

It is straightforward to see that a sufficiently high κ would eliminate the second equilibrium. However, such a policy would also lead to suboptimally low fossil investment in equilibrium, due to the distorted investment incentives.

Taxing carbon-intensive investments is a policy instrument which would naturally fall within the remit of fiscal policy. However, the cost of investments could also be increased by central bank policies, such as offering preferential rates to clean investments, or imposing punitive rates on 'brown' assets when offered as collateral. The aim of the latter policy mixes together both climate policy objectives and the maintenance of financial stability, and thus it is not fully clear whether it should be regarded as government-determined environmental and fiscal policy, or as central-bank determined financial stability regulation.

6.5 CONCLUSION

We have shown that the combination of lack of commitment to future policies and the threat of systemic crises may give rise to expectations-driven adverse equilibria. Given the centrality of financial (in)stability in this model, our mechanism inextricably connects climate policy to financial stability concerns. As such, it pulls the financial regulator—often, the central bank—into the field of climate policy also.

The conventional wisdom probably suggests that central banks should stick to their traditional mandates of maintaining price stability and ensuring the smooth functioning of the financial system. Climate policy would thus be left to the democratically elected decisionmakers. This straightforward partitioning of the policy areas fails when future climate policies are endogenous, and when expectations can steer investments which affect the cost of future policy decisions. This complication needs to be acknowledged and the role of climate change in central bank decisionmaking should be evaluated carefully.

We have been fairly silent about the identity of 'the regulator'. In terms of setting the carbon tax, the regulator clearly represents the government. However, other actions of the regulator are more properly the fief of a central banker, or a macroprudential or banking supervisor. For example, the premium required of fossil-backed assets, when posted as collateral, may more appropriately be seen as a policy tool operated by a central bank. Regulation of required levels of bank equity could be implemented via legislation, but a banking supervisor could have discretion in setting them.

Our expectations-driven framework puts emphasis on the importance of managing expectations, in steering society towards a desirable equilibrium. Technocratic central banks might be more appropriate agents to engage in such expectations management, given the role of expectations is standard monetary policy. To a central banker, credibility is everything. To an elected government, credibility lasts four years, at best.

We believe such policy conclusions are controversial and require public discussion. One option is for the democratically-elected governments to modify the mandates of central banks. Alternatively, a government could let central bankers out of the bind by proactively guiding the economy towards a rapid decarbonisation, thus also eliminating risks to future financial stability, and allowing the central bank to focus its traditional policy goals.

This paper has presented 'proof-of-concept' work only. Further work is required to assess the quantitative importance of the potential for multiple equilibria. A multi-period model would likely be required for any quantification. We note that one interesting aspect to such work is that expectations in our setting are endogenous, and can be managed by policies. We are not aware of work in this vein, as most of the literature on multiple equilibria in policy games either is silent on equilibrium selection, or considers stochastic switching of expectations.[6]

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[6] Mertens & Ravn (2014) is an example of a macroeconomic model with expectations-driven equilibria, but stochastic switching of expectations.

Appendices

6.A Proof of Lemma 6.1

Consider policies (p, s), with fossil capital K. It is straightforward to show that the set P of crisis-triggering policies defines locus $\bar{s}(p; K)$ in this space, with $s_p > 0$, $s_K > 0$. If $s < \bar{s}(p; K)$, the crisis happen as $B > \bar{B}$; if $s > \bar{s}(p; K)$, $B < \bar{B}$ and there is no crisis.

From the first-order conditions given by equations (6.12) and (6.13), the only solutions with an interior $B \neq \bar{B}$ are obtained by setting $D'(B) = 0$ or $D'(B) = \delta$, which yields cases (i) and (ii) with minimal manipulations. These are the only critical points and they are local maxima as the Hessian at these points is given by

$$H = \begin{pmatrix} \Lambda & \Gamma \\ \Gamma & \Psi \end{pmatrix} \tag{6.15}$$

with the entries

$$\Lambda := \frac{\partial Q}{\partial p}\left(a_L \frac{\partial L}{\partial p} + a_Q \frac{\partial Q}{\partial p}\right) + \frac{\partial L}{\partial p}\left(b_L \frac{\partial L}{\partial p} + b_Q \frac{\partial Q}{\partial p}\right)$$

$$\Gamma := \frac{\partial Q}{\partial s}\left(a_L \frac{\partial L}{\partial p} + a_Q \frac{\partial Q}{\partial p}\right) + \frac{\partial L}{\partial s}\left(b_L \frac{\partial L}{\partial p} + b_Q \frac{\partial Q}{\partial p}\right)$$

$$\Psi := \frac{\partial Q}{\partial s}\left(a_L \frac{\partial L}{\partial s} + a_Q \frac{\partial Q}{\partial s}\right) + \frac{\partial L}{\partial s}\left(b_L \frac{\partial L}{\partial s} + b_Q \frac{\partial Q}{\partial s}\right)$$

where

$$a := F_Q - (\xi + \zeta) + KD'(B)F_K Q$$

and

$$b := F_L - w(L) + KD'(B)F_K L$$

and thus $a_Q = F_{QQ} + K\delta F_{KQQ}$, $a_L = b_Q = F_{QL} + K\delta F_{KQL}$, and $b_L = F_{LL} - w'(L) + K\delta F_{KLL}$. The Hessian determinant is

$$\begin{aligned}
\det(H) &= \Lambda\Psi - \Gamma^2 \\
&= -\frac{AK^{\alpha}Q^{\beta-2}L^{-2(\alpha+\beta-1)}\beta(\frac{\partial Q}{\partial p})^2 w(L)^2(\alpha\delta+1)}{(s-1)^2(Lw'(L) + w(L)(\alpha+\beta))^2} \\
&\quad \cdot \left(\alpha A(\alpha+\beta-1)(\alpha\delta+1)K^{\alpha}Q^{\beta} + (\beta-1)w'(L)L^{\alpha+\beta+1}\right) \\
&> 0
\end{aligned}$$

and

$$\begin{aligned}\Lambda = &-\frac{\beta(\frac{\partial Q}{\partial p})^2 L^{-\alpha-\beta+1}}{Q^2(Lw'(L)+w(L)(\alpha+\beta))^2} \\ &\cdot \Bigg(\beta w(L)^2 w'(L) L^{\alpha+\beta+1} - A(\alpha\delta+1)K^\alpha Q^\beta \\ &\cdot \big((\beta-1)L^2 w'(L)^2 - 2\alpha L w(L) w'(L) - \alpha w(L)^2(\alpha+\beta)\big)\Bigg) \\ &< 0.\end{aligned}$$

Thus, the critical points are local maxima.

In addition, we need to consider possible corner solutions. The most important of these is to set a crisis-triggering policy $(p^*, s^*) \in P$, so that $B = \bar{B}$. In this case, the optimal controls satisfy solve the problem of equation (6.2), subject to the constraint $(p^*, s^*) \in P$. The first-order conditions include $F_Q - (\xi + \zeta) = -\lambda K F_{KQ}$ and $F_L - w(L) = -\lambda K F_{KL}$, where λ is the multiplier associated with the constraint. Using the firm's first-order conditions and this, we get

$$\frac{p-\xi}{s} = -\frac{\beta L w(L)}{(1-\alpha-\beta)Q} = \xi + \zeta. \tag{6.16}$$

Thus, the optimal policies will fall along the line in $(p-\xi, s)$-space passing through $(0,0)$ and $(-\alpha\delta(\xi+\zeta)/(1+\alpha\delta), \alpha\delta/(1+\alpha\delta))$.

As the planner's maximand is continuous, the optimal policies involve setting the interior solution $(p^*, s^*) = (\xi, 0)$ if $\bar{s}(\xi; K) < 0$; the interior solution $(p^*, s^*) = (p^{**}, s^{**})$ if $\bar{s}(p^{**}; K) > s^{**}$; and the corner solution $(p^*, s^*) \in P$ satisfying equation (6.16), otherwise.

6.B PROOF OF PROPOSITION 6.1

We only need to demonstrate that multiple equilibria exist for some parameterisations; continuity ensures that at least 'close' parameterisations also admit multiple equilibria.

We thus set $w(L) = \gamma L$, so that $\eta(L) = 1$. Further, we assume that the climate damage is uniform: $\Xi \sim \mathcal{U}(\xi_{\min}, \xi_{\max})$.

Using equations (6.3)–(6.5) , we can then solve explicitly for L^*, Q^* and r^* as functions of (K, p, s):

$$\begin{aligned}
L^*(K,p,s) &= \left(A \left(\frac{1-\alpha-\beta}{\gamma(1-s)} \right)^{1-\beta} \left(\frac{\beta}{\zeta+p} \right)^{\beta} K^{\alpha} \right)^{1/(1+\alpha-\beta)}, \\
Q^*(K,p,s) &= \frac{\beta}{1-\alpha-\beta} \frac{w(L^*(K,p,s))(1-s)}{\zeta+p} L^*(K,p,s), \\
r^*(K,p,s) &= \alpha \left(A^2 \left(\frac{1-\alpha-\beta}{\gamma(1-s)} \right)^{(1-\alpha-\beta)} \left(\frac{\beta}{\zeta+p} \right)^{2\beta} K^{-1+\alpha+\beta} \right)^{\frac{1}{1+\alpha-\beta}}.
\end{aligned}$$

Note that we also have

$$\frac{\partial r^*}{\partial K} = -\frac{1-\alpha-\beta}{1+\alpha-\beta} \frac{r^*(K,p,s)}{K}.$$

Take K_0 such that $\mathbb{E}_{\Xi} r^*(K_0, p^*(K_0, \xi, \bar{r}), s^*(K_0, \xi, \bar{r})) = \bar{r}$ satisfying $(\bar{r} - r^*(K_0, p^*(K_0, \xi_{\max}, \bar{r}), s^*(K_0, \xi_{\max}, \bar{r}))K = \bar{B}$; i.e. an equilibrium fossil capital stock level such that the worst possible climate outcome involves an equilibrium just at the threshold of a financial crisis, but without triggering it; this can always be achieved by taking a parameterisation with high enough δ. Then

$$\int_{\xi_{\min}}^{\tilde{\xi}(K,\bar{B})} r^*(K_0, \xi, 0) f(\xi) \mathrm{d}\xi + (1 - F(\tilde{\xi}(K_0; \bar{B})))(\bar{r} - \bar{B}/K_0) = \bar{r}, \tag{6.17}$$

where $\tilde{\xi}(K; \bar{B})$ is implicitly given by $(\bar{r} - r^*(K, \tilde{\xi}, 0))K = \bar{B}$, and we obtain

$$\frac{\partial \tilde{\xi}}{\partial \bar{B}} = \frac{1+\alpha-\beta}{2\beta} \frac{\zeta+\xi}{\bar{r}K - \bar{B}} > 0.$$

Note that $\tilde{\xi}(K_0, 0)$ is given by $r^*(K_0, \tilde{\xi}(K_0, 0), 0) = \bar{r}$, and must be positive, as $r^*(K_0, 0, 0) < \bar{r}$ would contradict with our choice of K_0. Also, $\lim_{\bar{B} \to \bar{r}K_0} \tilde{\xi}(K, \bar{B}) = \infty$.

We can consider $\mathbb{E}r^*$ as a function of K and get

$$\begin{aligned}
\left. \frac{\mathrm{d}\mathbb{E}r^*}{\mathrm{d}K} \right|_{\mathbb{E}r^* = \bar{r}} &= \int_{\xi_{\min}}^{\tilde{\xi}(K;\bar{B})} \frac{\partial r^*(K,\xi,0)}{\partial K} f(\xi) \mathrm{d}\xi + \frac{\bar{B}}{K^2}(1 - F(\tilde{\xi}(K;\bar{B}))) \\
&= K^{-1} \left(-\frac{1-\alpha-\beta}{1+\alpha-\beta} \int_{\xi_{\min}}^{\tilde{\xi}(K;\bar{B})} r^*(K,\xi,0) f(\xi) \mathrm{d}\xi + \frac{\bar{B}}{K}(1 - F(\tilde{\xi}(K;\bar{B}))) \right)
\end{aligned}$$

$$= \frac{\bar{B}}{K^2(1+\alpha-\beta)}\left(-(1-\alpha-\beta)\bar{r}K\frac{F(\tilde{\xi}(K;\bar{B}))}{\bar{B}} + 2\alpha(1-F(\tilde{\xi}(K;\bar{B})))\right), \quad (6.18)$$

where we have used equation (6.17) in the last step. The two terms in the brackets have opposite signs; if the latter term is high enough, then the slope of the expected rate of return is positive. As $\lim_{K\downarrow 0}\mathbb{E}r^*(K,\xi,0)=\infty$ and $\lim_{K\uparrow\infty}\mathbb{E}r^*(K,p,s)=0$ for any $p\geq 0$ and $s<1$, a positive slope implies there must exist at least two values of K such that $\mathbb{E}r^*(K,p^*,s^*)=\bar{r}$ and $\frac{\mathrm{d}\mathbb{E}r^*}{\mathrm{d}K}<0$.

To this end, we now adjust the parameters $(\bar{B},\xi_{\max},\delta)$ while constraining equation (6.17) to hold. This constraint implies $\lim_{\bar{B}\downarrow 0}\bar{r}F(\tilde{\xi}(K_0;\bar{B})))=\int_{\xi_{\min}}^{\tilde{\xi}(K_0;\bar{B})}r^*(K_0,\xi,0)f(\xi)\mathrm{d}\xi$; as $\lim_{B\downarrow 0}r^*(K,\tilde{\xi}(K_0,0),0)=\bar{r}<r^*(K_0,\xi,0)$ for all $\xi<\tilde{\xi}(K_0,0)$, this can only hold if $\lim_{B\downarrow 0}\xi_{\max}=\infty$. On the other hand,

$$\begin{aligned}\left.\frac{\mathrm{d}\xi_{\max}}{\mathrm{d}\bar{B}}\right|_{\mathbb{E}r^*(K_0,\xi,\bar{r})=\bar{r}} &= -\frac{-(1-F(\tilde{\xi}(K_0;\bar{B})))/K_0}{-\int_{\xi_{\min}}^{\tilde{\xi}(K;\bar{B})}r^*(K_0,\xi,0)\frac{1}{(\xi_{\max}-\xi_{\min})^2}\mathrm{d}\xi+(\bar{r}-\bar{B}/K_0)\frac{\tilde{\xi}(K;\bar{B})-\xi_{\min}}{(\xi_{\max}-\xi_{\min})^2}} \\ &= -\frac{\xi_{\max}-\xi_{\min}}{\bar{B}}(1-F(\tilde{\xi}(K_0;\bar{B}))),\end{aligned}$$

which is negative for $\xi_{\max}>\tilde{\xi}(K_0;\bar{B})$. With a slight abuse of notation, we can express the resulting locus $(\bar{B},\xi_{\max})$ as a function $\xi_{\max}=\xi_{\max}(\bar{B})$, defined for $\bar{B}\in(0,\bar{B}_0)$ where $\bar{B}_0$ satisfies $\xi_{\max}(\bar{B}_0)=\tilde{\xi}(K_0;\bar{B}_0)$, $\xi'_{\max}(\bar{B}_0)=0$.

The proof is complete if we find a pair of parameters $(\bar{B},\xi_{\max})$ such that

$$\frac{\bar{r}K_0}{1-F(\tilde{\xi}(K_0;\bar{B}))}\frac{\tilde{\xi}(K_0;\bar{B})-\xi_{\min}}{(\xi_{\max}-\xi_{\min})\bar{B}}<\frac{2\alpha}{1-\alpha-\beta}. \quad (6.19)$$

Here, as $\bar{B}$ vanishes, the term $F(\tilde{\xi}(K_0;\bar{B})$ also does. The key quantity of interest is $\bar{B}(\xi_{\max}-\xi_{\min})$. We rewrite equation (6.17) as

$$\int_{\xi_{\min}}^{\tilde{\xi}(K_0;\bar{B})}(r^*(K_0,\xi,0)-\bar{r})f(\xi)\mathrm{d}\xi=(1-F(\tilde{\xi}(K_0;\bar{B})))\bar{B}/K_0,$$

to get

$$\bar{B}(\xi_{\max}-\xi_{\min})=\frac{K_0\int_{\xi_{\min}}^{\tilde{\xi}(K_0;\bar{B})}(r^*(K_0,\xi,0)-\bar{r})\mathrm{d}\xi}{1-F(\tilde{\xi}(K_0;\bar{B}))},$$

and thus that the inequality (6.19) is equivalent to

$$\frac{1}{\tilde{\xi}(K_0;\bar{B})-\xi_{\min}}\int_{\xi_{\min}}^{\tilde{\xi}(K_0;\bar{B})}(r^*(K_0,\xi,0)/\bar{r}-1)\mathrm{d}\xi>\frac{1-\alpha-\beta}{2\alpha}.$$

The left-hand side is the average relative excess rate of return in the Pigovian regime. Note that the right-hand side is positive.

Using the following parameter values from Fullerton & Ta (2019) (c.f. their Table 1) we can show that this inequality holds.

We use $K_0 = 225$, $A = 2.9$, $\alpha = 0.42$, $\beta = 0.45$, $\zeta = 1$ rounded from their calibration exercise and get γ by $\gamma = w(L)/L = 1.6/47.2 = 0.034$ (note that 1.6 is the gross wage including a labor tax in their parameterisation). Additionally we assume that $\bar{r} = 0.2$, $\xi_{min} = 0$ and $\bar{B} = 0$.

Table 6.1: Parameter values for example

K_0	A	α	β	γ	ζ	$\bar{B}$
225	2.9	0.42	0.45	0.034	1	0

Using these parameter values we get $\tilde{\xi}(K_0, \bar{B}) = 4.92132$ for which the above inequality holds.

Numerically, we can also evaluate equation (6.18) for higher values of $\bar{B}$. Assuming $\bar{B} = 0.1K_0 = 22.5$ we get $\tilde{\xi} = 11.50$ and $\xi_{max} = 17.36$ which gives a positive slope.

7

Conclusion

This thesis sheds light on some of the many pressing research questions concerning the interaction of climate policies and asset stranding. It applies theoretical and quantitative methodologies to analyze asset stranding challenges in fossil fuel-dependent sectors with high relevance for climate policymaking. The review of the climate economics literature on asset stranding in Chapter 2 shows that more research on this topic is required to provide realistic policy advice and support policymakers in implementing effective policies. While a relatively large share of articles studies distributional effects of climate policies between countries, other distributional dimensions, e.g. intra- oder intergenerational, lack research despite their political relevance. Similarly, labor market effects, compensation schemes, political economy questions, and expectations-driven multiple equilibria remain under-researched. Researchers risk their policy advice not being heard if they ignore these topics.

In Chapter 3 we demonstrate the importance of accurately estimating stranded assets taking profits at stake in the fossil fuel extraction industry as an example. Such estimates are key to assess, among others, compensation claims and are thus highly relevant for political acceptance. Yet, extant estimates fail to represent the full range of possible numbers. We show that some estimates in the literature do not reflect cost and price changes resulting from climate policies and thus lead to particularly large numbers. Further, we highlight the political relevance of considering the whole spectrum of climate policies in assessing estimates of stranded assets: Including supply-side policies instead of only assessing climate policies targeting the demand of fossil fuels could lead to much smaller estimates of profits at stake.

In Chapter 4 we show that deposit markets are a promising example of such a supply-side policy. Our partial equilibrium model features market power exertion on the deposit markets, where multiple in-situ fuels are traded, which differ in extraction costs and emission intensity. We show that, on the one hand, deposit markets may be politically obsolete due to carbon leakage effects. On the other hand, under certain conditions the implementation of deposit markets is supported by all countries. In this case, deposit markets bring about advantages over other supply-side policies: For instance, they induce countries without climate ambitions to supply a cleaner fuel mix and they improve the welfare in all countries. When implementing deposit markets for multiple fuels, however, policymakers should consider the political economy of this policy option: Our results also show that consumer and producer rents differ for deposit markets covering one or multiple fuels with relevant implication for policy acceptance by these stakeholders. The results of this study more generally demonstrate the relevance of jointly analyzing the implementation of climate policies covering multiple fossil fuels as this can give rise to unexpected inter-fuel effects, which can determine support for and resistance to such policies.

We dig into the distributional effects of climate policies in the power sector in Chapter 5. The results of our empirical exercise illustrate the importance of assessing the incidence of asset stranding below the country level: For instance, in the US, stranded assets are relatively equally distributed between asset owners, which is in stark contrast to India, where a single owner is highly exposed to asset stranding. The formation of climate policy resistance could differ considerably between these two countries and should be accounted for in policy advice and implementation. Our results also demonstrate that exposure to stranded assets is not limited to the domestic level. Instead international investors – especially European, US and Chinese – may suffer considerably from asset stranding in foreign countries, which could be decisive for their opposition to the implementation of climate policies across national borders. Some stranded assets owners may show less resistance to policies as they also own alternative energy assets, which could even benefit from climate policies. However, policymakers cannot rely on this: While there is a positive correlation between ownership of stranded and alternative energy assets, some asset owners, e.g. India, own relatively little alternative energy assets compared to their asset stranding exposure.

In Chapter 6, we demonstrate that asset stranding due to climate policies may demand financial regulation to maintain financial stability. Our partial equilibrium model features investors who have expectations about climate policies under stochastic climate change. The policymaker is aware of these expectations and fears triggering a financial systemic crisis due to transition risks. We show that this set-up with an endogenous climate policy yields multiple equilibria: One with high fossil investments and insufficiently stringent climate policy and the other with low fossil investments and a Pigovian carbon price. The systemic crisis is central to our model and thus, we pull the financial regulator into the field of climate policymaking: If the policymaker is unable to credibly commit to the Pigovian carbon tax, the stability of the financial system is at risk. This is clearly the mandate of a financial regulator. Our recommended policy options, i.e. an increase in the equity buffer or the relative costs of investing in fossil technologies, can achieve the socially more desirable equilibrium in this setting. These policies could be implemented by a financial regulator, again demonstrating how transition risks tie together climate policymaking and financial regulation.

There are several limitations to the approaches used and the results generated in this thesis. Chapters 4 and 6 both employ partial equilibrium models, i.e. abstract representations of real-world situations. These rely on a number of simplifying assumptions and we use parametric versions of some of the general functions in the models. Such assumptions are necessary to break down the complexity of the settings analyzed and to facilitate arriving at answers to the targeted research questions. Application of the results in real-world situations should therefore be done carefully, ideally in combination with complementary studies, e.g. simulations of the models using suitable data. Further, in Chapter 5 our stranded assets estimates depend on the IEA's scenario assumptions, which determine power plant capacities compatible with the Paris goal. While these scenarios are widely accepted, our stranded assets estimates should not be discussed without acknowledging the underlying scenario assumptions. Altering these assumptions could either increase or decrease our estimates with high relevance for policymarking as discussed in Chapter 3.

This thesis advances our understanding of the interaction between climate policies and asset stranding. However, many research questions remain open and must be targeted in order to ease the implementation of effective climate policies. As outlined in Chapter 2, future research should focus on modeling endogeous climate policies instead of treating them as exogenously given. This way models can reflect the fact that investment decisions on fossil capital stocks depend on expectations about climate policies and in turn, policies depend on capital stocks. Further, economists should collaborate with political scientists to analyze distributional effects of climate policies and compensation schemes. More research should target issues of income and wealth inequality related to asset stranding as well as intergenerational and sector-specific challenges.

Future work should further focus on studying supply-side policies as they may encourage greater social support (Erickson et al., 2018, Piggot, 2018). For instance, building on Chapter 3 an estimate of fossil fuel producers' profits at stake due to supply-side policies could be decisive in assessing the political feasibility of such policy alternatives. In the same vein, a simulation of deposit markets analyzed using real-world data would be a valuable complement to the theoretical models presented in Chapter 4 and in related studies. Insights on distributional effects and deposit markets' effectiveness would be highly relevant for policy advice. Future studies on deposit markets should further carefully analyze features relevant for political feasibility we have so far ignored to keep complexity at bay. These include studying the stability of the climate coalition, commitment problems, and time-consistency issues.

Moreover, many avenues for future research arise from the results in Chapter 5 with high relevance for policymaking: The exercise targets the identification of adversely affected asset owners as well as patterns of asset stranding in the power sector. As power plants are geo-referenced in the data set employed, our estimates of stranded assets could be used to analyze the effects of power sector asset stranding on lobbying activities or labor markets. Further, the methodology and the data sets used to estimate stranded assets could facilitate assessing asset stranding in other energy-intense sectors, such as the transport or industry sector.

Finally, our systemic risk model in Chapter 6 shows that multiple expectations-driven equilibria can exist in theory. Future work should evaluate the importance of this result quantitatively, for instance in a multi-period model. Such a quantitative exercise would also facilitate ranking our suggested policy options, i.e. higher capital requirements or an increase in fossil investment costs, in terms of welfare.

Asset stranding adversely affects a plethora of stakeholders directly or indirectly related to fossil fuels. These stakeholders have played a key role in opposing climate policies and they will resist the implementation of effective GHG emission reduction measures in the future. To reach the goal of the Paris Agreement in a sustainable way regardless of this interaction between climate policies and asset stranding, joint efforts are necessary: Economist, political scientists, and policymakers must collaborate on improving the designs of climate policies taking into account the perspectives of affected stakeholders across various dimensions, including space, time, and income/wealth. This complex task must be tackled in a very timely manner as the climate crisis is already advancing in its adverse and irreversible effects. I hope that this thesis supports researchers and policymakers in implementing effective climate policies to mitigate the climate catastrophe.

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