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Fabian Dominik Naumann M.Sc.

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# Abstract

Climate change and its effects are accelerating, with climate-related disasters surging. To tackle climate change, the reduction of emissions by means of climate policy is vital. As such, the purpose of the present dissertation is to provide deeper insights about *market-based* and *non-market-based* environmental state interventions. Using regression analyses, the empirical part of this doctoral thesis investigates the adverse effect of financial subsidy payments on the energy market. Findings indicate that subsidized renewables may depress the profitability of energy storages and lower their own market values. Research projects demonstrate that carbon pricing is a promising solution to counteract the adverse effect. The theoretical part of this doctoral thesis examines the implementation of a unilateral price floor in emissions trading schemes and emissions cap negotiations. Results suggest that, under certain conditions, i) a unilateral price floor can be welfare-enhancing and ii) negotiations can achieve the socially optimal emissions cap. The dissertation helps provide a better understanding of climate policy design and emphasizes the advantage of carbon pricing as a *market-based* approach.

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# Introduction

Climate change is progressing rapidly and severe consequences have become already evident and will continue to pose enormous challenges to humanity for generations to come. Its main driver is the greenhouse effect. It is beyond doubt that the anthropogenic release of greenhouse gases (GHGs) is the main cause of global warming. Thus, research in all sub-disciplines to counteract this alarming trend is more necessary than ever.

$CO_2$, $CH_4$, and $N_2O$ concentrations in the Earth's atmosphere are at an all-time high, due to human activity. As a result, the global surface temperature increases, which, in turn, has a tremendous effect on the natural system (IPCC, 2021). Short-term measures to reduce emissions are particularly important to reduce projected mid to long-term consequences and to avoid passing irreversible tipping points. In this regard, the global warming level of 1.5 °C relative to pre-industrial times represents an important threshold, as exceeding it can lead to irreversible effects. The increasing complexity of climatic risks, caused by compound and cascade effects, influences risk management and forecasting (IPCC, 2022). Demands to reduce the emissions of GHGs and prevent the most catastrophic climate predictions have been increasing around the world in recent years. In 2015, the Paris Agreement, an international treaty between 195 parties, was concluded. The international agreement aims to limit warming to 2 or at best 1.5 °C, using the pre-industrial level as a baseline. Low- or zero-carbon solutions in emissions-intensive sectors, as well as countries' carbon neutrality targets, play an important role in achieving the set targets (UNFCCC, 2015).

In situations in which a market does not provide an efficient resource allocation on its own, economists speak of market failure. Market failure can be caused by market power, imperfect information, public goods, or externalities, and justifies, from an economic perspective, government intervention. If there is a negative externality, it leads to an overprovision of the good by the damaging party in the absence of regulation or compensation payments (Coase, 1960). As a result, the allocation is not Pareto efficient[1] and the market becomes inefficient. This is precisely the case with emissions of $CO_2$ and other GHGs that drive climate change. Since the impact of changes in climate could be catastrophic and even endanger global welfare, GHG emissions represent the ultimate negative externality and require regulatory intervention to ensure efficiency.

It was Pigou in the 1920s, who first proposed to impose a corrective tax on the externality in his prominent work "*The Economics of Welfare*" (Pigou, 1920). This would lead the damaging party to inter-

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[1] In economic theory, it defines an economic state in which no reallocation of resources exists that makes one party better off without making another party worse off.

nalize the externality, resulting in lower provisioning and thus lower damages. If the tax level correctly reflects the negative external effect, Pigou's approach leads to the social optimum and Pareto efficiency. This approach can be used to reduce the release of harmful emissions, such as $CO_2$ and other GHGs. Emissions trading schemes (ETS), as a quantity-based instrument, and emissions taxes, as a price-based instrument, both represent *market-based* approaches through a price signal. The idea behind a *market-based* approach is that it sends an incentive for all agents (producers and consumers). For the case of emissions, an emissions tax or an allowance price in an ETS represents a market signal which encourages a change in the behavior of polluters. If the price signal is set at the right level (i.e. at the level of the marginal external damage), this would lead to cost efficiency. Based on the insights by Coase (1960) and Dales (1968), tradable permits could serve as property rights. An ETS limits emissions to a set emissions cap and allows for permit trading between parties under regulation thereby achieving, under certain circumstances, a cost-efficient emissions reduction (Montgomery, 1972). That is, it drives emissions abatement to where it is cheapest. However, if the emissions market is not fully competitive or permit trading entails transaction costs, the functioning of the system would be impaired (e.g., Hahn, 1984; Stavins, 1995).

So would the introduction of an ETS or a CO2 tax, in a competitive emission market without transaction costs, fully correct the market failure of externalities, resulting in the social optimal emissions level? Without uncertainties and if optimally chosen, both measures internalize the externality and lead to a situation in which emissions levels and prices are identical. As benefits and costs of abatement induced by regulation are subject to uncertainties, outcomes change. The reason is that a quantity-based (price-based) instrument limits the quantity (sets a price signal), but the resulting emissions price (quantity) is *ex-ante* uncertain. In addition, the implementation of strict environmental regulations faces numerous obstacles, both at the national and international levels. The analysis of climate policies and their impacts, therefore, represents an important field of research. It can help better understand the mechanisms and provide useful policy recommendations to tackle climate change. This doctoral thesis aims to make an empirical and theoretical contribution to this debate.

The empirical part of this dissertation tries to disentangle an adverse effect of a *non-market-based* climate policy in the form of financial subsidy payments for renewable energies. Many countries around the world strive to decarbonize their energy sector to meet environmental targets. With the aim of a fast market penetration and fostering the competitiveness with conventional technologies, governments provide various monetary incentives for renewables, such as support payments via feed-in tariffs, premia, or tax credits. This is intended to reduce the levilized costs of energy (LCOE) by promoting learning by doing (Lòpez Prol et al., 2021; Reichenbach and Requate, 2012), improvements in the production processes (Jankowska et al., 2021), and R&D and technological progress (Fischer and Newell, 2008; Newell et al., 1999). However, support schemes should be maintained only until market maturity and competitiveness are achieved (Melliger and Chappin, 2022; Reichenbach and Requate, 2012). Since these technology-specific state interventions represent *non-market-based* approaches, it may lead to efficiency losses, according to the "general theory of second best" (Lipsey and Lancaster, 1956).

Feed-in tariffs for renewable energies are a form of exogenous state intervention to deploy renewable electricity generation capacity. The subsequent surge in renewable electricity infeed at zero marginal costs reduces the wholesale price of electricity (Bushnell and Novan, 2021; Würzburg et al., 2013). In the literature, this effect is referred to as the "merit order effect". However, the magnitude of the price reduction depends on how much renewable energy is fed into the market (treatment intensity), the steepness of the supply curve, and the level of electricity demand (load). The electricity price reduction, as driven by an exogenous intervention (subsidies for renewables), may place an unintended, adverse effect on other complementary electricity supply technologies, such as energy storage. The analysis of adverse effects of subsidized renewables on storage technologies constitutes a research gap. For the successful integration of fluctuating renewables into an energy system, generation technologies providing flexibility are a key factor. However, previous research on the profitability of energy storages lacks in providing causal empirical analyses (e.g., Hildmann et al., 2011) and does not include a high share of renewables (e.g., Gaudard, 2015; Kougias and Szabó, 2017; Wilson et al., 2018) or carbon pricing.

The first article, entitled **“Subsidizing Renewable Energies or Pricing Carbon? Causal Effects on Energy Storages"** (with Mario Liebensteiner and Adhurim Haxhimusa, revision and resubmission requested by Renewable and Sustainable Energy Reviews, impact factor: 16.799), investigates if there is empirical evidence that infeed from renewables undermines the profitability of energy storages and thus hinders a successful energy transition. For the case of the German-Austrian electricity market, the paper substantiates that subsidies for renewables in Germany – a *non-market-based* regulation – substantially lower profits of Austrian pumped storage power plants. While Germany’s energy generation shows a sizeable share of renewables, due to heavy support payments, Austria possesses a large portion of Europe’s storage capacity. Using an econometric two-stage least squares model, we find that subsidized renewables distort prices on the wholesale electricity spot market and subsequently reduce the profitability of pumped storage power plants. That is, the price difference between storing (costs) and generation (revenues) diminishes and thus affects the business model of storage technologies (price arbitrage). Our main regression results show that a 10% increase of renwables decreases the spot price by about 5%, which in turn lowers profits of pumped storage facilities by nearly 15% (evaluated at the means). As energy storages represent a key technology to balance renewables’ intermittent nature of production and are thus much needed for a successful decarbonization of the energy system, this makes it especially worrisome. Furthermore, we estimate the effect of a potential marked-based remedy for this paradox - a meaningful carbon price. We find that an increase in the carbon price by 10% boosts profits of energy storages by almost 8% (evaluated at the means). In consequence, the *marked-based* environmental policy of carbon pricing represents a practical measure to counteract the adverse effect of subsidizing renewables and to strengthen investment incentives for energy storage technologies. The study demonstrates the advantage of a *market-based* climate policy to prevent unintended and undesirable market distortions.

In addition, renewables may not only depress the profits of energy storages but also depress their own market values – the so-called "cannibalization effect". This, in turn, can hurt the competitiveness of renewables (c.f. Lòpez Prol et al., 2021; Zipp, 2017). Researchers have already pointed out the need to investigate possible countermeasures against the cannibalization effect (Lòpez Prol et al., 2021) and renewables' pathways after support schemes end (Melliger and Chappin, 2022). This problem is under-researched, but of great policy importance for countries with ambitious climate goals. Most studies have been conducted in energy markets characterized by a low share of renewables and therefore cannot address the issue in depth (e.g. Lòpez Prol et al., 2021, for California for the period 01/2013–06/2017; Clo et al., 2015, for Italy for the period 01/2008–10/2013; Zipp, 2017, for Germany/Austria for the period 01/2011–12/2013).

The second paper **"Can Carbon Pricing Counteract Renewable Energies' Self-Cannibalization Problem?"** (with Mario Liebensteiner, under review by Energy Economics, impact factor: 9.252) contributes to this debate. Characterized by a high share of renewables, Germany's energy market represents the perfect candidate to investigate the self-cannibalization effect of renewables. Moreover, we are the first to cover unprecedented high EU ETS allowance prices of over 60 €/t$CO_2$ in 2021 in our analysis (mean of 6.29 €/t$CO_2$ during 01jan2015–30jun2017). Using a simple linear model, we find that a 10% increase in renewable generation by wind or solar has a negative effect on the market value of wind of 3.7% or 0.98%, respectively (evaluated at the means). For the market value of solar, our estimations indicate a reduction of 4% (2.7%) for a 10% increase in wind (solar) infeed (evaluated at the means). However, our results show that carbon pricing can counteract this downtrend – a 1 € increase in the EU ETS allowance price boosts the market value of wind by 0.90 €/MWh and solar by 0.83 €/MWh (evaluated at the means). In addition, we estimate more flexible models, including squared and interaction terms. Although the results of this approach are not readily interpretable, they can be used for predictive purposes. Our estimates imply that, in order to offset the self-cannibalization effect of renewables, a carbon price of at least 40 €/t$CO_2$ is required. While the self-cannibalization effect hinders the self-sustaining survivability of renewables, we empirically present that a meaningful carbon price provides a promising remedy. This again demonstrates the advantage of *market-based* policies over other policies. Yet, once the power sector is fully decarbonized, this solution reaches its limit because a carbon price would not elevate the wholesale price of electricity anymore and a redesign of the energy market may be necessary (e.g. a switch to a capacity market). Our results are also relevant for other countries, which may want to successfully meet their climate targets and integrate a high share of renewables.

The theoretical part of this dissertation focuses on implementing an additional unilateral price floor and cap negotiations in emissions trading schemes. In his seminal study “*Prices vs. Quantities*" Weitzman (1974) demonstrates how uncertainty affects the two regulatory approaches. In the case of a more linear benefit function, a price instrument is the better choice; otherwise, the quantity instrument is preferable (Weitzman, 1974). Under uncertainty, hybrid systems which combine price and quantity instruments could pave the way to restoring efficiency. The approach of creating a price floor and ceiling (in form of a subsidy or penalty) in a pollution licenses market goes back to Roberts and Spence (1976). There are several ways to implement such a hybrid scheme, which have already been investigated (e.g. a fixed price to purchase allowances, Pizer, 2002; an allowance reserve, Fell et al., 2012; or an additional tax on top of the allowance market price, Heindl et al., 2014). While a top-up tax leads to an additional burden, even in times of high permit prices, a price floor via a variable carbon tax only intervenes when the market price is lower than expected. This is a crucial difference that makes the analysis of this type of hybrid system design relevant.

The third article, entitled **"Unilateral Carbon Price Floor by a Country Engaged in Emissions Trading"**, analyzes a unilateral environmental regulation, in the form of a price floor for permits, complementary to an existing bilateral emissions trading scheme. In a symmetric two-country setting with abatement cost uncertainty, conditions under which the additional introduction of a unilateral carbon price floor is beneficial for a country are determined. If abatement costs are lower than expected (negative abatement cost shock), the resulting emissions permit price is low, and not all cheap abatement opportunities are used. In this case, the additional price regulation leads to the exploitation of otherwise unused cheap abatement opportunities. If political negotiations on a common price floor fail, a unilateral price floor can, under certain conditions, also be welfare-enhancing for the country that introduces it. That is, it can lead to a situation in which abatement activities in the country under additional unilateral regulation exceed the implemented abatement target of the joint emissions trading scheme. Consequently, additional benefits are generated that can increase the country’s welfare. A relatively loose emissions cap and/or a large abatement cost shock both favor the introduction of a unilateral price floor. Therefore, results are especially relevant if there is great uncertainty about actual abatement costs or no strict emissions cap, such as at the beginning of an emissions trading scheme or in case of an allowance surplus. The article helps understand why unilateral climate policies are introduced in addition to existing regulations.

The introduction of an appropriately stringent emissions cap is crucial to ensure that the resulting emissions price correctly reflects the externality and that emissions abatement is sufficient. Here, the negotiation of an international arrangement between the countries involved plays an important role. Since not all countries have the same intentions or incentives, this complicates the prospects for success in reaching an agreement on an optimal emissions cap. It has been shown that a lower overall pollution level is not guaranteed if countries can choose their emission levels endogenously (Helm, 2003). Since environmental protection efforts differ between countries, due to heterogeneous, national characteristics, emission reduction intentions may neutralize each other. It becomes apparent, that international agreements are needed to achieve a net reduction in emissions. If a country's share of a fixed emissions cap is the object of negotiations, the collapse of negotiations is very likely, in the event that too many parties are confronted with under-proportional shares (Smead et al., 2014). The provision of a public good has already been analyzed via two cooperation mechanisms, namely the Exchange Matching Lindahl solution and the Nash Bargaining solution (Dijkstra and Nentjes, 2020). If countries have already agreed to jointly implement an emissions trading system, what level of emissions will be set in a subsequent negotiation? The question of whether the socially optimal amount of allowances will be implemented constitutes a relevant research task.

Finally, the fourth paper **"Emissions Trading Schemes: Negotiations on the Emissions Cap"** (with Tom Rauber) focuses on the bargaining process between two asymmetric countries to determine the total number of allowances issued. We assume that a country's share of the resulting emissions cap is exogenous and not part of the negotiation. Using an alternating-offers model, we analyze under which conditions the social emissions optimum is implemented and the criteria for deviations. For an allocation of allowances based on the proportion of historical emissions, the negotiation never leads to the socially optimal emissions cap. Nonetheless, we find that for allocations that differ from this, the social optimum can indeed be achieved. That is, the allocation of allowances between countries can serve as a kind of side payment. However, if countries are too diverse, there exists no allocation of allowances that guarantees the social optimum. We show that even then the bargaining solution can lead to an emissions cap that is closer to the social optimum than national emission caps. This could explain why the introduction of a strict emissions cap might fail.

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# Subsidized Renewables' Adverse Effect on Energy Storages and Carbon Pricing as a Potential Remedy

*(Revision and resubmission requested by Renewable and Sustainable Energy Reviews, impact factor: 16.799)*

Mario Liebensteiner* Adhurim Haxhimusa† Fabian Naumann‡

**Abstract:** Large-scale energy storage is viewed as a key complementary technology in a power system fed by a large share of intermittent renewable energies (RE). However, subsidies for RE – a well-intended market intervention – may distort price signals, thereby adversely undermining the profitability of energy storages and thus adequate investment incentives. We provide novel causal estimates supporting this notion, using a two-stage IV framework and data on Austrian pumped storages, operating in the German-Austrian electricity market, characterized by a vast share of generously subsidized RE. We find that RE significantly depress storage profitability and that further deployment of RE will intensify this effect. This may pose an obstacle against adequate investment in bulk energy storage capacity. Moreover, we estimate that intensifying carbon pricing would significantly counteract the problem via a market-based price signal. Our paper contributes to the general debate on the design and effects of environmental regulation and particularly shows that a non-market-based policy for a green technology may adversely affect complementary technologies.

**Keywords:** Carbon pricing; Decarbonization; Energy transformation; Energy storages; Renewable energies

**JEL Classification:** H23, H54, L51, L94, Q48, Q58.

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*Friedrich-Alexander-Universität (FAU) Erlangen-Nürnberg, Energy Markets and Energy Systems Analysis, Germany, mario.liebensteiner@fau.de

†University of Applied Sciences of the Grisons, Centre for Economic Policy Research, Switzerland, adhurim.haxhimusa@fhgr.ch

‡Technische Universität Kaiserslautern, Chair of Environmental Economics, Germany, fabian.naumann@wiwi.uni-kl.de

# 1 Introduction

Many countries around the globe have implemented ambitious support schemes for renewable energies (RE) to tackle anthropogenic greenhouse-gas emissions. The Intergovernmental Panel on Climate Change estimates that it requires a global share of RE of well beyond 70% to reduce global warming to 1.5°C (IPCC, 2018). However, the most important RE technologies, wind and solar, pose severe challenges to the energy system, because of their weather-dependent, volatile electricity production, which is decoupled from demand. As a result, network operators are often obliged to undertake undesirable steps, such as partial curtailments of renewable electricity infeed and redispatch measures to keep grid stability, eventually reducing the effectiveness of climate policies. In expectation of an energy system fed by a large share of RE, there is widespread consensus that *energy storage* will be essential to balance RE's weather-dependent production volatility (Dunn et al., 2011; Zerrahn et al., 2018), thus sustaining electricity supply security, supporting the system integration of renewables (Braff et al., 2016; Carson and Novan, 2013), as well as ensuring a smooth and effective decarbonization transition (López Prol and Schill, 2021; Sinn, 2017).

Hydroelectric pumped storages are currently the only economically viable utility-scale electricity storage technology, representing almost the entire global storage capacity (about 96% in 2018; Rathi, 2018). The basic business model of pumped storage relies on differences in the electricity price over time. Atlow prices (e.g., at night), water is pumped uphill and then used to produce and sell electricity at peak prices. However, if subsidized RE decreased the electricity price and/or curbed price peaks (e.g. solar power may reduce the price peak around noon; Tveten et al., 2013), the profitability of pumped storages could be affected – with potentially long-lasting investment effects (Kougias and Szabó, 2017). Our idea is that subsidies for RE (guaranteed feed-in tariffs, as in our case) represent a form of state intervention into the electricity market, which boosts RE deployment independently of free-floating market signals arising from the interplay between demand and supply. We will discuss this argument in more detail along this paper.

At the outset, it is not clear if the run-up of RE, as generally financed via financial support schemes, stimulates or deters the business of pumped storage. On the one hand, subsidized RE may increase the profitability of pumped storage, for example, if their intermittent electricity production increases the volatility of electricity prices, thereby enhancing the opportunity to arbitrage prices. On the other side, a potentially negative effect of the support policy for renewables on the profitability of energy storages would be especially worrisome, because storages represent the ideal complementary technology to balance the intermittent nature of RE (Carson and Novan, 2013; Dunn et al., 2011; Liski and Vehviläinen, 2020).

The neoclassical economic theory argues that exogenous market interventions, such as subsidizing RE, would deter otherwise undistorted price signals, needed for optimal investment (in our case, in energy storage capacity). Since Pigou's seminal work in 1920 (Pigou, 1920), neoclassical economics views carbon pricing as an efficient (and thus first-best) solution to greenhouse-gas emissions, with some recent empirical studies (Bayer and Aklin, 2020; Gugler et al., 2021) supporting this notion. The mainstream economics literature argues that carbon pricing sets *market-based incentives* for all economic agents (producers and consumers) to change their behavior according to their individual abatement costs. A carbon price would thus internalize the emissions externality efficiently, thereby avoiding any adverse effects on other technologies (e.g. energy storage).

Despite these efficacy arguments, policy makers in many jurisdictions around the world are rather reluctant against carbon pricing, which is often explained by a lack of public support for environmental taxes, among many other issues (Huang and Xiao, 2021). In contrast, other policies than pricing the externality (e.g. via a carbon tax or tradable emissions certificates) would result in an inefficient market outcome, going back to the "general theory of second best" by Lipsey and Lancaster (1956) (see also Helm and Mier, 2021; Linn and Shih, 2019). Thus, financial support schemes for RE can be viewed as less efficient (Borenstein, 2012), potentially also creating *undesirable market distortions*. One example may be "winner picking" (Kverndokk and Rosendahl, 2007) of subsidies for particular technologies based on imperfectly informed policy-makers. Another example of an adverse effect may be that financial support for RE may adversely drive less pollutant gas-fired power plants out of the market, whereas highly pollutant lignite plants remain (Gugler et al., 2020; Liebensteiner and Wrienz, 2020). In this study, we uncover yet another adverse effect: subsidy payments for RE may undermine the profitability of energy storage through distorted wholesale electricity prices. Despite the arguments of the economics literature in favor of carbon pricing compared to other policy measures, there is still a debate that carbon pricing may not suffice, but that a mix of climate policies would be necessary (Hepburn et al., 2020; Rosenbloom et al., 2020), with some scholars even arguing against carbon pricing (Patt and Lilliestam, 2018). This raises the need for further empirical research on the effects of RE subsidies and carbon pricing to guide the political progress towards successful climate-change policies. We contribute to this debate by showing that financial support for RE may eventually hinder a successful rollout of energy storage capacity, under the circumstance that RE "shaved" peak prices relative to off-peak prices.

While there is already a large body of empirical literature on the dampening effect of RE on the electricity wholesale price (e.g. Bushnell and Novan, 2021; Würzburg et al., 2013) – the so called "merit-order effect" – the adverse effects of subsidized renewables on other complementary technologies are largely under-researched. In contrast to our setting, which finds that RE shave peak electricity prices more than off-peak prices, Bushnell and Novan (2021) (for California) and Jha and Leslie (2021) (for Australia) find that RE depress off-peak prices relative to peak prices, leading to a somewhat different conclusion. This even further raises the need for an analysis of how large-scale energy storages react to RE and in which manner. The economic rational for the need for storages is their potential to provide flexibility in a future electricity system fed predominately by a large share of volatile RE, even more so as the economic costs of a blackout would be enormous.In this sense, investment in bulk energy storage capacity would enhance welfare.

The literature on the nexus between subsidized RE and energy storages is scarce, lacks rigorous causal empirical analysis, and has not yet investigated the effects of carbon pricing on energy-storage profitability. Hildmann et al. (2011) merely discuss (but do not estimate or model) the idea based on descriptive statistics that a vast share of intermittent RE may undermine the business model of pumped storage. Gaudard (2015) simulates the economic performance of a Swiss pumped-storage unit, using assumptions about plant size, efficiency, and other technical aspects, finding that the unit is not economically viable under current market circumstances. RE are, however, not part of the modelling. Wilson et al. (2018) use simple descriptive statistics of wholesale electricity price data from Germany and Britain to conclude that lower prices and lower price volatility depress the operating revenues of a simulated pumped-storage plant. In contrast, the influence of RE is not modelled. Kougias and Szabó (2017) provide descriptive evidence of uneven (increasing and decreasing) utilization rates of pumped storage units over time in select European countries, although RE do not enter the modelling. None of these studies establishes causality between RE and storage profits, for example, based on econometric modelling, or disentangles the effect of interest from potentially confounding factors. Liu and Woo (2017) apply an econometric model and control for potentially confounding factors, yet find no evidence of a profit-decreasing effect of RE on pumped storages in California. One potential explanation could be the rather low share of RE during their sample period (12/2012–04/2015) and that operational profits of pumped storages were merely approximated by differences in the wholesale prices during typical pumping and generation hours. In contrast, we investigate a market with a significant share of RE and also employ data on storages' actual pumping and electricity production.

The aforementioned publications provide a valuable background for our analysis, by either relying merely on descriptive evidence and economic reasoning or a more sophisticated methodology (Liu and Woo, 2017), but cannot establish credible evidence for a negative effect of RE on storage profits. To the best of our knowledge, we are the first to identify a significantly negative causal effect of subsidized RE on pumped-storage profits via a distortion of the electricity wholesale price, relying on sophisticated econometric modelling. Moreover, our study is novel in showing that carbon pricing supports the business model of pumped storage and can thus alleviate the problem.

We demonstrate, for the case of Austrian pumped-storage plants, operating in the joint German-

Austrian (DE/AT) electricity market, that subsidized RE indeed significantly undermine their profitability via electricity price distortions. With a further deployment of RE, this effect will intensify and may thwart the system integration of large-scale storage facilities. While Austria, with its large pumped-storage capacities, is known as the "battery of Europe", Germany is the country with the highest per-capita support payments for RE and with the largest installed RE capacity (predominantly wind and solar power) in the European Union (CEER, 2021). This setup makes it a relevant case for investigation, where energy storages are constantly interacting with substantial, volatile electricity infeed from RE. We also estimate that carbon pricing countervails this adverse effect by lifting the wholesale electricity price, thereby supporting the business model of pumped storage – a finding that has not yet been shown in the existing literature.

We derive our results from an econometric two-stage least squares model, which estimates the *causal chain effect* of subsidized RE via the wholesale spot price (the market distortion) on the profitability of pumped storage. To do so, we use high-frequency data on pumping and generation of pumped storage, day-ahead forecasts of wind and solar infeed, and wholesale electricity spot prices, spanning the *hourly* period 2015/01/01–2018/06/30. We exploit the exogenous variation in electricity from wind and solar, subject to prioritized and guaranteed infeed at a-priori set feed-in tariffs, to disentangle the causal partial effect of RE on pumped storage profits via the wholesale price. Our baseline regressions have no dynamic considerations of storage owners regarding optimal discharge – an assumption that we relax in in the robustness section 6.3). Moreover, we run a battery of other robustness tests to rule out concerns about potential threats to identification (e.g., including lags of RE infeed to test for dynamic processes; changing the data aggregation level to the daily frequency to check if storage owners optimize across days, not within days; testing for a potential non-linear effect to relax the constant linear effects assumption; testing the exogeneity assumption of RE infeed using wind speed and solar radiation as instruments; estimating the effects of wind and solar infeed separately; or testing if other channels than the electricity price or its spread cause the effect of RE on storage profits via a reduced-form model).

We can derive rich policy implications based on our results. Pumped storage operators often demand for state aid as a potential relief to losing profitability. Yet, in this study, we discuss and empirically estimate that intensifying carbon pricing can solve the current situation based on market incentives. An emissions price lifts the wholesale price of electricity and thus maintains the profitability of energy storage. Since there is still a debate among scholars about which climate policy measures would be necessary to decarbonize the economy (e.g., carbon pricing or direct financial aid for RE), our study provides another argument in favor of carbon pricing. The reason is that carbon pricing would not only abate emissions effectively through a market-based measure (as is argued in the theoretical, and partly in the empirical literature cited above), but also maintain investment incentives for energy storages (and thus potentially also for other complementary storage facilities). More generally speaking, our analysis provides empirical support for the theory that carbon pricing, as a market-based climate-policy measure, does not distort markets' price signals as investment incentives for any complementary technologies. In contrast, non-market-based measures, such as subsidies, may lead to adverse effects.

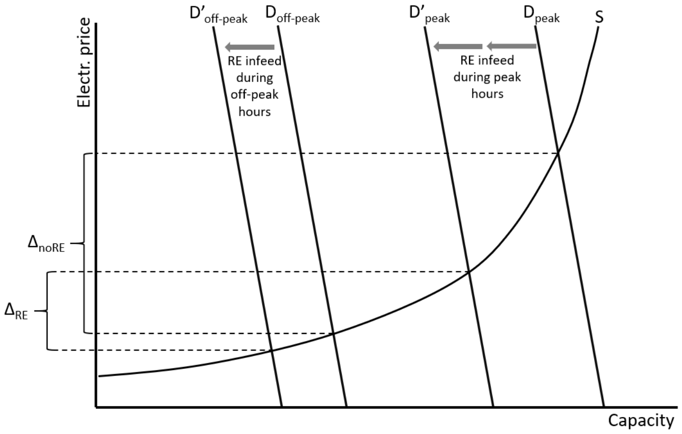
Our findings are also relevant for other countries, as we show that large-scale investments in energy-storage capacity may not be incentivized as long as support schemes for RE distort the workings of their electricity markets. Moreover, the profit-distorting effect that we measure may also apply to other storage technologies, relying on price arbitrage, and which may gain importance in the future. When subsidized RE distort the electricity price spread, batteries, hydrogen fuel cells, flywheels, capacitors, and superconducting magnetic energy storages, all of which mainly operate within a short time (intraday) due to a pronounced daily self-discharge (see, e.g., Amiryar and Pullen, 2017; Bradbury et al., 2014; Lamp and Samano, 2022; Wang et al., 2019), will be distorted in their profitability, which will therefore adversely affect investment in such technologies. Our study may also be informative for other settings, where state intervention (to mitigate a negative externality) may have unintended consequences. For example, Adda and Cornaglia (2010) show that smoking bans (as a form of a non-market-based policy) unintendedly increase nonsmokers' exposure to smoke by relocating smokers to private places, whereas tobacco levies (as a form of a Pigouvian market-based policy) avoid this adverse effect. In terms of welfare effects, our main conclusion that subsidized RE adversely affect future profitability of arbitrage units and that a carbon tax would support their business, is somewhat weakened by the fact that the price-depressing effect of RE clearly elevates consumer surplus.

# 2 Background

## 2.1 Potential effect of RE on pumped-storage profits

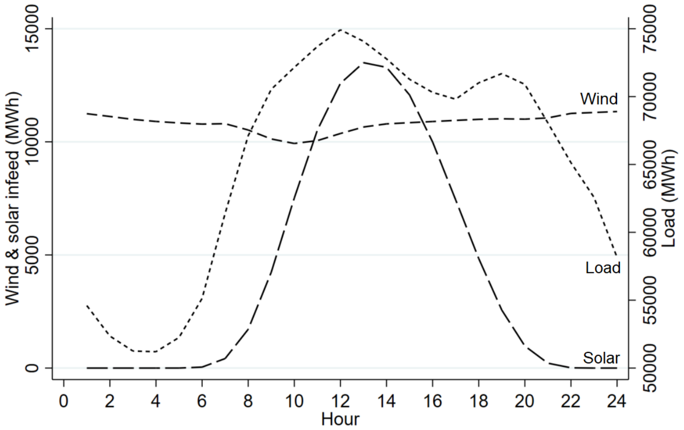
It is worth discussing how RE may affect the price spread between pumping and generating, to infer potential profitability impacts. Any price distortions, for example through stochastic supply shocks arising from intermittent RE infeed, will affect storage profits. Figure 1 provides a simple stylized illustration of how RE infeed may impact the price spread between peak and off-peak hours. Due to the typical convexity of the supply curve (as determined by increasing fuel costs from base- to peak-load plants), the divergence between low demand during off-peak times and high demand during peak times results in a price spread. The residual electricity demand curve is shifted to the left whenever RE feeds into the system. While wind infeed exhibits, *on average*, a rather flat infeed profile across the hours of a day, solar infeed peaks at around noon, which coincides with peak demand (see Figure 2). Hence, while

**Figure 1: Schematic effect of subsidized RE on the electricity price spread ($\Delta_p$)**



RE infeed reduces residual demand (D'). While wind power has a rather flat generation profile across daily hours, solar's peak at noon coincides with peak demand, indicated by the second arrow during peak hours. RE infeed diminishes the price spread ($\Delta_p$) between peak and off-peak demand for a typical convex electricity supply curve.

**Figure 2: Profiles of load and wind & solar infeed, sample averages**

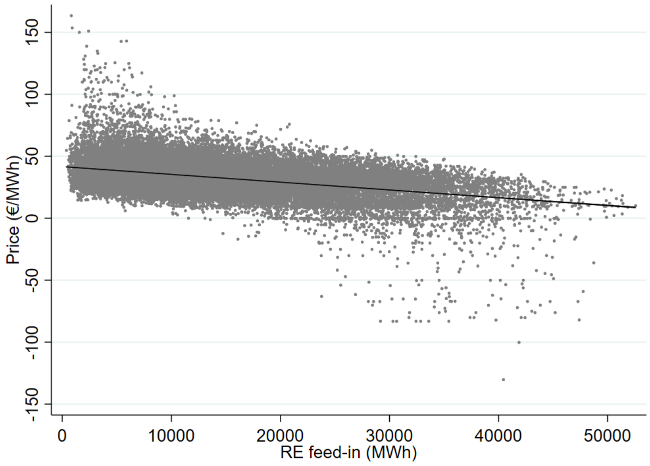


there is evidence that *average* solar infeed is load-following, this hides significant stochastic volatility of weather-driven infeed across hours. As a result, a high and increasing share of *intermittent* RE would require storage facilities to avoid ever-increasing needs for balancing measures or import dependency.

Two aspects are noteworthy in Figure 1. First, even for a flat RE feed-in profile, as with wind power, which would approximately equally shift the residual demand during peak ($D'_{peak}$) and off-peak times ($D'_{off-peak}$) , the convexity of the supply curve would lead to a reduced price spread ($\Delta_{RE} < \Delta_{noRE}$). Second, the coincidence that solar energy mostly impacts peak demand implies that the shift is stronger during peak times, which means that the price spread gets even further reduced. Wozabal et al. (2015) underpin our argument that RE reduce the price spread by empirically estimating that RE infeed reduced the electricity price variance in Germany during 2007–2013.

Hence, before presenting our econometric model's main findings, this is stylized evidence that subsidized RE may deter the business model of pumped storages via distortions of the wholesale electricity

**Figure 3: Wholesale electricity price & RE feed-in**



The graph shows combinations of hourly day-ahead forecasts of renewables infeed and day-ahead electricity prices.

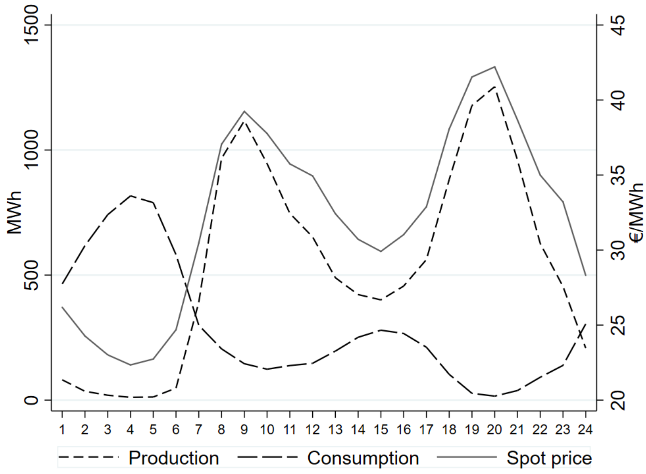
price (and its spread during peak off-peak times). To further underline this argument, Figure 3 shows for our data sample that RE and day-ahead wholesale electricity prices are negatively correlated and that price peaks cannot be observed during high levels of RE feed-in. Moreover, the Appendix presents a simple theoretical model to guide our empirical analysis. It shows that the peak/off-peak price spread is indeed the profitability driver of storages (and that the price spread must be large enough to even exceed efficiency losses of storage cycles).

## 2.2 Additional information

European pumped storage plants' installed capacity amounted to 45,622 MW in 2018, with a low mean annual growth rate of around 1% during 2006–2018 (S&P Global, 2019). This low storage capacity growth rate cannot support the system integration of vastly expanding RE (Arbabzadeh et al., 2019; Braff et al., 2016; Carson and Novan, 2013; Sinn, 2017). Despite its small size, Austria has 10% (i.e. 4,420 MW) of this capacity (S&P Global, 2019). It is thus often called the "battery of Europe." Pumped-storage plants require specific geographical peculiarities (e.g. an upper and lower water reservoir and a sufficient height difference), limiting its capacity expansion, potentially explaining the slow growth rate. On the other hand, there is still significant potential for pumped-storage capacity in Austria and Europe, according to the EU project eSTORAGE (2015).

Germany's share of renewable energies in total electricity production has increased steadily from 6.3% in 2000 to 37.8% in 2018 (BMWi, 2019a). It is expected to grow further to at least 80% by 2050 (BMWi, 2019b). The roll-up of Germany's RE is largely financed by substantial financial support via guaranteed feed-in tariffs (CEER, 2021). This development is likely to impact on the wholesale price of

**Figure 4: Production & consumption of pump storages by hour of day**



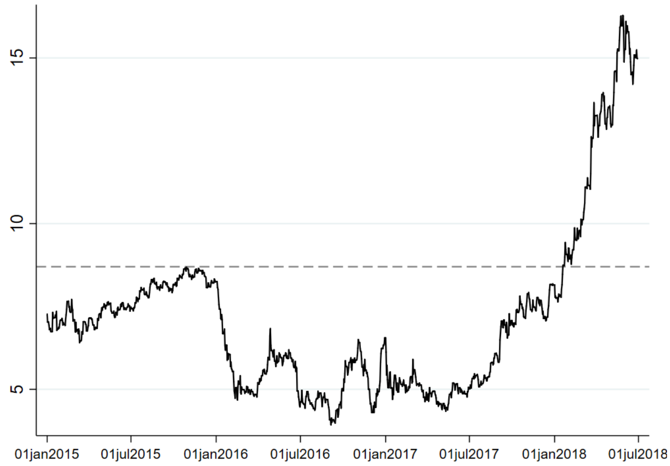
The graph shows sample averages of electricity production and consumption in MWh of pumped-storage plants (left y-axis), as well as the electricity day-ahead spot price in €/MWh (right y-axis).

electricity severely. Based on our data sample, Figure 3 provides descriptive evidence that renewables are negatively correlated with the wholesale electricity price and that price peaks vanish for moderate to high RE feed-in.

One caveat of our study is that we only observe data on wholesale electricity prices from the DE/AT day-ahead spot market. We acknowledge that pumped-storage plant operators may also serve other markets, such as reserve or balancing markets. in contrast the day-ahead market represents the most relevant market and may thus be viewed as the opportunity market (see section 3 for more details). Figure 4 depicts hour-of-day sample averages of production and consumption of Austrian pumped-storage power plants, together with the day-ahead spot price, showing strong correlations, which indicate that the day-ahead spot price is indeed relevant for the pumped-storage activity. We take up this issue again in Section 3.3, discussing important identifying assumptions.

Power plants operating in the DE/AT market are subject to the EU Emissions Trading System (ETS), which puts a price on tradable emission permits. Yet, the emissions price was low since its establishment in 2005 (mostly because of an abundance of permits and a generous policy of crediting low-carbon investments in third countries for permits; Koch et al., 2014). Figure 5 shows the development of the carbon price for our sample period. Not until January 19, 2018, that the carbon price exceeds its historic local maximum of only 8.7 €/tCO$_2$. Such a low price may not send proper incentives to invest in renewable energies or induce significant emissions abatement (Lilliestam et al., 2020). However, during the last six months of our sample the carbon price climbed up to about 16 €/tCO$_2$ (most likely induced by a reduction in the emissions cap). As we argue later, political action towards a significantly higher carbon price may be a viable strategy to relieve the depressing effect of subsidized renewables on the profits of

**Figure 5: Carbon price (€/tCO$_2$) in the EU ETS**



European Emission Allowances (EUA) price, daily closing value in €/tCO$_2$. The dashed line is for the local maximum carbon price of 8.7 €/tCO$_2$ before 2018.

pumped storage.

# 3 Research design

## 3.1 Baseline model: causal effect of *RE* via *P* on $\pi$

Our goal is to estimate the causal chain effect of RE on the profitability of pumped-storage plants, where the causal link is via the wholesale electricity price. We thus apply an econometric two-stage least squares (2SLS) model. The fist-stage regression estimates the effect of RE on the wholesale price:

$$P_t = \alpha_{RE}^{1st} RE_t + X_t' \alpha^{1st} + \epsilon_t^{1st}, \tag{1}$$

where $RE$ is the day-ahead forecast of RE infeed, $X$ is a vector of control variables (i.e. load, temperature, temperature squared, price of coal, price of gas, price of CO$_2$; c.f. data description in section 4) including seasonal fixed effects (i.e. fixed effects per year, month, day-of-week, and hour-of-day;), and $\epsilon_t$ is the error term. The subscript $t$ is a running time indicator for each sample hour.

In the second stage, we estimate the effect of the predicted price, $\hat{P}$, on the variable profit of pumped storages ($\pi$):

$$\pi_t = \alpha_P^{2nd} \hat{P}_t + X_t' \alpha^{2nd} + \epsilon_t^{2nd}. \tag{2}$$

The first stage (eq. (1)) estimates the merit-order effect, where $\hat{\alpha}_{RE}^{1st}$ measures how much the wholesale price decreases for a marginal increase in the feed-in of RE. Together with the estimates from the second stage (eq. (2)), we can estimate the *causal chain* of a change in RE on the wholesale price and further on the profit of pump storages as $\hat{\alpha}_{RE}^{1st} \times \hat{\alpha}_{P}^{2nd}$ (Kling, 2001).

A potential benefit of our 2SLS strategy is that we estimate our parameter of interest without bias even if we had omitted important control variables.

### 3.2 Price spread

At first sight, the application of the price *level* may not seem to align with our reasoning that the *price difference* between peak and off-peak hours (i.e. $\Delta_P$ in our theoretical model in the Appendix) is the main profitability driver of pumped storages. Since we use high-frequency data at the hourly resolution, this is no contradiction, because the prediction of the price series ($\hat{P}_t$) incorporates the effect of RE on the electricity wholesale price in each hour of the sample, including the effect on price peaks. One way of proofing this is to substitute the price level $P$ for an hourly measure of the price spread ($\Delta_p$) in equation (1), which we define as the price difference between the actual price per hour ($P_t$) and the daily mean spot price ($\bar{P}$): $\Delta_p = P_t - \bar{P}$. By definition, the results must be congruent with the baseline model's. The results (see Table 2) and are indeed consistent.

### 3.3 Identifying assumptions

Our just presented research design uses some important assumptions that deserve attention. First, the 2SLS analysis rests on the exclusion restriction, which requires the instrument (forecasted RE infeed) to impacts the outcome variable (storage profits) only through the endogenous variable (spot price). Otherwise, the error term would be correlated with the endogenous variable, leading to estimation bias. The exclusion restriction is not testable, but using economic rationale, it is likely to hold, because RE are determined by wind speed and solar radiation, which may not influence storage operations. There are good reasons that wind and sunshine are unrelated to storage operations. For example, wind and sunshine may not have a pronounced effect on the water levels of the upper or lower storage basins, as to significantly influence the short-run business of hydro-pumped storage. Moreover, to be a valid instrumental variable, forecasted RE infeed must be correlated with storage profits, which is testable: the first-stage statistics show a statistically significant partial coefficient estimate and the Kleibergen-Paap first-stage F statistic, testing for weak instruments, is sufficiently high.

Second, our baseline specification is contemporaneous and thus abstracts from dynamic considerations. However, in Section 6.3, we provide a lengthy discussion of this assumption, including arguments against a potential estimation bias, alternative regressions at the daily level, and regressions using up to 24 hour lags, to rule out concerns about disregarding dynamic effects. For example, daily data regression suggests that a profit-reducing effect of RE can even be estimated across days, implying that the effect is not only driven by within-day changes.

Third, storage operations may not significantly influence electricity prices. This is because storage infeed makes up only a small fraction of the DE/AT electricity mix, so market power should be fairly limited. According to our data, the average electricity infeed of pumped storages makes up 0.77% of the load. In any case, our baseline econometric model treats the wholesale electricity price as endogenous to storage profits. By applying an instrumental-variable approach we circumvent any problems of endogeneity or reverse causality.

Fourth, as we will state in the data section (Section 4), our measure of storage profitability is derived from the day-ahead spot market: the costs of observed pumping activity and the revenues of observed production activity are evaluated for day-ahead electricity prices, because from the data we cannot distinguish in which markets (e.g. day-ahead spot, intraday, balancing) the storage plants operate. For this reason, we employ the day-ahead spot price as the *reference price*, essentially assuming that there is no arbitrage across markets. This assumption is necessary to conduct our analysis. However, it also seems evident that the day-ahead spot market, as by far the largest and most relevant market, represents the opportunity market for all other markets. Industry experts also told us that Austrian pumped-storage plants accrue most of their revenues from the day-ahead market. Moreover, many academic studies follow a similar avenue. Analyzing revenue streams of pumped storages in Germany and Britain, Wilson et al. (2018) also use day-ahead spot prices. Deb (2000) and Figueiredo et al. (2006) are further examples of studies of electrical storages in day-ahead markets. Analogously, Gugler et al. (2020) and Puller (2007) assume that the day-ahead market serves as the reference market for electricity-generating power plants, which may also participate in other markets (e.g. intraday). Ortner and Totschnig (2019) show quantitatively that Germany's and Austria's day-ahead markets are the most relevant markets in terms of revenues and traded volumes (e.g. balancing markets' monetary volume is less than 3% of day-ahead markets' volume in these countries). However, we acknowledge that our profitability measure is a proxy for actual profitability, representing a lower bound of actual profits (because prices tend to be higher at subsequent markets).

Fifth, there may be the suspicion that owners of storage capacity, who also own RE capacity, may jointly optimize RE generation and storage. This way, RE would be endogenous to storage operations. However, RE enjoy prioritized feed-in at guaranteed, subsidized tariffs in Germany. This way, RE plants will feed into the system whenever the wind blows or the sun shines. To rule out doubts about the exogeneity assumption, in Section 6.6 we will discuss this issue further and run regressions using wind speeds and solar radiation as instrumental variables.

Sixth, our paper investigates *short-run* profitability. We measure short-term variable profits, which disregard output-independent fixed costs. Our assumption is that short-run profits are significantly distorted by exogenous market intervention in the form of subsidized feed-in tariffs for RE. This way, wholesale price signals are not (anymore) driven solely by free market forces of demand and supply, thereby sending distorted price signals for investments in other (complementary) technologies, such as pumped storages. However, our analysis cannot deliver estimates to infer any longer-run implications, such as learning and innovation, which would nevertheless be among the important elements in understanding the impact of high shares of RE.

Finally, this study is for pumped storage only, which makes up almost the entire current storage capacity. Even though our results show that their arbitrage opportunities are distorted by subsidized RE, future electricity markets may also see the deployment of other storage technologies (e.g. batteries), which may be subject to other driving forces or geographical constraints. Although our results may be informative about other arbitraging facilities, the effect magnitude may be different, as other driving factors may gain significance.

### 3.4 Effect of RE on peak vs. off-peak prices

We may also show that RE have not only a negative average effect on the electricity wholesale price, but that the effect is stronger during peak times (as suggested by Figure 1), thereby dampening the peak/off-peak price spread. To do so, we extend the first-stage equation (1) by an indicator for peak hours and its interaction term with RE:

$$P_t = \beta_{RE} RE_t + \beta_D D_t + \beta_{RE \cdot D} RE_t \cdot D_t + X_t' \beta + \epsilon_t, \tag{3}$$

where $D$ is a binary indicator, which takes up a value of one during peak hours (i.e. 8h–20h) and zero otherwise. Following the same procedure as above, we can then obtain the price prediction ($\hat{P}_t$) and re-estimate the second stage (equation (2)), which should yield qualitatively similar results as the above procedure. While the estimate of $\hat{\beta}^{1st}_{RE}$ measures the effect of $RE$ on $P$ during off-peak hours, $\hat{\beta}^{1st}_{RE} + \hat{\beta}^{1st}_{RE \cdot D}$ measures the effect during peak hours. We expect RE's effect to be more negative during peak than off-peak hours: $\hat{\beta}^{1st}_{RE} + \hat{\beta}^{1st}_{RE \cdot D} < \hat{\beta}^{1st}_{RE}$.

## 4 Data

This analysis combines high-frequency (i.e. hourly and daily) data from several sources for 2015/01/01, 01h–2018/06/30,24h. Our sample thus ends before the common German-Austrian electricity market was split on 1 October 2018 into two national price zones (during hours of cross-border electricity flows exceeding a capacity limit of 4.9 GW).

**Table 1: Sample statistics**

| Variable | Obs | Mean | Std. Dev. | Min | Max |
|---|---|---|---|---|---|
| *Dependent variable* | | | | | |
| Variable profit (€)$^{a}$ | 30,592 | 18,557 | 42,940 | -88,345 | 445,249 |
| *Variables of Interest* | | | | | |
| RE infeed (MWh)$^{a,c}$ | 30,592 | 15,072 | 9,563 | 372 | 52,550 |
| RE infeed, 8–20h (MWh)$^{a,c}$ | 16,571 | 18,415 | 9,594 | 372 | 52,550 |
| RE infeed, 20–7h (MWh)$^{a,c}$ | 14,021 | 11,121 | 7,869 | 524 | 44,404 |
| Wind infeed (MWh)$^{a,c}$ | 30,592 | 10,825 | 8,212 | 241 | 44,404 |
| Solar infeed (MWh)$^{a,c}$ | 30,592 | 4,247 | 6,456 | 0 | 29,484 |
| *Control variables* | | | | | |
| Electr. price (€/MWh)$^{a}$ | 30,592 | 32.19 | 14.77 | -130.09 | 163.52 |
| Electr. price, 8–20h (€/MWh)$^{a}$ | 16,571 | 35.66 | 16.00 | -130.09 | 163.52 |
| Electr. price, 21–7h (€/MWh)$^{a}$ | 14,025 | 28.08 | 11.92 | -83.06 | 109.92 |
| Load (MWh)$^{a}$ | 30,592 | 62,661 | 10,901 | 33,951 | 86,408 |
| Price of coal (€/MWh)$^{b}$ | 30,592 | 7.61 | 1.77 | 4.62 | 11.32 |
| Price of gas (€/MWh)$^{b}$ | 30,592 | 17.50 | 3.17 | 10.83 | 43.86 |
| Price of CO$_2$ (€/tCO$_2$)$^{b}$ | 30,592 | 7.12 | 2.57 | 3.93 | 16.28 |
| Temperature (°C)$^{a}$ | 30,592 | 10.20 | 7.42 | -11.68 | 35.59 |
| *Instrumental variables* | | | | | |
| Wind speed (m/s)$^{a}$ | 30,592 | 3.97 | 1.65 | 1.09 | 14.08 |
| Sunshine (min)$^{a}$ | 30,592 | 11.88 | 17.02 | 0.00 | 60.00 |

Sample period: 2015/01/01,01h–2018/06/30,24h. $^{a}$Hourly resolution. $^{b}$Daily resolution. $^{c}$Day-ahead forecast.

We calculate the hourly variable *profits* of pumped storages at the aggregate (i.e., industry) level as the revenue of generating electricity minus the costs of pumping water uphill: $\pi_t = (q_{Gen,t} - q_{Pump,t}) \cdot p_t$, where $q_{Gen}$ and $q_{con}$ represent generation and consumption, $p$ the spot price, and the subscript $t$ the hour of our sample. Data on electricity production and consumption of pumped-storage power plants in Austria are obtained from the European Network of Transmission System Operators for Electricity (ENTSO-E, 2019). Unfortunately, consumption data were missing for most other European countries, which eventually narrowed our analysis to Austrian pumped storages, for which the data were comprehensively available.

As the reference price of wholesale electricity, we use the hourly day-ahead price for the common DE/AT EPEX spot market, as obtained from the Transparency Platform of the European Energy Exchange (EEX) (EEX, 2019). It is worth noting that the spot price can be negative for the rare events of feed-in of renewable energies (which is guaranteed and prioritized) exceeding the demand for electricity (less must-run electricity production from base-load power plants).

Regarding RE infeed, we use data on hourly *day-ahead forecasts*, because we analyze day-ahead spot price of electricity. The data comprise onshore wind, offshore wind, and solar for Germany and Austria, as provided by ENTSO-E (2019). Please note that day-ahead *forecasted* and *actual* wind and solar electricity generation are highly correlated (i.e. 98%). The same source provides hourly data on the joint electricity demand (load) in Germany and Austria.

Data on the input prices of coal and natural gas are obtained from S&P Global Platts (S&P Global, 2019), a major independent data and information provider for the energy and commodities markets.

We use the Europe CIF ARA price of coal, converted from US$ per ton to €/MWh, which is available for the daily frequency. We use the daily exchange rate from the European Central Bank for currency conversion. The price of natural gas is derived from Gaspool Germany in €/MWh. The price of $CO_2$ is obtained from EEX (EEX, 2019), representing the daily closing value of the EUA Primary Spot Auction, in €/$tCO_2$.

Hourly data on the temperature (in °C) stem from the German Weather Service ("Wetterdienst") for many weather stations. For our purposes, we chose 16 stations, each located in a city approximately in the center of a German federal state and took the mean values. The locations are Berlin-Tegel, Braunschweig, Bremen, Chemnitz, Düsseldorf, Erfurt-Weimar, Frankfurt, Haumburg-Fuhlsbüttel, Nürnberg, Potsdam, Rostock-Warnemünde, Saarbrücken-Ensheim, Sankt Peter-Ording, Seehausen (Sachsen-Anhalt), Stuttgart-Schnarrenberg, Trier-Petrisberg.

Table 1 provides descriptive statistics of our sample. Comparing means with standard deviations suggests that our main variables of interest (variable profits, RE infeed, electricity price) have sufficient variation. It is worth noting that, on average, the pumped storage industry makes positive profits of 18,557 € per hour. The average electricity spot price is 32.18 € per MWh, whereas it is significantly higher during peak hours from 8–20h (35.66 €/MWh) compared to off-peak hours (28.08 €/Mwh). Renewables have an average infeed of 15,072 MWh, with a significantly higher infeed during peak hours (18,415 MWh) than during off-peak hours (11,121 MWh). Moreover, Online Appendix Table A2 shows correlations of our main variables, indicating that multicollinearity is no issue in our regressions.

# 5 Results

## 5.1 Baseline model

Table 2 summarizes the estimates of our baseline two-stage model, the model using the price spread (instead of price) as the endogenous variable, and the model on peak versus off-peak prices. Full regression output tables of all regressions are provided in the Online Appendix. Apart from the main coefficients of interest, all control variables (except for the price of natural gas in some specifications) are statistically significant (see Online Appendix Table A1) and have the expected signs. All IV regressions yield high Kleibergen-Paap first-stage F statistics (the critical value is about 10), rejecting the null hypothesis of weak instruments.

Column (1) of Table 2 reports the estimates of the first-stage model, which gives a negative and statistically significant effect of $RE$ on $P$. We estimate that a partial increase in the feed-in of RE by one MWh depresses the electricity wholesale price by 0.105 cents per MWh. Evaluated at means of the respective variables, we can calculate an elasticity: a 10% increase in RE (i.e. 1,507 MWh) leads to a decrease in the electricity wholesale price by 4.90% (i.e. -1.58 €/MWh) – an economically sizable effect.

Evaluated at the mean feed-in of RE of 15,072 MWh, the wholesale price already dropped by 15.77 €/MWh, relative to the counterfactual of no RE feeding into the system. Against a sample mean price of 32 €/MWh, this effect is considerable. Our estimate is also in line with Würzburg et al. (2013), who estimate that one MWh of RE decreases the DE/AT electricity spot price by 0.103 cents per MWh during 2010/07/01–2012/06/30 (when the share of RE was not as pronounced as during our sample).

As presented in column (2), the second stage shows that a marginal change in electricity wholesale price by one €/MWh is associated with a statistically significant increase in pumped-storage profits by 1,701 € per hour. Assessing the causal chain, an 10% increase in subsidized RE leads to a decrease in pumped-storage profitability by 14.46%, via a distortion of the electricity wholesale price (i.e., –4.90% or -1.58 €/MWh), evaluated at mean values of the respective variables. Thus, subsidized RE indeed have a significantly negative effect on pumped storages' profits.

### 5.2 Price spread

Importantly, investigating the price *level* at a high data frequency (hourly resolution), including all peaks and lows, is qualitatively similar to analyzing the price *spread*, which we identified as the profitability driver of pumped storages in the theoretical model (see the Appendix). The price-spread model in Table 2 shows that the estimated effect of $RE$ via $\Delta_p$ on $\pi$ (following the estimation procedure described in section 3.2) delivers fully robust results. Our findings also support the notion that RE have a depressing effect on the price spread between peak and off-peak hours (i.e., -0.032 cents per MWh), as shown in a stylized manner in Figure 1.

### 5.3 Peak vs. off-peak

Table 2 estimates another first-stage regression (c.f. eq. (3)), which includes an interaction term of RE with a dummy for peak hours (8–20h). We estimate price effects of -0.105 cents and -0.106 cents per MWh during off-peak and peak hours, respectively, which is again in line with expectations. Also, the second-stage regression (column (4)) delivers qualitatively similar results as our baseline regression: a 10% increase in RE deters pumped-storage profits by 14.3%.

## 6 Threats to identification, robustness & additional results

In this section, we present additional estimation results and robustness regressions to rule out threats to identification. Table 3 summarizes these estimates. Moreover, full regression output tables are provided

## Table 2: Main regression results

| | Baseline model | | Price spread | | Peak vs. off-peak | |
|---|---|---|---|---|---|---|
| | (1) IV: 1st stage Price ($P$) | (2) IV: 2nd stage Profit ($\pi$) | (3) IV: 1st stage Price spread ($\Delta_p$) | (4) IV: 2nd stage Profit ($\pi$) | (3) IV: 1st stage Price (P) | (4) IV: 2nd stage Profit ($\pi$) |
| RE | -0.00105*** | | -0.000317*** | | -0.00101*** | |
| | (1.13e-05) | | (6.32e-06) | | (1.57e-05) | |
| Price | | 1,701*** | | | | 1,736*** |
| | | (44.59) | | | | (44.73) |
| Price spread | | | | 5,621*** | | |
| | | | | (143.9) | | |
| $D^{peak}$ | | | | | 0.8778** | |
| | | | | | (0.360) | |
| $RE \cdot D^{peak}$ | | | | | -5.29e-05** | |
| | | | | | (2.09e-05) | |
| Control variables | yes | yes | yes | yes | yes | yes |
| Seasonal FE | yes | yes | yes | yes | yes | yes |
| Observations | 30,592 | 30,592 | 30,592 | 30,592 | 30,592 | 30,592 |
| $R^2$ | 0.788 | 0.558 | 0.550 | 0.222 | 0.789 | 0.552 |
| First-stage F stat. | 8,612 | | 2,511 | | 2,908 | |
| Effect 10% ΔRE on $P$ | -4.90% | | | | | |
| – during 8–20h (peak) | | | | | -5.00% | |
| – during 21–7h (off-peak) | | | | | -4.75% | |
| Effect 10% ΔRE on $\pi$ | | -14.46% | | -14.46 | | -14.31% |

Notes: Standard errors in parentheses are robust to heteroskedasticity and allow for first-order serial correlation (Newey-West SE). *** $p < 1\%$, ** $p < 5\%$, * $p < 10\%$. Sample period is 2015/01/01,01h–2018/06/30,24h. Columns 1: instrumented for price by RE. Column 3: instrumented for price spread by RE. Column 5: instrumented for price by RE, D & D·RE. At the bottom of the table, we present changes in $P$ and $\pi$ for a 10% partial change in $RE$, evaluated against mean values of all variables. Control variables: load, temperature, temperature squared, price of coal, price of gas, price of $CO_2$. Seasonal fixed effects: annual, monthly, day-of-week, and hour-of-day.

## Table 3: Summary of alternative regressions

| | (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) | (10) |
|---|---|---|---|---|---|---|---|---|---|---|
| | Red. form | Wind vs. solar | | Inclusion of RE lags | | | Daily frequency | | Non-linear effect | |
| | Profit ($\pi$) | IV: 1st stg Price (P) | IV: 2nd stg Profit ($\pi$) | Lag: 1h Profit ($\pi$) | Lags: 1h & 24h Profit ($\pi$) | Lags: 1h–24h Profit ($\pi$) | IV: 1st stg Price (P) | IV: 2nd stg Profit ($\pi$) | IV: 1st stg Price (P) | IV: 2nd stg Profit ($\pi$) |
| RE | -1.780*** | | | | | | -4.33e-05*** | | -0.000783*** | |
| | (0.0414) | | | | | | (1.76e-06) | | (3.09e-05) | |
| RE$^2$ | | | | | | | | | -6.95e-09*** | |
| | | | | | | | | | (8.97e-10) | |
| Wind | | -0.00103*** | | | | | | | | |
| | | (1.19e-05) | | | | | | | | |
| Solar | | -0.00116*** | | | | | | | | |
| | | (2.25e-05) | | | | | | | | |
| $\sum_{t=-24}^{t=0} RE_t$ | | | | -1.795*** | -1.691*** | -1.252*** | | | | |
| | | | | (0.0417) | (0.0467) | (0.0482) | | | | |
| Price | | | 1,731*** | | | | | 1,176*** | | 1,643*** |
| | | | (44.68) | | | | | (124.8) | | (45.87) |
| Control variables | yes | yes | yes | yes | yes | yes | yes | yes | yes | yes |
| Seasonal FE | yes | yes | yes | yes | yes | yes | yes | yes | yes | yes |
| Observations | 30,592 | 30,592 | 30,592 | 30,587 | 30,560 | 30,472 | 1,275 | 1,275 | 30,592 | 30,592 |
| R$^2$ | 0.550 | 0.789 | 0.557 | 0.550 | 0.551 | 0.584 | 0.829 | 0.539 | 0.791 | 0.560 |
| First-stage F stat. | | 4,377 | | | | | 2,001 | | 641 | |
| Effect 10% $\Delta$RE on $P$ | | | | | | | -4.87% | | -3.67% | |
| Effect 10% $\Delta$RE on $\pi$ | -14.46% | | | -14.58% | -13.74% | -10.17% | | -9.93% | | -10.45% |
| Effect 10% $\Delta$W on $P$ | | -3.47% | | | | | | | | |
| Effect 10% $\Delta$S on $P$ | | -1.53% | | | | | | | | |
| Effect 10% $\Delta$W on $\pi$ | | | -10.41% | | | | | | | |
| Effect 10% $\Delta$S on $\pi$ | | | -4.58% | | | | | | | |

Notes: Standard errors in parentheses are robust to heteroskedasticity and allow for first-order serial correlation (Newey-West SE). *** $p < 1\%$, ** $p < 5\%$, * $p < 10\%$. Sample period is 2015/01/01,01h–2018/06/30,24h.

in Online Appendix.

## 6.1 Reduced-form model

We can also estimate the reduced-form model, which measures the *direct* effect of RE on pumped-storage profits:

$$\pi_t = \delta_{RE} RE_t + X_t'\delta + \epsilon_t. \tag{4}$$

The results of this model should be qualitatively similar to the baseline model as long as the electricity wholesale price is indeed the main channel through which RE affect $\pi$. Indeed, the results, as presented in Column 1 of Table 3, are fully robust: a marginal increase in subsidized RE by one MWh depresses pumped-storage profits by 1.78 € per hour, which is equivalent to a drop in profits by 14.46% evaluated for a 10% increase in RE.

## 6.2 Wind vs. solar

The above discussion already points to differential effects of wind and solar power. Moreover, recent studies support this notion. Bushnell and Novan (2021) find for California and Jha and Leslie (2021) for Western Australia that solar power decreases the electricity price during daytime, whereas prices increase during non-daylight hours. Similarly, Novan (2015) argues for Texas that wind and solar follow different feed-in patterns during the hours of the day, thus having significantly heterogeneous effects on emissions abatement. Moreover, Linn and Shih (2019) show for Texas that wind and solar have contrasting relationships with demand. In the DE/AT electricity market, the feed-in profile of wind is rather flat during the 24 hours of a day. In contrast, solar's peak at noon partly overlaps with high electricity demand during the day (see Figure 2).

Against this backdrop, we quantify the separate effects of wind and solar power. We follow our baseline approach, but replace *RE* with day-ahead forecasts of wind and solar infeed. Columns 2 and 3 of Table 3 provide the regression estimates. The first-stage estimates are, as expected, that solar's coefficient estimate (-0.00116) is more pronounced than wind's (-0.00103) (a t-test rejects the H0 of equal coefficients at the 1% level). However, in the DE/AT electricity market, the sample mean hourly infeed of wind (10,825 MWh) is significantly higher than that of solar (4,247 MWh). Hence, we find a stronger profit-decreasing effect for a 10% increase in the wind infeed (-10.41%) compared to that of solar infeed (-4.58%).

We conclude that both forms of renewable energies, wind and solar power, have significantly negative effects on the electricity wholesale price and the profitability of pumped-storage power plants. While solar's marginal effect is more pronounced than wind's, the higher feed-in level of wind is eventually more responsible for the decreasing profits of pumped storage.

### 6.3 Data frequency & level of aggregation

There has been a discussion around the appropriateness of our approach using hourly data. For example, it was argued that our regressions would only be informative about the effect of a within-hour change in RE generation on pumped-storage profits within the same hour. However, an incremental change in RE generation within an hour may likely affect storage profits in other subsequent hours. For example, if renewables caused a price decrease in one hour, this might lead a storage facility to pump (i.e., reduce profits in that hour), while the storage plant may earn a higher profit in a later hour, when it releases the stored water to produce electricity. This way, our econometric model at the hourly level would not capture the full effect of a change in RE on storage profits due to the dynamic incentives of storage operators. One way of addressing across-hour effects would be to run regressions at a higher aggregation level (e.g. at the daily level, c.f. Bushnell and Novan, 2021 or Holland and Mansur, 2008) or to stay with the hourly specification add lags in RE generation to control for dynamic effects (c.f. Jha and Leslie, 2021).

Despite these arguments, we believe that our so-far analysis has been valid, because we use of hourly observed data on actual pumping and generation activity of pumped storages and actual wholesale electricity prices. This way, we know exactly how much energy used for pumping and for which electricity price, as well as how much electricity was generated and for which price. Hence, even if changes in RE infeed led to a change in the pumping-production behavior of pumped storages (such as delaying production to later hours when solar depresses the price peak at noon), we observe and can analyze these patterns in our data. This reassures us that there are no profit leakages arising from the data aggregation level that we chose in our empirical approach.

One may think that adaptations of pumping or production activity to supply shocks through changes in RE infeed might take time (as is the case with base-load power plants, such as lignite plants), which would justify the inclusion of lags in RE infeed. Pumped storages are, however, designed to react fast to changing market circumstances, mitigating this concern. Nevertheless, we also present econometric regressions addressing this issue.

**Hourly frequency with lags of RE —** Given that using several lagged variables of RE infeed would lead to over-identification issues (even the inclusion of only one one-hour lag already gives a p-value of the Hansen J statistic of 0.000), we run the reduced form and additionally include lags of RE infeed. In the first specification, we include a lag of one hour. Both coefficients enter statistically significant. Their composite coefficient estimate is -1.795 and statistically significant (p-value of 0.00). In relative terms, this means that an increase in RE by 10% relative to the mean decreases storage profits by 14.58%. This is a qualitatively robust result. In another specification, we add both a one-hour lag and a 24-hour lag (i.e., the same hour during the previous day). The results are again robust: the composite coefficient estimate is -1.691 and statistically significant (p-Value of 0.00), implying that a 10% increase in RE leads to a decrease in profits by 13.74%. Finally, we include the whole series of all 24-hour lags, resulting in a statistically significant composite coefficient estimate of -1.252. This yields a drop in profits by 10.17% for an increase in RE by 10%. This result is somewhat less pronounced but still suggests a strong profit-decreasing effect of RE on storage profits.

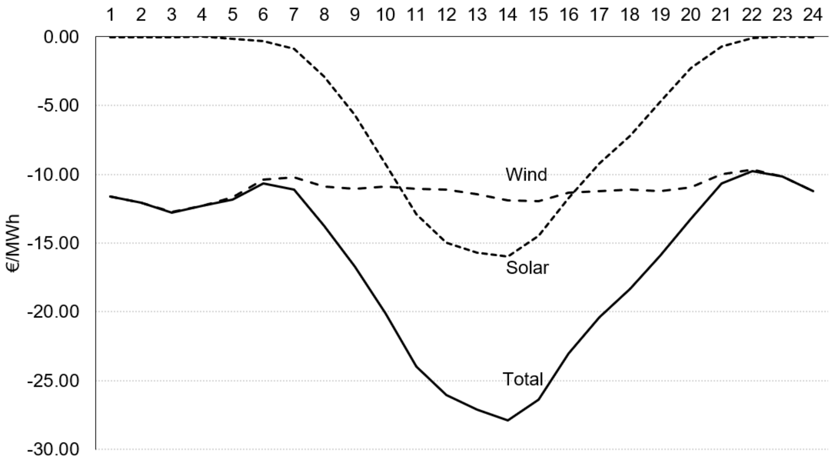
**Aggregation at the daily frequency —** Turing now to the daily aggregate level, we should emphasize that we do not think this is an adequate approach to identify our effect of interest. This is because daily mean values take out a lot of variation coming from price peaks and lows within a day, which may result from intra-day changes in RE generation. With daily aggregates, we cannot observe during which hours (e.g., peak vs. off-peak) and by how much RE infeed influenced the electricity price. Thus, our first-stage regression based on daily averages may come to different results than using hourly data (and eventually also influencing our second-stage estimates).

Nevertheless, we run the regressions, as presented in columns 7 and 8 of Table 3. The results again show pronounced and statistically significant effects of subsidized RE infeed on the daily mean price of electricity and pumped-storage profits: a 10% change in RE infeed reduces the daily price by 4.87% and further reduces pumped-storage profits by 9.93%. We can conclude that even for daily averages, which smooth the variation within a day, we find econometric evidence for a significant distortion of the wholesale price of electricity by subsidized RE, which translates into a significant profit distortion of pumped storage. The less pronounced estimated elasticity (compared to the baseline estimates for hourly data) may be explained by averaging out variation within a day.

### 6.4 Nonlinear effect

A potential threat to credibility may be that our applied model assumes a constant linear effect. It may be that the effect is different for higher than for lower RE levels. We thus relax this assumption by introducing a second-order polynomial of RE ($RE$ and $RE^2$) in our regression. The results (see columns 9 and 10 in Table 3 show that our results stay qualitatively robust, whereas the effect of a 10% increase in RE on $\pi$ of -10.45% is slightly lower than in the baseline regression.

**Figure 6: Effect of mean RE infeed on $P$ by hour of day**



The graph shows the estimated effects of $RE$ on $P$ by hour of day (c.f. equation (6)) evaluated for average RE infeed (in MWh) by hour of day. These effects are to be interpreted as effects relative to the counterfactual scenario of no RE in place.

## 6.5 Effects of *RE* on *P* by hour of day

A similar approach as investigating the hourly price spread or the effect during peak and off-peak times is to estimate the effect of $RE$ on $P$ *per hour of day*, as to show that wind reduces the price across all hours, but that the additional effect of solar particularly dampens peak prices:

$$P_t = \sum_{h=1}^{24} \gamma_{RE,h} RE_t \cdot \psi_h + X_t' \gamma + \epsilon_t, \tag{5}$$

where $\psi_h$ are hour-of-day fixed effects. $\gamma_{RE,h}$ captures the marginal effects of wind and solar infeed by hour of day. This then allows for measuring the partial change in the electricity price ($\Delta_p$) for a marginal change in RE, evaluated for the mean RE infeed by hour of day ($\overline{RE}_h$):

$$\Delta_p = \hat{\gamma}_{RE,h} \cdot \overline{RE}_h. \tag{6}$$

This approach yields price effects by hour of day for average wind and solar infeed, evaluated at sample means of all variables. Figure 6 visualizes the results. We can see that the decrease in the wholesale price is most pronounced during noon, when solar feeds into the system, in addition to the rather flat feed-in profile of wind, which eventually causes a decrease in the peak/off-peak price spread.

## 6.6 Exogeneity of *RE*

So far, we assumed RE to be exogenous. Our discussion above already suggests that RE feed into the system whenever the wind blows or the sun shines (due to prioritized feed-in at guaranteed feed-in tariffs), supporting the notion that $RE$ are exogenous. However, to rule out any concerns, we also run a robustness estimation based on a two-stage instrumental variables (IV) approach with hourly wind speed ($W$), sunshine ($S$), and their squared terms ($W^2, S^2$) as instruments for $RE$. [1] The first stage of this procedure is:

$$RE_t = \zeta_w^{1st} W_t + \zeta_{ww}^{1st} W_t^2 + \zeta_s^{1st} S_t + \zeta_{ss}^{1st} S_t^2 + X_t' \zeta^{1st} + \epsilon_t^{1st}. \tag{7}$$

Then, the second-stage regression includes the prediction of RE, $\widehat{RE}_t$, from the first stage:

$$\pi_t = \zeta_{RE}^{2nd} \widehat{RE}_t + X_t' \zeta^{2nd} + \epsilon_t^{2nd}. \tag{8}$$

Similar estimates of $\alpha_{RE}$ (standard OLS) and $\beta_{RE}^{2nd}$ (IV) would indicate the exogeneity of $RE$.

With this approach, we can rule out any concerns about the exogeneity of RE infeed. The findings, as provided in the Online Appendix Table A8, are robust: a 10% increase in RE decreases pumped-storage profits by 12.77%.

## 7 Discussion

Our results are economically and politically relevant, because we find that renewable energies undermine the competitiveness of pumped-storage power plants. This effect will intensify with higher levels of RE infeed following the ambitious RE targets by the German and Austrian governments, as part of their national climate agendas. Germany, for example, plans to increase its share of RE from 38% in 2018 to 65% by 2030 and 80%–95% by 2050 (German Federal Government, 2020). However, our estimates warrant caution as a high share of subsidized wind and solar power may significantly negatively affect the short-run profitability of pumped storages. Ironically, on the one hand the very intermittency of RE would require a vast deployment of large-scale storage capacity to decouple generation and demand and to secure grid stability. On the other hand, the rollout of wind and solar power counteracts the competitiveness of pumped storage.

A potential countermeasure to this dilemma would be a "meaningful" carbon price, which would increase the marginal costs of fossil-fueled technologies relative to carbon-free technologies, such as hydro power plants. A carbon price would set market-based incentives and avoid subsidized renewables' electricity price distortion, which undermines the business model of pumped storage. Moreover, a carbon price may lead to significant emissions abatement (Hepburn et al., 2020), foster R&D and investment in RE (IEA, 2020), while at the same time avoiding the problem that the state has to choose

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[1] We include $W$ and $S$ in levels and squared terms, because this specification yields the highest first-stage F statistic. However, the results stay robust when we omit $W^2$ and $S^2$ as instruments.

which technologies to subsidize based on imperfect information ("winner picking").

We may use the estimates of our baseline model (columns (1) & (2) of Appendix Table A1) to test our hypothesis. The first-stage coefficient estimate of $P_{\mathrm{CO2}}$ is 1.198, implying that a change in the carbon price by one euro per ton of $CO_2$ increases the electricity wholesale price by around 1.2 euro per MWh (in line with Fabra and Reguant, 2014). The second-stage result shows that for a marginal change in the carbon price by one €/t$CO_2$, pumped-storage profits increase by 1,670 € per hour. Evaluated at the relatively low sample mean carbon price of 7.12 €/t$CO_2$, a 10% increase in the carbon price increases the wholesale electricity price by 2.65% (or 85 cents per MWh) and further elevates storage profits by 7.67%. This already shows that the carbon price counteracts the negative impact of subsidized RE on storage profits. Our results are fully robust to an alternative specification, which uses both $RE$ and $P_{CO2}$ as instruments for $P$, as shown in the Online Appendix Table A9.

These estimates are economically significant and suggest that carbon pricing can counteract the negative adverse effect of directly subsidized RE. Altogether, this analysis underlines the importance of carbon pricing as a climate policy, supporting the business model of electricity storage.

## 8 Conclusion

Scientists have a broad consensus among scientists that energy storage is needed to support both the integration and effectiveness of intermittent RE, thereby enhancing social welfare. This study tests if RE, which enjoy generous support payments, destroy large-scale energy storages' competitiveness. The argument is that subsidies for RE are a form of market intervention to foster the deployment of wind and solar power independently of an otherwise undistorted price signal arising from the interplay between demand and supply. The suspicion was that subsidized wind and solar power might depress the wholesale price of electricity, especially during peak load, which may eventually undermine the business model of pumped-storage power plants (i.e. price arbitrage).

We estimate the causal chain of RE via the electricity wholesale price on pumped-storage profits, employing a two-stage IV model. For this purpose, we use data on Austrian pumped-storage power plants, which operate in the common German-Austrian electricity market. The vast share of heavily subsidized wind and solar power in Germany, together with the substantial pump-storage capacity installed in Austria, make it a relevant case for investigation, which also bears relevance for other countries with similar RE ambitions and for other settings where market interventions, although well-meant, may adversely impact market outcomes. We estimate that subsidized RE significantly distort the electricity wholesale price and depress the price spread between peak and off-peak periods. This price distortion eventually reduces pumped-storage profits. With a further deployment of RE via subsidy payments, as planned by the German government according to its climate agenda, pumped-storage profits will likely be strongly influenced (and may even turn negative) in the near future (ceteris paribus). It seems a paradox that the weather-dependent volatility of renewables requires system flexibility enabled by energy storage, whereas the distortionary effect of subsidies for renewables on the electricity price counteracts the success of energy storage.

Our results are alarming and call for political action. State aid for pumped-storage power plants could relieve this situation. However, we argue and estimate that a market-based policy in the form of carbon pricing would counteract the adverse effect of subsidized RE. As there is still a debate among scholars, which policy measures would be necessary to decarbonize the economy, our study provides another argument in favor of carbon pricing, as a market-based policy, to abate emissions efficiently and also maintain investment incentives for energy storages.

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# Appendix

## Simple Model of Hydro-Pump Storages

In the following, we present a simple theoretical model of pumped storage, to provide basic insights into plant-specific operations and profit-making. The main focus lies on the illustration of the plant scheduling and the effect of a variation of the wholesale price of electricity over time (i.e. price spread). Although the model is simple, increasing its complexity (e.g., a dynamic framework over a longer horizon of multiple pumping-generating cycles) does not alter the intuition of the basic conception of pumped storage.

Pump storages generate revenues from letting water flow from an uphill reservoir through a turbine, which generates electricity by the energy input ($q_{Gen}$), and then sell this electricity for the wholesale price at that time ($p_{Gen}$). Costs, on the other hand, emerge if energy potential ($q_{Pump}$) from the lower reservoir is pumped uphill, for which the plant has to consume electricity for the actual wholesale spot price ($p_{Pump}$). Naturally, $q_{Gen}$ and $q_{Pump}$ cannot happen simultaneously, implying that electricity generation and consumption happen in sequence. Our model, thus, represents a full cycle of plant operation.

A typical feature of an Austrian pumped-storage plant is a natural water inlet ($q_{In}$), which can be used for electricity generation without cost and increases the total energy input for generation to $q_{Gen} + q_{In}$. Moreover, the circular energy flow of pumping and generating electricity via hydropower cannot happen without a loss of efficiency, which we model by the round-trip efficiency factor $\eta$ (i.e. $0 < \eta < 1$; it is typically between 70%–80%; Liu and Woo, 2017; Sinn, 2017)). The realized profit can be defined as:

$$\pi(q_{Gen}, q_{Pump}) = p_{Gen} \cdot (q_{Gen} + q_{In}) \cdot \eta - p_{Pump} \cdot q_{Pump}. \tag{9}$$

Of course, the storage plant operator will plan its business activities so that it generates electricity during times of high prices (e.g. peak hours), whereas it will pump during times of low prices (e.g. off-peak hours), so that $p_{Gen} > p_{Pump}$. We can express the price difference (the so-called "peak-off-peak spread") between hours of pumping and generating as $\Delta_p = p_{Gen} - p_{Pump}$. In this simplified model, we assume that the entire energy potential is being used for energy generation ($q_{Pump} = q_{Gen}$). Using $q_{Gen} = q_{Pump} = q$, $p_{Gen} = p_{Pump} + \Delta_p$ and $p_{Pump} = p$, we can rewrite the realized profit function to:

$$\pi(q, \Delta_p) = (p + \Delta_p) \cdot (q + q_{In}) \cdot \eta - p \cdot q. \tag{10}$$

From the perspective of the storage plant operator, the actual price spread $\Delta_p$ is ex-ante uncertain. Hence, the *expected* profit function reads:

$$E[\pi(q, \Delta_p)] = (p + E[\Delta_p]) \cdot (q + q_{In}) \cdot \eta - p \cdot q. \tag{11}$$

Therefore, the storage operator bases plant decisions on the effect of a change in $q$ on the *expected* profit: $\frac{\partial E[\pi]}{\partial q} = (p + E[\Delta_p]) \cdot \eta - p$. For $E[\Delta_p]$ greater (less) than $\frac{1-\eta}{\eta} \cdot p$, it follows that raising $q$ positively (negatively) affects the *expected* profit $E[\pi(q, \Delta_p)]$.

$$\frac{\partial E[\pi]}{\partial q} = \begin{cases} > 0 & \text{for } E[\Delta_p] > \frac{1-\eta}{\eta} \cdot p \\ \leqslant 0 & \text{otherwise} \end{cases} \tag{12}$$

As a result, the operator ex-ante optimally chooses the highest (lowest) $q$ level possible. In this simple framework, the maximum energy storage capacity ($\overline{q}$) less the natural inflow ($q_{In}$), defines the maximum $q$, with $q = \overline{q} - q_{In}$. The operator sets $q = 0$ in the other case.

$$q = \begin{cases} \overline{q} - q_{In} & \text{for } E[\Delta_p] > \frac{1-\eta}{\eta} \cdot p \\ 0 & \text{otherwise} \end{cases} \tag{13}$$

This simple model thus shows that price arbitrage is the profitability driver of energy storages. While the realization of the price spread affects the profitability, the expectation about the price spread affects the storage operation. The price difference must not only be positive but also exceed the efficiency loss to maintain the profitability of hydro-pump storages.

# ONLINE APPENDIX

# Subsidized Renewables' Adverse Effect on Energy Storages and Carbon Pricing as a Remedy

Mario Liebensteiner[†] Adhurim Haxhimusa[‡] Fabian Naumann[§]

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[†] Friedrich-Alexander-Universität (FAU) Erlangen-Nürnberg, Chair of Energy Markets and Energy Systems Analysis, Germany, mario.liebensteiner@fau.de

[‡] University of Applied Sciences of the Grisons, Centre for Economic Policy Research, Switzerland, adhurim.haxhimusa@fhgr.ch

[§] Technische Universität Kaiserslautern, Chair of Environmental Economics, Germany, fabian.naumann@wiwi.uni-kl.de

## Table A1: Main regression results

| | Baseline model | | Price spread | | Peak vs. off-peak | |
|---|---|---|---|---|---|---|
| | (1) IV: 1st stage Price ($P$) | (2) IV: 2nd stage Profit ($\pi$) | (3) IV: 1st stage Price spread ($\Delta_p$) | (4) IV: 2nd stage Profit ($\pi$) | (3) IV: 1st stage Price (P) | (4) IV: 2nd stage Profit ($\pi$) |
| RE | -0.00105*** | | -0.000317*** | | -0.00101*** | |
| | (1.13e-05) | | (6.32e-06) | | (1.57e-05) | |
| Price | | 1,701*** | | | | 1,736*** |
| | | (44.59) | | | | (44.73) |
| Price spread | | | | 5,621*** | | |
| | | | | (143.9) | | |
| $D^{peak}$ | | | | | 0.8778** | |
| | | | | | (0.360) | |
| $RE \cdot D^{peak}$ | | | | | -5.29e-05** | |
| | | | | | (2.09e-05) | |
| Load | 0.00112*** | 1.013*** | 0.000721*** | -1.135*** | 0.00112*** | 1.345*** |
| | (2.30e-05) | (0.0844) | (1.38e-05) | (0.119) | (2.30e-05) | (0.0725) |
| Temp | -0.466*** | 405.6*** | 0.241*** | -1,743*** | -0.474*** | 540.6*** |
| | (0.0342) | (154.9) | (0.0236) | (142.3) | (0.0341) | (156.1) |
| $Temp^2$ | 0.0179*** | -30.77*** | -0.0156*** | 87.43*** | 0.0181*** | -32.07*** |
| | (0.00106) | (4.778) | (0.000752) | (4.880) | (0.00105) | (4.816) |
| $P_{Coal}$ | 1.814*** | -2,874*** | -0.177*** | 1,207*** | 1.822*** | -2,971*** |
| | (0.0811) | (408.1) | (0.0660) | (406.8) | (0.0811) | (407.8) |
| $P_{Gas}$ | -0.0653 | 17.29 | -0.143*** | 712.3*** | -0.0706* | -27.17 |
| | (0.0423) | (197.3) | (0.0366) | (231.8) | (0.0420) | (196.7) |
| $P_{CO2}$ | 1.198*** | -1,244*** | 0.265*** | -694.9** | 1.201*** | -1,188*** |
| | (0.0613) | (264.8) | (0.0446) | (287.1) | (0.0613) | (266.8) |
| Year FE | yes | yes | yes | yes | yes | yes |
| Month FE | yes | yes | yes | yes | yes | yes |
| Day-of-week FE | yes | yes | yes | yes | yes | yes |
| Hour-of-day FE | yes | yes | yes | yes | yes | yes |
| Observations | 30,592 | 30,592 | 30,592 | 30,592 | 30,592 | 30,592 |
| $R^2$ | 0.788 | 0.558 | 0.550 | 0.222 | 0.789 | 0.552 |
| First-stage F stat. | 8,612 | | 2,511 | | 2,908 | |
| Effect 10% ΔRE on $P$ | -4.90% | | | | | |
| – during 8–20h (peak) | | | | | -5.00% | |
| – during 21–7h (off-peak) | | | | | -4.75% | |
| Effect 10% ΔRE on $\pi$ | | -14.46% | | -14.46 | | -14.31% |

Notes: Standard errors in parentheses are robust to heteroskedasticity and allow for first-order serial correlation (Newey-West SE). *** $p < 1\%$, ** $p < 5\%$, * $p < 10\%$. Sample period is 2015/01/01,01h–2018/06/30,24h. Columns 1: instrumented for price by RE. Column 3: instrumented for price spread by RE. Column 5: instrumented for price by RE, D & D·RE. At the bottom of the table, we present changes in $P$ and $\pi$ for a 10% partial change in *RE*, evaluated against mean values of all variables.

## Table A2: Correlations

| | Profit | RE | Price | Load | Temp | $P_{\text{Coal}}$ | $P_{\text{Gas}}$ |
|---|---|---|---|---|---|---|---|
| RE | -0.1910 | | | | | | |
| Price | 0.6545 | -0.4059 | | | | | |
| Load | 0.3236 | 0.5211 | 0.3246 | | | | |
| Temp | -0.0291 | 0.1725 | -0.1103 | -0.1309 | | | |
| $P_{\text{Coal}}$ | 0.0951 | 0.1264 | 0.2459 | 0.1004 | -0.1085 | | |
| $P_{\text{Gas}}$ | 0.0405 | 0.0532 | 0.2102 | 0.0982 | -0.1672 | 0.3421 | |
| $P_{\text{CO2}}$ | 0.0222 | 0.1020 | 0.1059 | -0.039 | 0.0451 | 0.1550 | 0.5753 |

## Table A3: Reduced-form model

| | (1)<br>Profit ($\pi$) |
|---|---|
| RE | -1.780*** |
| | (0.0414) |
| Load | 2.915*** |
| | (0.0668) |
| Temp | -386.3** |
| | (153.8) |
| $\text{Temp}^2$ | -0.335 |
| | (4.625) |
| $P_{\text{Coal}}$ | 211.1 |
| | (408.2) |
| $P_{\text{Gas}}$ | -93.77 |
| | (196.6) |
| $P_{\text{CO2}}$ | 793.2*** |
| | (230.1) |
| Year FE | yes |
| Month FE | yes |
| Day-of-week FE | yes |
| Hour-of-day FE | yes |
| Observations | 30,592 |
| $R^2$ | 0.550 |
| Effect 10% $\Delta$RE on $\pi$ | -14.46% |

Notes: Standard errors in parentheses are robust to heteroskedasticity and allow for first-order serial correlation (Newey-West SE). *** p < 1%, ** p < 5%, * p < 10%. Sample period is 2015/01/01,01h–2018/06/30,24h.

**Table A4: Separate effects for wind and solar power**

| | (1)<br>IV: 1st stage<br>Price (*P*) | (2)<br>IV: 2nd stage<br>Profit ($\pi$) |
|---|---|---|
| wind | -0.00103*** | |
| | (1.19e-05) | |
| solar | -0.00116*** | |
| | (2.25e-05) | |
| Price | | 1,731*** |
| | | (44.68) |
| Load | 0.00112*** | 0.983*** |
| | (2.30e-05) | (0.0848) |
| Temp | -0.501*** | 447.9*** |
| | (0.0356) | (155.0) |
| $\text{Temp}^2$ | 0.0211*** | -31.54*** |
| | (0.00121) | (4.787) |
| $P_{\text{Coal}}$ | 1.844*** | -2,966*** |
| | (0.0814) | (407.7) |
| $P_{\text{Gas}}$ | -0.0782* | 37.90 |
| | (0.0423) | (197.3) |
| $P_{\text{CO2}}$ | 1.199*** | -1,295*** |
| | (0.0612) | (265.7) |
| Year FE | yes | yes |
| Month FE | yes | yes |
| Day-of-week FE | yes | yes |
| Hour-of-day FE | yes | yes |
| Observations | 30,592 | 30,592 |
| $R^2$ | 0.789 | 0.557 |
| First-stage F stat. | 4,377 | |
| Effect 10% $\Delta$wind on *P* | -3.47% | |
| Effect 10% $\Delta$solar on *P* | -1.53% | |
| Effect 10% $\Delta$wind on $\pi$ | | -10.41% |
| Effect 10% $\Delta$solar on $\pi$ | | -4.58% |

Notes: Standard errors in parentheses are robust to heteroskedasticity and allow for first-order serial correlation (Newey-West SE). *** p < 1%, ** p < 5%, * p < 10%. Sample period is 2015/01/01,01h–2018/06/30,24h. Column (2): instrumented for *P* by forecasted wind and solar infeed.

**Table A5: Inclusion of up to 24h lags**

| | (1)<br>RE lag: 1h<br>Profit ($\pi$) | (2)<br>RE lags: 1h & 24h<br>Profit ($\pi$) | (3)<br>RE lags: 1h–24h<br>Profit ($\pi$) |
|---|---|---|---|
| $\sum_{t=-24}^{t=0} RE_t$ | -1.795*** | -1.691*** | -1.252*** |
| | (0.0417) | (0.0467) | (0.0482) |
| Load | 2.869*** | 2.853*** | 2.797*** |
| | (0.0666) | (0.0673) | (0.0654) |
| Temp | -372.9** | -406.0*** | -1,114*** |
| | (153.8) | (153.4) | (153.7) |
| Temp$^2$ | -0.168 | 0.153 | 41.22*** |
| | (4.631) | (4.620) | (4.829) |
| $P_{Coal}$ | 185.4 | 231.7 | 741.0* |
| | (407.4) | (406.2) | (400.8) |
| $P_{Gas}$ | -70.17 | -61.10 | -318.9 |
| | (196.6) | (196.0) | (196.9) |
| $P_{CO2}$ | 764.4*** | 775.3*** | 893.9*** |
| | (230.2) | (229.9) | (223.9) |
| Year FE | yes | yes | yes |
| Month FE | yes | yes | yes |
| Day-of-week FE | yes | yes | yes |
| Hour-of-day FE | yes | yes | yes |
| Observations | 30,587 | 30,560 | 30,472 |
| R$^2$ | 0.550 | 0.551 | 0.584 |
| Effect 10% $\Delta$RE on $\pi$ | -14.58% | -13.74% | -10.17% |

Notes: $\sum_{t=-24}^{t=0} RE_t$ measures the composite effect as the sum over the coefficients of the contemporary and all lagged values of RE infeed. Specification (1) includes a 1h lag of RE; specification (2) includes a 1h lag and a 24h lag of RE; specification (3) includes the full series of 1h–24h lags of RE. Standard errors in parentheses are robust to heteroskedasticity and allow for first-order serial correlation (Newey-West SE). *** p < 1%, ** p < 5%, * p < 10%. Sample period is 2015/01/01,01h–2018/06/30,24h.

**Table A6: Data aggregated to daily frequency**

| | (1)<br>IV: 1st stage<br>Price ($P$) | (2)<br>IV: 2nd stage<br>Profit ($\pi$) |
|---|---|---|
| RE | -4.33e-05*** | |
| | (1.76e-06) | |
| Price | | 1,176*** |
| | | (124.8) |
| Load | 4.11e-05*** | 0.00282 |
| | (4.46e-06) | (0.0120) |
| Temp | -0.553*** | -775.5* |
| | (0.128) | (442.2) |
| $\text{Temp}^2$ | 0.0254*** | 25.50* |
| | (0.00431) | (15.24) |
| $P_{\text{Coal}}$ | 1.816*** | -1,438 |
| | (0.237) | (1,030) |
| $P_{\text{Gas}}$ | -0.0416 | 85.06 |
| | (0.129) | (571.3) |
| $P_{\text{CO2}}$ | 1.127*** | -1,063* |
| | (0.187) | (637.9) |
| Year FE | yes | yes |
| Month FE | yes | yes |
| Day-of-week FE | yes | yes |
| Hour-of-day FE | yes | yes |
| Observations | 1,275 | 1,275 |
| $R^2$ | 0.829 | 0.539 |
| First-stage F stat. | 2,001 | |
| Effect 10% $\Delta$RE on $P$ | -4.87% | |
| Effect 10% $\Delta$RE on $\pi$ | | -9.93% |

Notes: This regression uses data aggregated to the daily frequency. Standard errors in parentheses are robust to heteroskedasticity and allow for first-order serial correlation (i.e. one day) (Newey-West SE). *** p < 1%, ** p < 5%, * p < 10%. Sample period is 2015/01/01–2018/06/30. At the bottom of the table, we present a change in $\pi$ for a 10% partial change in $RE$, evaluated against mean values of all variables.

### Table A7: Non-constant marginal effect of RE

| | (1)<br>IV: 1st stage<br>Price ($P$) | (2)<br>IV: 2nd stage<br>Profit ($\pi$) |
|---|---|---|
| RE | -0.000783*** | |
| | (3.09e-05) | |
| $RE^2$ | -6.95e-09*** | |
| | (8.97e-10) | |
| Price | | 1,643*** |
| | | (45.87) |
| Load | 0.00112*** | 1.072*** |
| | (2.25e-05) | (0.0833) |
| Temp | -0.473*** | 325.0** |
| | (0.0334) | (155.5) |
| $Temp^2$ | 0.0174*** | -29.31*** |
| | (0.00105) | (4.785) |
| $P_{Coal}$ | 1.794*** | -2,699*** |
| | (0.0817) | (409.8) |
| $P_{Gas}$ | -0.0358 | -22.02 |
| | (0.0427) | (197.5) |
| $P_{CO2}$ | 1.149*** | -1,147*** |
| | (0.0606) | (263.5) |
| Year FE | yes | yes |
| Month FE | yes | yes |
| Day-of-week FE | yes | yes |
| Hour-of-day FE | yes | yes |
| Observations | 30,592 | 30,592 |
| $R^2$ | 0.791 | 0.560 |
| First-stage F stat. | 641 | |
| Effect 10% ΔRE on $P$ | -3.67% | |
| Effect 10% ΔRE on $\pi$ | | -10.45% |

Notes: Standard errors in parentheses are robust to heteroskedasticity and allow for first-order serial correlation (Newey-West SE). *** p < 1%, ** p < 5%, * p < 10%. Sample period is 2015/01/01,01h–2018/06/30,24h. Column (2): instrumented for $P$ by $RE$ and $RE^2$.

## Table A8: Exogeneity of RE

| | (1)<br>IV: 1st stage<br>$RE$ | (2)<br>IV: 2nd stage<br>Profit ($\pi$) |
|---|---|---|
| W | 5,982*** | |
| | (103.2) | |
| $W^2$ | -137.3*** | |
| | (11.26) | |
| S | 37.34*** | |
| | (6.528) | |
| $S^2$ | 1.274*** | |
| | (0.120) | |
| RE | | -1.573*** |
| | | (0.0452) |
| Load | 0.0420*** | 2.895*** |
| | (0.00710) | (0.0660) |
| Temp | -5.180 | -572.3*** |
| | (13.68) | (154.7) |
| $Temp^2$ | 11.03*** | 1.176 |
| | (0.510) | (4.630) |
| $P_{Coal}$ | -460.1*** | 456.3 |
| | (38.17) | (412.3) |
| $P_{Gas}$ | 244.2*** | -216.5 |
| | (20.34) | (198.4) |
| $P_{CO2}$ | -357.7*** | 890.5*** |
| | (29.17) | (230.6) |
| Year FE | yes | yes |
| Month FE | yes | yes |
| Day-of-week FE | yes | yes |
| Hour-of-day FE | yes | yes |
| Observations | 30,592 | 30,592 |
| $R^2$ | 0.890 | 0.548 |
| First-stage F stat. | 14,307 | |
| Effect 10% ΔRE on $\pi$ | | -12.77% |

Notes: Standard errors in parentheses are robust to heteroskedasticity and allow for first-order serial correlation (Newey-West SE). *** p < 1%, ** p < 5%, * p < 10%. Sample period is 2015/01/01,01h–2018/06/30,24h. Column (2): instrumented for $RE$ by wind speed ($W$), sunshine ($S$), and their squared terms.

## Table A9: Carbon price as additional instrument

| | (1)<br>IV: 1st stage<br>Price (P) | (2)<br>IV: 2nd stage<br>Profit ($\pi$) |
|---|---|---|
| RE | -0.00105*** | |
| | (1.13e-05) | |
| $P_{CO2}$ | 1.198*** | |
| | (0.0613) | |
| Price | | 1,670*** |
| | | (43.88) |
| Load | 0.00112*** | 1.078*** |
| | (2.30e-05) | (0.0800) |
| Temp | -0.466*** | 270.5* |
| | (0.0342) | (147.3) |
| $Temp^2$ | 0.0179*** | -28.29*** |
| | (0.00106) | (4.655) |
| $P_{Coal}$ | 1.814*** | -2,008*** |
| | (0.0811) | (366.8) |
| $P_{Gas}$ | -0.0653 | -479.7*** |
| | (0.0423) | (163.7) |
| Year FE | yes | yes |
| Month FE | yes | yes |
| Day-of-week FE | yes | yes |
| Hour-of-day FE | yes | yes |
| Observations | 30,592 | 30,592 |
| $R^2$ | 0.788 | 0.558 |
| First-stage F stat. | 4,359 | |
| Effect 10% $\Delta P_{CO2}$ on $P$ | 2.65% | |
| Effect 10% $\Delta P_{CO2}$ on $\pi$ | | 7.67% |

Notes: Standard errors in parentheses are robust to heteroskedasticity and allow for first-order serial correlation (Newey-West SE). *** p < 1%, ** p < 5%, * p < 10%. Sample period is 2015/01/01,01h–2018/06/30,24h. Column (2): instrumented for $P$ by $RE$ and $P_{CO2}$.

# Can Carbon Pricing Counteract Renewable Energies' Self-Cannibalization Problem?

*(Under review by Energy Economics, impact factor: 9.252)*

Mario Liebensteiner* Fabian Naumann†

**Abstract:** Support payments for renewable energies (RE) are a key climate-change policy in many jurisdictions globally. However, RE feed-in lowers the wholesale electricity price, thus cannibalizing their own market values. Despite steep cost degression, self-cannibalization endangers the hopes that RE may eventually survive in the market independently from subsidies. We apply a flexible econometric model to quantify the self-cannibalization effect together with influential factors that may counteract the problem. Our data are for the German electricity market, which is characterized by a high and increasing share of intermittent RE. We show that wind and solar infeed significantly cannibalize their own market values and that a meaningful carbon price can substantially counteract this problem. Thus, market-based climate policy may significantly boost RE's integration. This is also relevant for other countries' climate agendas. However, once power generation is fully decarbonized, support from carbon pricing will lapse and the design of the energy market will need to be reconsidered.

**Keywords:** Carbon price; Cannibalization effect; Merit-order effect; Renewable energy; Market values

**JEL Classification:** D4, H2, Q4, Q5

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*Friedrich-Alexander-Universität Erlangen-Nürnberg (FAU), Lange Gasse 20, 90403 Nuremberg, Germany, mario.liebensteiner@fau.de

†Technische Universität Kaiserslautern, Gottlieb-Daimler-Str., 42, 67663 Kaiserslautern, Germany, fabian.naumann@wiwi.uni-kl.de

# 1 Introduction

Renewable energies (RE) are essential to decarbonize energy systems around the globe. The Intergovernmental Panel on Climate Change estimates that a global RE share of more than 70% is needed to limit global warming to 1.5°C (IPCC, 2018). Yet, an increasing market penetration of RE reduces the wholesale price of electricity (i.e. the so called merit-order effect), thereby "cannibalizing" their own market values.[1] Regionally and temporarily correlated infeed from wind and solar power plants even aggravates this problem. This is worrisome against the hopes that RE may eventually survive in the market independently from any financial aid. If RE's market values deteriorate faster than their costs, RE's competitiveness with conventional fossil-fuelled technologies would be in danger (c.f. Lòpez Prol et al., 2021; Zipp, 2017). However, a 'meaningful' price on $CO_2$ emissions may counteract the cannibalization effect of RE, as we argue in this study. Hence, a climate policy that sets on market-based incentives to abate greenhouse-gas emissions may at the same time help integrating a vast share of RE by counteracting the cannibalization effect.

In the last two decades, Germany has experienced a severe and continuous increase in the share of RE in electricity consumption from 6.5% in 2000 to 46.6% in 2020 (see Figure 1). The main source of growth was wind, followed by solar electricity, while biomass has stagnated since 2012 and hydropower remained constant over time. Moreover, the share of RE is expected to grow much further, given the ambitious RE goals set by the German government of 80% by 2030[2] and nearly 100% by 2050[3]. This leads to the natural question of how to design and operate an electricity system dominated by intermittent renewable energy sources. One important aspect of which is whether the state has to keep on financing RE via support payments. The answer to this question depends foremost on the development of RE's levelized costs of energy (LCOE) and market values. On the one hand, RE's LCOE tend to deteriorate faster than anticipated and are expected to decrease further (López Prol and Schill, 2021; Schmidt et al., 2017), raising hopes that RE may eventually reach economic maturity and become competitive with conventional, polluting electricity generating technologies. On the other hand, RE's decline in market values thwarts their potential success, underlining the necessity for research on potential countermeasures against the self-cannibalization effect of RE.

Since about 2017, we can increasingly observe hours of RE infeed coming close to, or even

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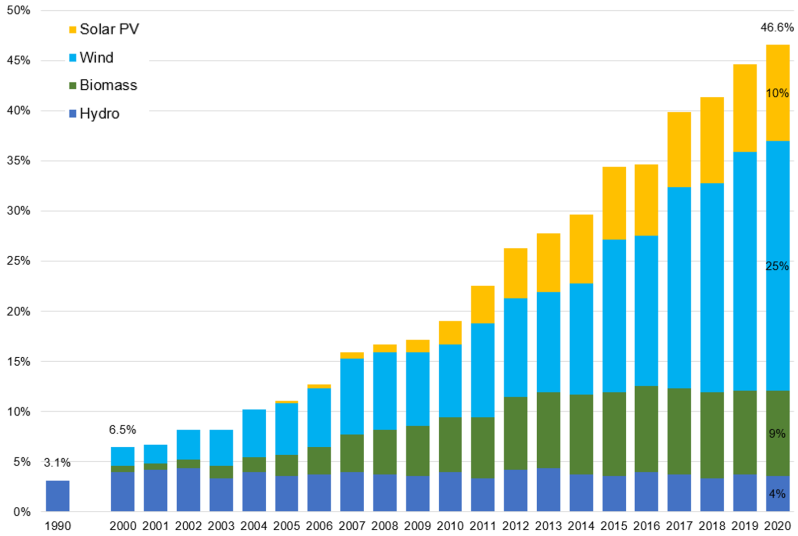
[1] The market value of an electricity production unit is determined by the revenue it can generate. The market value (or unit revenue) of a renewable power station thus depends on the correlation between resource availability (wind speed or sunshine) and electricity prices or demand in a given hour (Fell and Linn, 2013). In this study, we use the terms "market value" and "unit revenue" synonymously.

[2] www.euractiv.com/section/energy/news/new-german-coalition-aims-for-80-renewable-power-by-2030-more-gas-as-back-up/, 29 January 2022.

[3] www.bmwi-energiewende.de/EWD/Redaktion/Newsletter/2020/10/Meldung/topthema.html, 29 January 2022.

**Figure 1: RE in total gross electricity consumption, DE (%)**



Source: own calculations based on data from BMWi (2021a).

overshooting, electricity demand (see Figure 2), resulting in low to even negative electricity spot prices (see Figure 3).[4] Moreover, while the price of emission certificates in the EU Emission Trading System (EU ETS) remained low until mid of 2017 (i.e. mean of 6.29 €/tCO$_2$ during 01jan2015–30jun2017), it increased to well above 60 €/tCO$_2$ by mid of 2021 and reached a peak at almost 100 €/tCO$_2$ for the first time in February 2022. These peculiarities make it a relevant case for empirically investigating the self-cannibalization of RE's market values in Germany, as well as how carbon pricing may help alleviate the problem.

This study uses an ex-post econometric analysis of high-frequency data from Germany on electricity spot prices and day-ahead forecasts of RE infeed volumes, together with a set of control variables (e.g. infeed from conventional electricity technologies, load, input prices, net imports, and seasonality fixed effects) to assess the self-cannibalization effect of wind and solar power. Following Lòpez Prol et al. (2021), we calculate daily market values from hourly data. Importantly, we also collected data on the EU ETS emissions allowance price, as to test its impact on the market values of RE. We employ a highly flexible model to estimate non-linear impacts. Econometric identification comes from the exogeneity of wind and solar electricity production, which is determined by weather. This way, our estimates can be interpreted as causal effects. We find economically pronounced results. An increase in wind and solar electricity decreases their respective market values, although the effect is concave (diminishing) for solar, but convex (intensifying) for wind. Noteworthy in this regard, the average daily infeed from wind (284 GWh per day) is almost three

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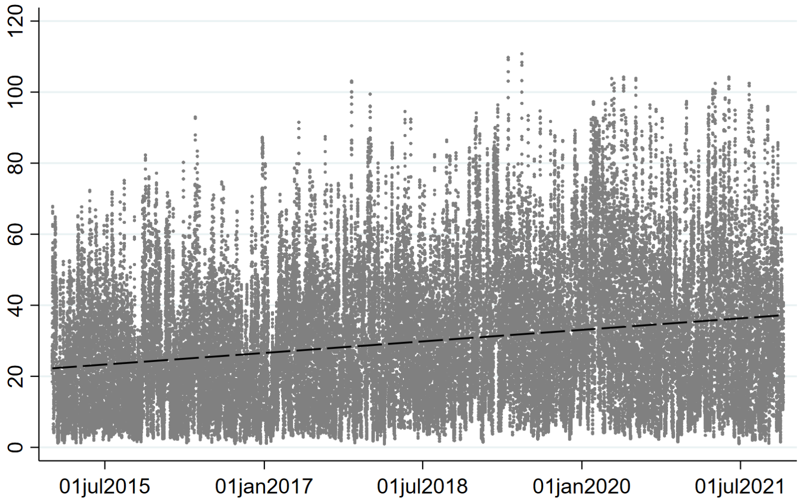
[4] Negative prices are a consequence of some types of conventional power plants, which are willing to accept negative bids to meet their production restrictions (e.g., must-run, ramping, and cycling constraints) during high RE infeed.

**Figure 2: Share of wind and solar in total electricity consumption, hourly (%)**

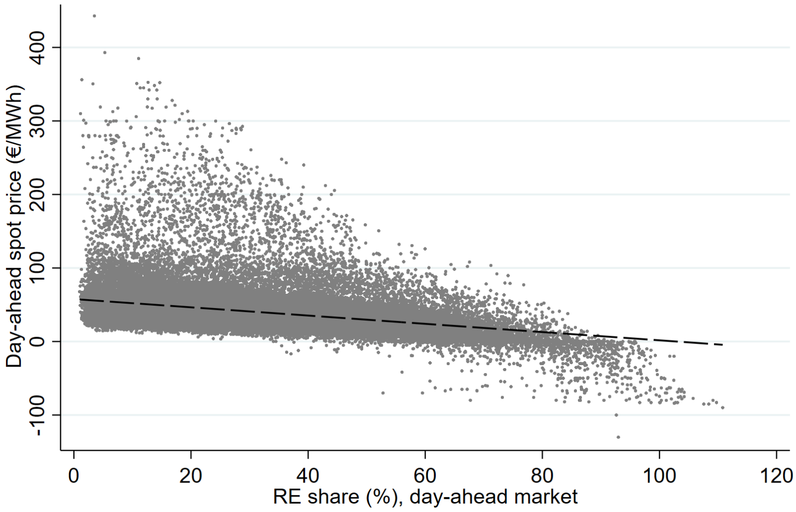


The graph visualizes the hourly shares of electricity infeed from wind and solar power in electricity consumption in Germany's day-ahead market. Shares greater than 100% are possible during hours of high solar radiation and high wind speed and imply exports to other countries.

times larger than from solar power (107 GWh). In contrast to the negative impact of RE, we find a pronounced positive effect of the carbon price on the market values of RE. This is evidence that carbon pricing can counteract RE's self-cannibalization effect.

Our paper complements the existing literature in several ways. (i) We provide a rich discussion about the functioning and challenges of future energy markets, which have to deal with a significant share of intermittent RE. We thus consider that RE's generation occasionally overshoots load during windy and sunny hours, followed by hours of RE supply shortages, which are to be balanced by complementing technologies. (ii) We analyze RE's self-cannibalization empirically and provide an estimate of a promising countermeasure in the form of carbon pricing, which turns out to significantly elevate the market values of RE. This is novel and has not yet been analyzed econometrically, as far as we know. In this respect, we also address claims that more research is needed on RE pathways after support is phased out (Melliger and Chappin, 2022) and on mitigation measures to the cannibalization effect of RE (Lòpez Prol et al., 2021). (iii) To the best of our knowledge, this is the first study on RE's market values or wholesale price effects utilizing data on high carbon prices (up to around 50 €/$tCO_2$ during our sample period; see Figure 5). This may be because the EU emissions allowance price only started to increase in 2018 and reached a level of well above 40 €/$tCO_2$ not before 2021. Moreover, with few exemptions (e.g. Britain's carbon tax for the power sector, c.f. Gugler et al., 2021, or Sweden's carbon tax, mostly for the mobility sector, c.f. Andersson, 2019) such high carbon prices could not be observed outside Europe. (iv) We extend existing econometric studies on the market value of RE by applying a highly

**Figure 3: Electricity spot price & RE share**



The graph visualizes the hourly day-ahead spot price of electricity against the hourly share of electricity infeed from wind and solar power in electricity consumption. RE shares greater than 100% are possible during hours of high solar radiation and high wind speed and imply exports to other countries.

flexible econometric model, allowing to estimate non-linear impacts through higher-order terms and variable interactions. To the best of our knowledge, no other study has used such a flexible model to assess the self-cannibalization of RE, although it seems natural that non-linearities and interaction effects may play an important role. (v) This study uses recent data from Germany, which advanced to one of the world's leading countries in terms of wind and solar electricity[5], with an increasing number of hours where RE infeed overshoots load (see Figure 2). This makes it a relevant case for investigation, with policy implications for other countries, with ambitious RE targets. In contrast, other related econometric studies employ older data and from regions characterized by significantly lower shares of wind and solar electricity (e.g. Lòpez Prol et al., 2021, for California during 01/2013–06/2017; Clo et al., 2015, for Italy during 01/2008–10/2013; Zipp, 2017, for Germany/Austria during 01/2011–12/2013). (vi) Finally, we add on the debate on market-based climate policy versus other measures (e.g. command-and-control instruments or subsidies) (see, e.g., Hepburn et al., 2020; Rosenbloom et al., 2020; Patt and Lilliestam, 2018) and derive several policy conclusions, which are also informative for other countries, as to guide the global decarbonization transition of the power sector based on empirical evidence.

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[5] According to Ember – a climate charity (formerly known as Sandbag) – Germany ranks fourth (behind Denmark, Uruguay, and Ireland) among the countries with the highest percentages of wind and solar in electricity production in 2020: https://ember-climate.org/commentary/2021/07/08/top-15-wind-and-solar-power-countries-in-2020/, 20 January 2022.

# 2 Background

## 2.1 Self-cannibalization

The two most promising forms of RE, wind and solar power, create challenges via their weather-dependent output intermittency. This bears two consequences, which are often discussed as drawbacks of RE. Firstly, the 'merit-order effect' states that, for a given installed RE capacity, whenever the sun shines or the wind blows, RE infeed depresses the wholesale price of electricity. As a result, RE infeed pushes some marginal technologies (e.g. gas-fired plants) out of merit (i.e. the extensive-margin effect) and decreases the variable profits for all other technologies in the market (i.e. the intensive-margin effect) due to a lower wholesale electricity price. Secondly, wind and solar electricity follow generation profiles dependent on the weather. These generation profiles determine their revenues according to the capture prices (i.e. the value that owners of renewable power sell their electricity at). A solar plant, for example, generates predominantly during peak hours,[6] implying that its capture prices are above the daily average wholesale spot price. Intuitively, how wholesale electricity prices develop during daytime matters for the owner of a solar power station, whereas price developments during nighttime are irrelevant. In contrast to solar, wind's generation profile is rather flat across the hours of the day in Germany. As more wind and solar capacity is added over time, the wholesale prices will deteriorate according to the generation profiles of RE. Hence, the fact that sunshine and wind are geographically clustered, implies that sunshine or wind decrease the market value of *all* solar or wind production units at the same time. This is coined as the 'cannibalization effect'.

In light of the ongoing debate about whether a high average RE share in the electricity production mix (e.g. 80% per year or more) can sustain in an energy system without having to rely on any subsidy payments, the self-cannibalization effect may be viewed as a focal problem that deserves the attention of policy makers and academic scholars.

## 2.2 Support measures for RE

Despite near-zero marginal costs, wind and solar power have initially relatively high fixed costs (per unit of capacity), hampering their competitiveness with other conventional electricity generation technologies, such as nuclear, gas, or coal power stations. Thus, the preponderance of states in Europe, the U.S., and elsewhere have been granting financial support payments (e.g. guaranteed feed-in tariffs, feed-in premia, support for RE capacity investments) or tax credits (often

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[6] In Germany and Central Europe, the hours from 8am until 8pm are typically considered peak hours. Solar power's infeed profile overlaps well with this period, reaching a peak at around noon.

in combination with renewable portfolio standards) in order to push the market penetration of RE. The economic justification for RE subsidies goes back to the infant-industry argument (e.g., Sunderasan, 2011), stating that early-stage technology adoption needs supportive measures to allow for the realization of cost reductions through learning by doing (Lòpez Prol et al., 2021; Reichenbach and Requate, 2012), optimization of production processes (Jankowska et al., 2021), R&D, and technological advancement (Newell et al., 1999; Fischer and Newell, 2008). Although steep learning curves have already drastically reduced the LCOE of various renewable technologies (Melliger and Chappin, 2022; IRENA, 2020), conventional technologies still dominate the global power provision. Once an RE technology matures and achieves competitiveness, subsidies should be cut back (Reichenbach and Requate, 2012; Melliger and Chappin, 2022). However, it is worth mentioning that many fossil fuels also still enjoy generous subsidy payments (IRENA, 2020), for which economic theory does not offer any justification and which represent another obstacle against the competitiveness of RE (Timperley, 2021). It is thus necessary to eliminate market distortions that support fossil fuels.

Nevertheless, there is a high-level debate among economists and policy-makers whether RE can, in principle, achieve technological maturity and become profitable without having to rely on any financial aid (e.g., Held et al., 2019). In this regard, it is often claimed that over time and with further cost savings of RE, market-based measures should become more prevalent (e.g., IRENA, 2021). Market-based measures are, according to theory, more cost efficient than other measures, such as subsidies or command-and-control regulations (see, e.g. Linn and Shih, 2019; Helm and Mier, 2021; Borenstein, 2012; Fell and Linn, 2013). For example, auctioning off financial support needs (e.g. feed-in premiums) for RE plants has already superseded high and non-differentiated feed-in tariffs granted during the early stages of RE deployment in the EU (EC, 2014). Moreover, the state could ensure an investor-friendly market environment, which may support private sector investment into RE, for example, via power purchase agreements (Jones and Rothenberg, 2019). However, the threat of self-cannibalization of RE may eventually thwart RE's competitiveness.

## 2.3 Carbon pricing

In the wake of climate change and its negative consequences, emissions trading schemes and carbon taxes, which represent the main types of carbon pricing, are being increasingly adopted around the world. On the road to decarbonizing the economy, carbon pricing represents an important policy option (Hepburn et al., 2020). The idea goes back to Pigou's seminal work in 1920 (Pigou, 1920). Carbon pricing aims to price the negative externality of emissions, such as $CO_2$ and other greenhouse gases (often measured in $CO_2$ equivalents), to reduce their release.

However, according to the highly influential "Report of the High-Level Commission on Carbon Pricing" (Stiglitz et al., 2017), it may require a mix of different climate policy measures, including carbon prices of at least 40-80 $\$/tCO_2$ by 2020 and 50-100 $\$/tCO_2$ by 2030 to achieve international climate targets.[7]

While the coverage of global emissions by a carbon-pricing scheme was only 15.1% in 2020, it widened to 21.5% in 2021, and the number of carbon pricing instruments expanded from 58 to 64 during this period (World Bank, 2021). In our study, emissions of German electricity producers are covered by the EU ETS – the second-largest emissions trading scheme after China's national ETS. An ETS requires electricity producers (and other firms covered) to hold an emission certificate for each ton of $CO_2$ equivalent released into the atmosphere. Hence, the price of emissions allowances increases the production costs of power plants according to their emissions intensity. This way, carbon pricing sets *market-based incentives* to all energy producers to reduce emissions. By contrast, *non-market-based approaches* may result in efficiency losses (going back to the "general theory of second best" by Lipsey and Lancaster, 1956; see also Borenstein, 2012).

Due to different $CO_2$ intensities, lignite-fired power plants are more affected by carbon pricing than hard coal plants and significantly more affected than natural gas plants. The emissions factors of lignite, hard coal and natural gas are about 0.375, 0.363, and 0.240 $tCO_2$ equivalent per MWh of electricity output (EC, 2017). Carbon pricing mainly elevates the steeper part of the merit order curve, because this is where most of the thermal plants are located. Accordingly, carbon pricing leads to a higher electricity price whenever a fossil fuelled power plant is the marginal production unit. This is why a (meaningful) carbon price increases the wholesale price of electricity and thus elevates the market value of RE.

In this regard, an increasing carbon price would not only reduce the competitiveness of fossil-fuelled power plants (gas, coal, and lignite plants) relative to RE, by elevating their marginal costs according to their emission intensities, but also counteract the cannibalization effect through increasing RE's market values. Brown and Reichenberg (2021) lay a theoretical foundation for this argument and provide simulation results. Yet, this theory has so far not been put to an empirical test using real-world data. In any case, a stronger orientation of climate policy toward market-based measures, with a particular commitment to a sufficiently high carbon price, would potentially help minimizing the fiscal burden on the grounds of efficiency, thereby strengthening public support for a green energy transition (Gugler et al., 2021).

The wholesale price of EU ETS allowances has largely remained below expectations (Böhringer, 2020) since the system was introduced in 2005, because of a surplus of allowances,

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[7] Converted into Euros, this corresponds to €36-72/$tCO_2$ by 2020 and €45-90/$tCO_2$ by 2030.

including a generous policy of crediting low-carbon investments in third countries for allowances (Ellerman and Buchner, 2007). Koch et al. (2014) also find that the economic activity and the expansion of RE partly explain the low price in the early phases of the system. To reduce the surplus of allowances and counteract undesirable effects, the system saw reforms, including banking and borrowing of allowances, back-loading of auctions, and the introduction of a Market Stability Reserve (MSR). As the EU ETS matured, the allowance price has risen sharply since 2018, almost doubling during the last months of the sample (see Figure 5).

The impact of a specific carbon price level on a particular RE technology is, nevertheless, uncertain and depends on many peculiarities, such as the generation profile of the RE technology, load, the emissions factor of the marginal technology that determines the electricity spot price, and other exogenous market circumstances. It is thus an empirical task to estimate the impact of different carbon price levels on RE's market values. Nonetheless, the carbon price will lose its supportive power for RE's market values during times of no infeed from fossil-fuelled power plants (e.g. whenever RE and other low-emission technologies, such as nuclear, generate enough electricity to displace fossil fuels).

# 3 Data

## 3.1 Market values

We calculate the market values of wind and solar power, following the established literature (Lòpez Prol et al., 2021; Clo et al., 2015; Hirth, 2016; Winkler et al., 2016), which will serve as the dependent variables in our econometric model.[8] We start with the aggregation of hourly revenues to obtain the daily revenue of each technology

$$R_{n,t} = \sum_{h=1}^{24} p_h \cdot q_{n,h}, \tag{1}$$

where $p_h$ is the day-ahead wholesale electricity price and $q_{n,h}$ is technology $n$'s forecasted electricity production. We then use the daily revenue (eq. (1)) to calculate the market value (eq. (2)), which represents the realized average revenue, weighted by actual infeed:

$$MV_{n,t} = \frac{R_{n,t}}{\sum_{h=1}^{24} q_{n,h}}, \tag{2}$$

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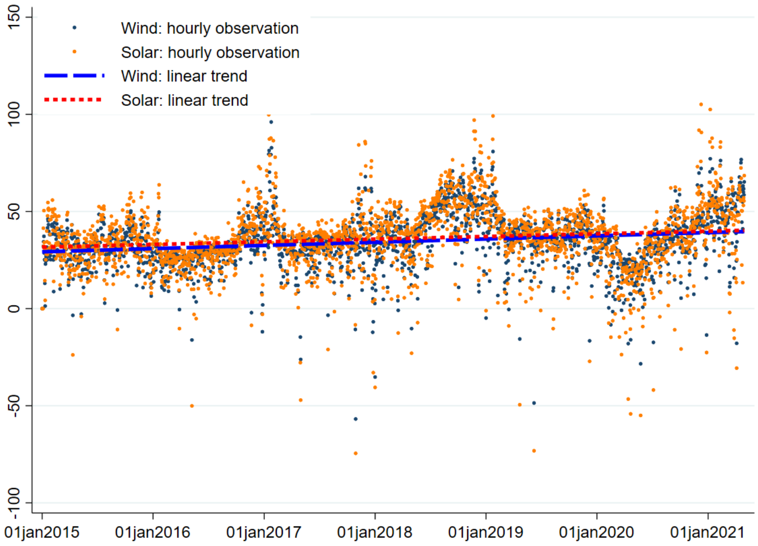
[8] In the literature, the terms "unit revenues" and "market values" are used synonymously.

## Figure 4: Market values (€/MWh)



This figure depicts hourly market values of wind and solar power in Germany and their linear trends during the sample period. This graph, however, masks potentially offsetting influential effects from other market trends (e.g. increasing carbon prices and increasing RE infeed), which our econometric analysis tries to uncover.

Figure 4 displays technology-specific market values over the sample period 01/2015-04/2021. Although the market values appear to be fairly constant (even modestly increasing) over time, the graph hides significant ceteris-paribus infuences by confounding influential factors (e.g. of changes in the carbon price, load, RE infeed, etc.), which might partly offset each other (and as our econometric analysis will uncover).

We should mention that the relevant literature applies not only market values (as an "absolute" measure), but also value factors (VF), as a "relative" measure (see, e.g. Lòpez Prol et al., 2021; Clo et al., 2015; Hirth et al., 2015; Hirth, 2016). It is calculated as the absolute market value relative to the average electricity price: $VF_{n,t} = MV_{n,t}/\bar{P_t}$), where $\bar{P_t}$ is the average electricity price ($\bar{P_t} = \sum_{h=1}^{24} p_h/24$). The idea is that the average electricity price represents the market value of a hypothetical power plant that continuously produces electricity and thus faces the electricity price at every hour. While Lòpez Prol et al. (2021), Hirth (2016) and Clo et al. (2015) include VF in their studies, we focus on market values, because such a hypothetical power plant does not exist in the energy system, and thus the comparison and interpretation of a ratio between market value and average wholesale electricity price are not meaningful for our study. Furthermore, we believe that using market values of wind and solar will allow us to make better statements about the resulting investment incentives into these technologies. According to Hirth (2016), the VF approach corrects for price fluctuations that follow business cycles. In our regression specifications, we control for these factors, using fixed effects. Therefore, we believe that absolute market value is a better measure to analyze the cannibalization effect of RE and figure out whether or not renewables can live without subsidies or other policy instruments.

### 3.2 Data sources

We use high-frequency data (i.e. hourly and daily) for the German wholesale electricity market for the period 01/2015–04/2021.[9] Hourly electricity generation and renewable production day-ahead forecasts differentiated by generation type, cross border physical flows (which we use to quantify net imports), load, and day-ahead prices are obtained from the European Network of Transmission System Operators for Electricity (ENTSO-E, 2021). Since the day-ahead electricity price is the reference price for calculating market values, we use data on day-ahead forecasts for RE generation. Please note, however, that there is an almost perfect correlation between day-ahead forecasted and actual generation of RE (wind onshore: 0.985, wind offshore: 0.952, solar: 0.994).

To control for changes in input prices, we use the Dutch TTF future price of natural gas[10] in a daily resolution, provided by the financial markets platform "investing.com". We converted the price in USD to EUR using the daily exchange rate from the European Central Bank. The daily EU ETS emissions allowance spot price in €/t$CO_2$ is obtained from the European Energy Exchange AG EEX (2021).

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[9] Our sample includes the period of the Coronavirus disease in Germany, starting mid of March 2020. This time is characterized by a collapse in economic activity and energy demand due to containment measures (Haxhimusa and Liebensteiner, 2021). We therefore present alternative estimates on the restricted sample, 2015/01/01–2020/01/31, prior to COVID-19 in Figure A2 of the Appendix. The results stay fully robust.

[10] Dutch TTF natural gas base-load future from the ICE in EUR/MWh, stated at the Intercontinental Exchange (ICE).

**Table 1: Sample statistics**

| Variable | Mean | Std. Dev. | Pctl 10 | Pctl 25 | Pctl 50 | Pctl 75 | Pctl 90 |
|---|---|---|---|---|---|---|---|
| *Dependent variable* | | | | | | | |
| Market value RE (€/MWh) | 34.50 | 14.55 | 18.14 | 26.86 | 34.18 | 42.76 | 51.83 |
| Market value wind (€/MWh) | 34.46 | 13.81 | 19.15 | 27.34 | 34.06 | 42.14 | 51.44 |
| Market value solar (€/MWh) | 36.01 | 17.27 | 17.12 | 27.63 | 35.75 | 45.34 | 55.34 |
| *Variables of Interest* | | | | | | | |
| RE infeed forecast (GWh) | 391.14 | 191.28 | 182.96 | 249.16 | 350.93 | 496.70 | 664.18 |
| Wind infeed forecast (GWh) | 284.01 | 205.99 | 73.48 | 126.53 | 225.33 | 389.07 | 598.58 |
| Solar infeed forecast (GWh) | 107.02 | 69.57 | 20.06 | 41.08 | 103.13 | 164.15 | 203.50 |
| *Control variables* | | | | | | | |
| Price of $CO_2$ (€/$tCO_2$) | 15.79 | 10.42 | 5.13 | 6.41 | 10.55 | 25.02 | 28.09 |
| Load (GWh) | 1,318.79 | 143.28 | 1,095.09 | 1,227.99 | 1,336.42 | 1,421.43 | 1,497.80 |
| Natural gas infeed (GWh) | 105.58 | 64.99 | 32.64 | 51.66 | 89.83 | 150.37 | 201.14 |
| Nuclear infeed (GWh) | 199.99 | 35.66 | 154.29 | 176.96 | 195.68 | 224.96 | 249.73 |
| Price of gas (€/MWh) | 16.39 | 4.86 | 10.24 | 13.28 | 16.49 | 19.85 | 21.98 |
| Net electricity imports (GWh) | -113.12 | 88.88 | -219.66 | -174.76 | -122.37 | -57.29 | 8.96 |
| *Underlying variables* | | | | | | | |
| Electricity spot price (€/MWh) | 35.43 | 13.85 | 20.17 | 27.89 | 34.81 | 42.91 | 52.18 |

Sample period: 2015/01/01–2021/04/30. 2,309 daily observations.

A summary of descriptive statistics of our sample is presented in Table 1. Moreover, market developments of our right-hand-side variables are depicted in Figure 5. We can see that wind infeed, and to a lesser degree solar infeed, increase, on average, over time. However, their production profiles are highly intermittent. Load varies strongly by season, but its long-term trend remains fairly constant. Net imports are highly volatile and increasing, on average. Gas generation is increasing, while nuclear generation is decreasing (due to the planned nuclear phaseout by the German government) over time. The price of gas does not follow a clear trend but varies between around 5 and 30 €/MWh. Moreover, the EU ETS allowance price in €/tCO$_2$ increased over time from well below 10 €/tCO$_2$ to almost 50 €/tCO$_2$ by the end of April 2021.

# 4 Research design

## 4.1 Identification

In this section, we discuss our econometric approach to identify the effects of wind and solar infeed and carbon pricing on the market values of wind and solar. An unbiased estimation of the effects of interest requires wind and solar infeed as well as the carbon price to be exogenous to the market values of wind and solar power, conditional on all other included control variables.

For variable RE, the exogeneity assumption is likely to hold, because weather conditions (wind speed and solar radiation) determine the feed-in levels of wind and solar power installations. Moreover, wind and solar electricity have zero marginal costs and can thus feed into the system before other technologies with positive marginal costs. In addition, German wind and solar installations enjoy prioritized feed-in at guaranteed tariffs, thus feeding into the system whenever possible. Thus, it is most likely that wind and solar infeed is exogenous (at least in the short run). The carbon price, on the other hand, is determined by supply and demand for emission certificates, whereas in the short run, the market values of wind and solar should not have material impact on the price level of emission allowances.

## 4.2 Simple linear model

We start our analysis with a simple linear model of market values as a function of our main variables of interest, namely the day-ahead forecasts of wind ($W$) and solar ($S$) infeed,[11] as well as the allowance price of CO$_2$-equivalent emissions ($P_{CO2}$). We also include a set of other variables

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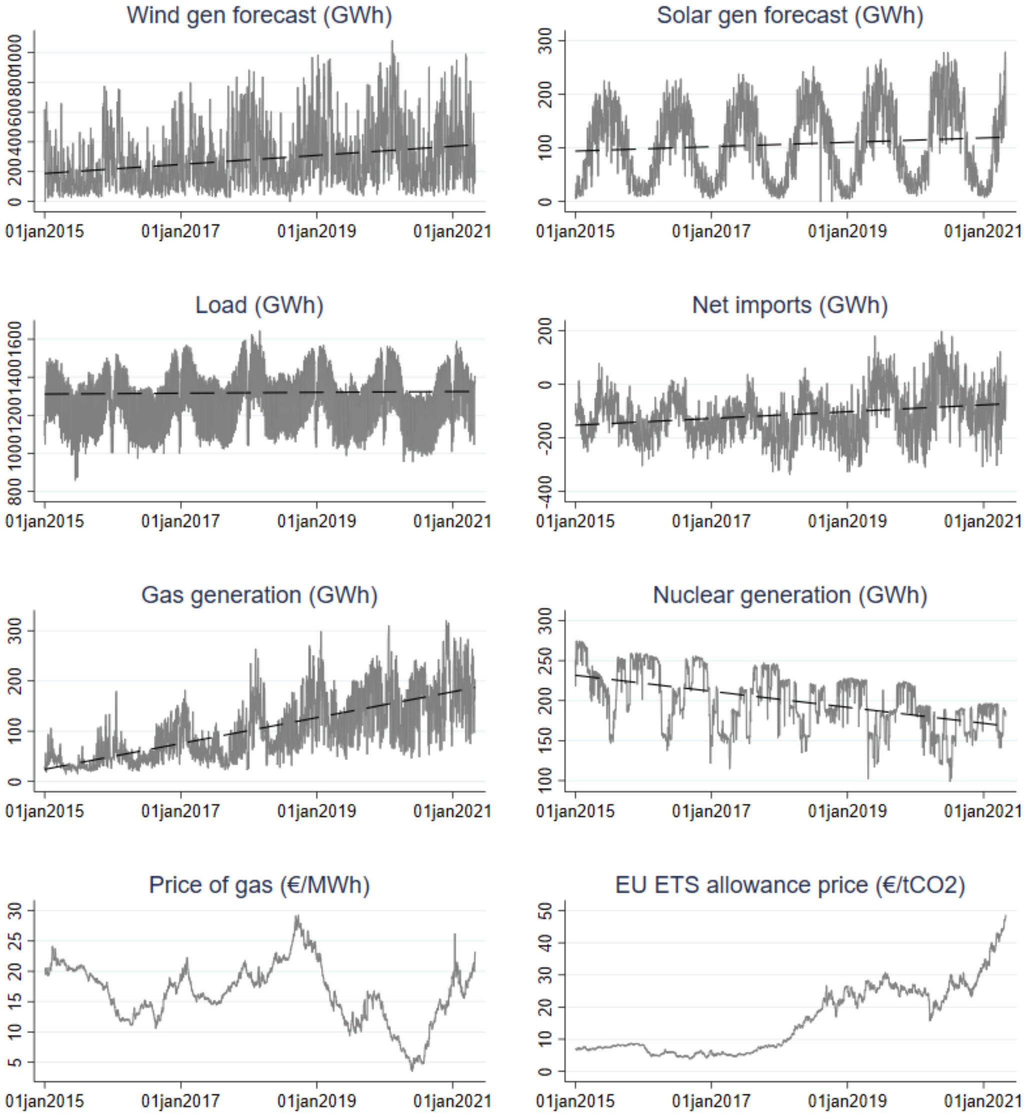
[11] We use forecasts of wind and solar infeed in units (MWh) in our model. In contrast, López Prol and Schill (2021) use relative measures, namely wind and solar infeed in percent of load. When we apply relative measures instead of units, our results stay qualitatively robust.

**Figure 5: Market developments of right-hand-side variables**



This figure depicts the developments (and linear trends) of right-hand-side variables during our sample period 2015/01/01–2021/04/30.

to control for the influence of potentially confounding effects. These variables are the load ($L$), infeed of must-run nuclear power ($Nuc$), infeed of peaking natural gas ($Gas$), the price of natural gas ($P_{gas}$), net electricity imports ($IM$), as well as fixed effects for days-of-week ($D_{dow}$), months ($D_m$), and years ($D_y$) to control for seasonality and other temporal effects.

$$\begin{aligned} MV_{n,t} = {} & \beta_W W_t + \beta_S S_t + \beta_{PCO2} P_{CO2,t} + \beta_L L_t + \beta_{Nuc} Nuc_t + \beta_{Gas} Gas_t + \\ & \beta_{Pgas} P_{gas,t} + \beta_{IM} IM_t + D_{dow} + D_m + D_y + \epsilon_t. \end{aligned} \tag{3}$$

The subscript $n$ denotes the technology ($n = wind, solar$). This means, we run two regressions for the two dependent variables $MV_W$ and $MV_S$. The subscript $t$ stands for each sample hour. $\epsilon$ is a heteroscedasticity and first-order autocorrelation consistent error term.

This simple model delivers first evidence, which is easily interpretable, because the coefficient estimates directly represent marginal effects. For instance, the estimate of $\hat{\beta}_W$ tells us by how much (in €/MWh) the market values of wind ($MV_{W,t}$) and solar ($MV_{S,t}$) would change for a marginal increase in the day-ahead forecast of wind infeed ($W$) by one MGWh per day. The drawback is that this simple model only estimates constant linear relationships, thus neglecting potential non-linearities or interdependencies among some of the predictor variables. Hence, we proceed by estimating a richer, more flexible model.

### 4.3 Flexible model

In a more flexible specification, we allow for interaction effects and squared terms, to allow for interdependencies and non-linear effects:

$$\begin{aligned} MV_{n,t} = {} & \beta_W W_t + \beta_{W^2} W_t^2 + \beta_S S_t + \beta_{S^2} S_t^2 + \beta_{PCO2} P_{CO2,t} + \beta_{PCO2^2} P_{CO2,t}^2 + \beta_L L_t + \\ & \beta_{L^2} L_t^2 + \beta_{Nuc} Nuc_t + \beta_{Nuc^2} Nuc_t^2 + \beta_{Gas} Gas_t + \beta_{Gas^2} Gas_t^2 + \beta_{Pgas} P_{gas,t} + \\ & \beta_{Pgas^2} P_{gas,t}^2 + \beta_{IM} IM_t + \beta_{IM^2} IM_t^2 + \beta_{WS} W_t \cdot S_t + \beta_{W \cdot PCO2} W_t \cdot P_{CO2,t} + \\ & \beta_{WL} W_t \cdot L_t + \beta_{S \cdot PCO2} S_t \cdot P_{CO2,t} + \beta_{SL} S_t \cdot L_t + \beta_{PCO2 \cdot L} P_{CO2,t} \cdot L_t + \\ & D_{dow} + D_m + D_y + \epsilon_t. \end{aligned} \tag{4}$$

This flexible model is an extension of related studies (e.g. Lòpez Prol et al., 2021; Clo et al., 2015; Welisch et al., 2016) estimating the effect of RE on market values in more simplistic models (similar our simple linear model presented in Section 4.2).[12]

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[12] We also run a model, which estimates the compound effect of of how RE infeed ($RE$, i.e. wind plus solar infeed) impacts the market value of compound RE: $MV_{RE,t} = \beta_{RE} RE_t + \beta_{RE^2} RE_t^2 + \beta_{PCO2} P_{CO2,t} + \beta_{PCO2^2} P_{CO2,t}^2 + \beta_L L_t + \beta_{L^2} L_t^2 +$

From this model's estimates, we can calculate non-linear predictions of RE's market values for ceteris-paribus changes in variables of interest, $x$ (e.g. forecasted wind and solar infeed or carbon price): $\partial\widehat{MV}_n/\partial x$. For example, the predicted market values of wind with respect to a change in wind feed-in would be $\partial\widehat{MV}_W/\partial W = \hat{\beta}_W + 2\cdot\hat{\beta}_{W^2}\cdot W + \hat{\beta}_{WS}\cdot\bar{S} + \hat{\beta}_{W\cdot PCO2}\cdot\bar{P}_{CO2} + \hat{\beta}_{WL}\cdot\bar{L}$, where bars over variables indicate their sample means. The predicted values can then be assessed for any wind infeed level $W$ (see Figure 6).

## 5 Results

### Simple linear models

Table 2 shows the regression estimates concerning the market values of wind and solar electricity ($MV_W, MV_S$). Columns (1) and (2) provide estimates from our simple linear model, for which the coefficient estimates can be interpreted as constant marginal effects. In both models, the coefficient estimates on wind and solar are negative and statistically significant, implying that a marginal increase in wind or solar, ceteris paribus, decreases the market values of wind and solar, whereas their magnitudes differ quite substantially.

Looking at specification (1), the cannibalization effect on wind is more pronounced with wind infeed than with solar infeed (the coefficients are statistically significantly different at the 1% level). A marginal change in wind or solar electricity by one GWh decreases the unit revenue of wind by 0.045 €/MWh or 0.033 €/MWh, respectively. We can also calculate an elasticity: Evaluated at sample means (see 1), an increase in wind or solar infeed by 10% (i.e. 28.4 GWh or 10.7 GWh, respectively), decreases the market values of wind or solar by 3.7% ($= -0.045\cdot 28.4/34.46$) or 0.98% ($= -0.033\cdot 10.7/36.01$), respectively. Specification (2) shows that the market value of solar electricity gets also significantly cannibalized with increasing wind and solar penetration. A marginal change in wind or solar infeed by one MWh decreases the market value of solar power by 0.049 €/MWh or 0.092 €/MWh, respectively. The elasticities for sample means are -4.0% ($= -0.049\cdot 28.4/34.46$) or -2.7% ($= -0.092\cdot 10.7/36.01$), respectively. In conclusion, this is evidence that wind and solar power cannibalize their own market values.

Importantly, in both specifications (1) and (2), we find that a marginal change in the carbon price increases the market values of wind and solar electricity. An increase in the carbon price by one €/tCO$_2$ increases the market values of wind by 0.90 €/MWh and that of solar by 0.83 €/MWh – an economically pronounced effect. Hence, the estimates from the simple linear models corroborate

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$\beta_{Nuc}Nuc_t + \beta_{Nuc^2}Nuc_t^2 + \beta_{Gas}Gas_t + \beta_{Gas^2}Gas_t^2 + \beta_{Pgas}P_{gas,t} + \beta_{Pgas^2}P_{gas,t}^2 + \beta_{IM}IM_t + \beta_{IM^2}IM_t^2 + \beta_{RE\cdot PCO2}RE_t\cdot P_{CO2,t} + \beta_{RE\cdot L}RE_t\cdot L_t + \beta_{PCO2\cdot L}P_{CO2,t}\cdot L_t + D_{dow} + D_m + D_y + \epsilon_t$. (5)

### Table 2: Main regression results: market values of wind and solar

| | (1)<br>Simple linear models | (2) | (3)<br>Flexible models | (4) |
|---|---|---|---|---|
| | $MV_W$ | $MV_S$ | $MV_W$ | $MV_S$ |
| W | -0.04515*** | -0.04924*** | -0.12566*** | -0.11330*** |
| | (0.00186) | (0.00232) | (0.01258) | (0.01810) |
| S | -0.03299*** | -0.09219*** | -0.13850*** | -0.31357*** |
| | (0.00387) | (0.00545) | (0.02864) | (0.04806) |
| $P_{CO2}$ | 0.90241*** | 0.82864*** | 1.48600*** | 1.72050*** |
| | (0.06600) | (0.09030) | (0.27012) | (0.37689) |
| L | 0.04323*** | 0.05279*** | 0.02486 | 0.03734 |
| | (0.00349) | (0.00459) | (0.02041) | (0.03204) |
| Gas | 0.02539*** | 0.03719*** | 0.09671*** | 0.12532*** |
| | (0.00614) | (0.00833) | (0.01503) | (0.02288) |
| Nuc | -0.02297*** | -0.02374** | 0.11496** | 0.21964*** |
| | (0.00723) | (0.00955) | (0.05504) | (0.07735) |
| $P_{gas}$ | 0.96081*** | 1.14313*** | 0.95827*** | 1.07024*** |
| | (0.07058) | (0.08766) | (0.20651) | (0.29320) |
| IM | -0.01515*** | -0.00429 | -0.02647*** | -0.02575*** |
| | (0.00331) | (0.00450) | (0.00353) | (0.00514) |
| $W \cdot W$ | | | -0.00002*** | -0.00002*** |
| | | | (0.00000) | (0.00001) |
| $S \cdot S$ | | | 0.00006* | 0.00031*** |
| | | | (0.00004) | (0.00006) |
| $P_{CO2} \cdot P_{CO2}$ | | | -0.01412*** | -0.02097*** |
| | | | (0.00343) | (0.00454) |
| $W \cdot S$ | | | -0.00000 | -0.00008** |
| | | | (0.00002) | (0.00003) |
| $W \cdot P_{CO2}$ | | | 0.00007 | 0.00021 |
| | | | (0.00015) | (0.00021) |
| $S \cdot P_{CO2}$ | | | 0.00089*** | 0.00061 |
| | | | (0.00029) | (0.00040) |
| $L \cdot L$ | | | -0.00000 | -0.00001 |
| | | | (0.00001) | (0.00001) |
| $W \cdot L$ | | | 0.00007*** | 0.00006*** |
| | | | (0.00001) | (0.00001) |
| $S \cdot L$ | | | 0.00005*** | 0.00011*** |
| | | | (0.00002) | (0.00003) |
| $P_{CO2} \cdot L$ | | | -0.00005 | -0.00003 |
| | | | (0.00016) | (0.00023) |
| $Gas \cdot Gas$ | | | -0.00021*** | -0.00025*** |
| | | | (0.00005) | (0.00008) |
| $Nuc \cdot Nuc$ | | | -0.00037*** | -0.00065*** |
| | | | (0.00014) | (0.00020) |
| $P_{gas} \cdot P_{gas}$ | | | 0.00062 | -0.00067 |
| | | | (0.00586) | (0.00827) |
| $IM \cdot IM$ | | | -0.00002* | -0.00007*** |
| | | | (0.00001) | (0.00002) |
| FE dow, months, years | yes | yes | yes | yes |
| Observations | 2,309 | 2,309 | 2,309 | 2,309 |
| $R^2$ | 0.842 | 0.811 | 0.868 | 0.838 |
| p-value: $\beta_W = \beta_S$ | 0.00 | 0.00 | | |

Notes: Heteroscedasticity and autocorrelation consistent (Newey-West) standard errors in parentheses. *** p < 1%, ** p < 5%, * p < 10%. Sample period is 2015/01/01–2021/04/30.

our suspicion that an intensification of carbon pricing counteracts the self-cannibalization of renewables.

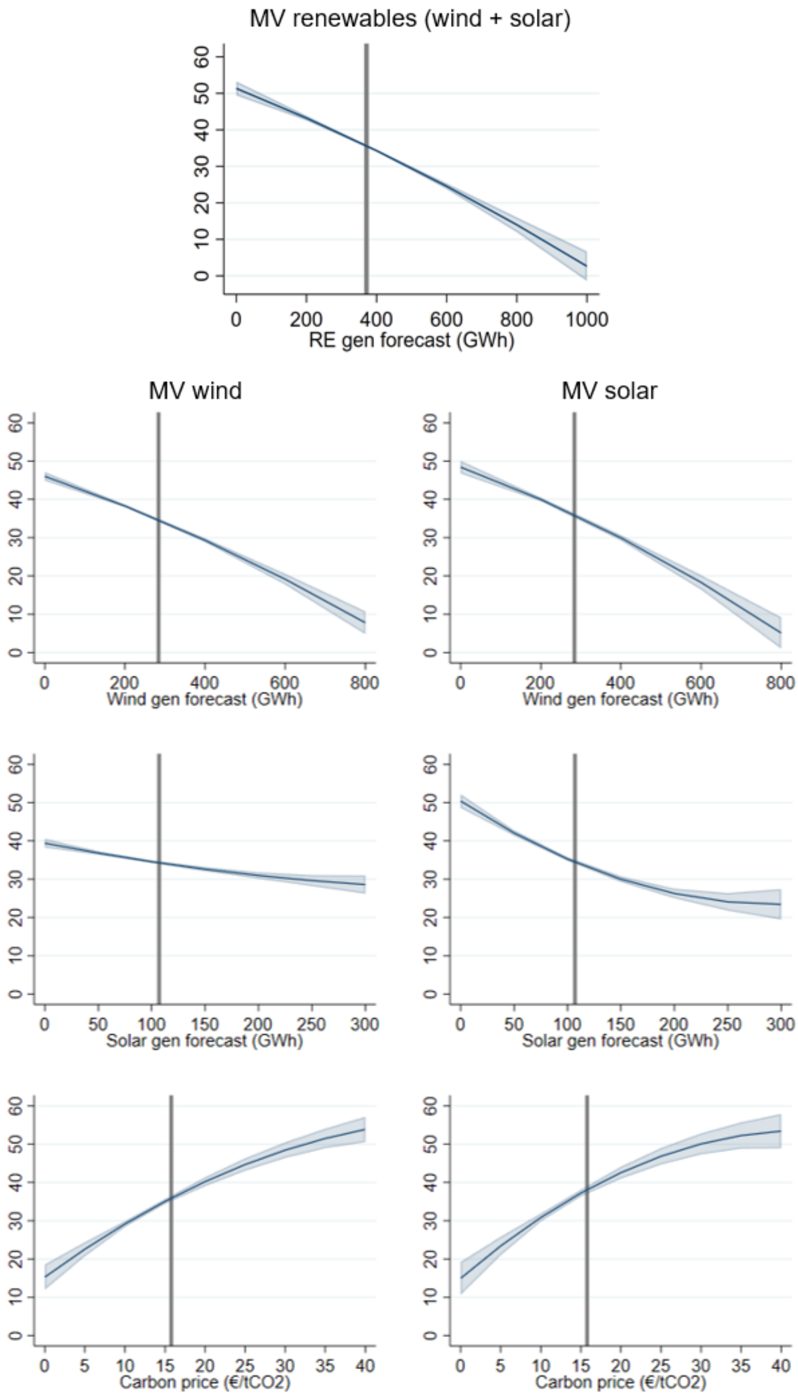
Looking at other control variables, our results in specifications (1) and (2) indicate that a higher electricity demand and a higher price of gas significantly elevate the market values of wind and solar power. The fist effect aligns well with Ruhnau (2022), who shows that an increase in flexible load (from hydrogen electrolyzers) may significantly counteract RE's self-cannibalization problem. Moreover, we expect electricity demand to increase during the next decade, because of an intensification of sector coupling (e.g. increasing e-mobility, hydrogen electrolysis, electrification of residential heating). For example, BMWi (2021b) forecasts an increase in load by 13% during 2020–2030, which may help elevate RE's market values. On the other hand, it is more difficult to predict the development of the gas price in Europe. The current "energy crisis" and the Russian invasion of Ukraine led to an explosion of gas prices for an uncertain duration. The estimates also indicate that imports decrease the market values of wind and solar power, which is not surprising, given that imports reduce the wholesale electricity price (Gugler et al., 2018).

### More flexible models

Let us now move to the more complex models (3) and (4), as presented in Table 2. These models estimate the variation in the market values of wind and solar, using a more flexible functional form, including squared and interaction terms. In this case, the coefficient estimates (see Table 2) are not readily interpretable. For this reason, Figure 6 visualizes *model predictions* of RE market values for sample values of (day-ahead forecasts of) wind and solar infeed, and the carbon price, while all other variables are held constant at their sample means. The grey vertical line indicates the sample mean of each independent variable. Appendix Figure A3 extends the analysis by showing analogously the impact of other right-hand-side variables (i.e. load, gas generation, nuclear generation, and price of gas).

For an initial overview, the top panel of Figure 6 shows the compound effect of how RE infeed (wind plus solar infeed) impacts the market value of compound RE. The effect is negative, concave, and pronounced. Holding other confounding factors constant, the market value of RE falls almost to zero for high RE infeed (1,000 GWh or more). The lower panels of Figure 6 disentangle the effects for wind and solar power. We can see that the market values of wind and solar fall with increasing infeed of wind and solar electricity. It is worth noting that solar power's penetration (with up to about 300 GWh) per day is much less pronounced than wind's (with up to more than 600 GWh per day). Especially for high levels of wind penetration in the range of 800 GWh, the market values of wind and solar electricity fall below 10 €/MWh, ceteris paribus. This means,

**Figure 6: Predicted market values of renewable energies dependent on key variables of interest (€/MWh)**



The Figure shows predicted values of market values (MV) of RE in €/MWh for ceteris-paribus changes in key variables of interest. Other variables are held constant at their sample means. Predicted values are based on regression models 3 (for wind), 4 (for solar), and 5 (for RE). Vertical lines in gray indicate the sample mean of each independent variable. The 95% confidence intervals are based on heteroscedasticity and autocorrelation consistent standard errors.

holding all other variables at their sample averages, wind and solar power installations turn economically unprofitable with high wind penetration. The negative effect on the market values of wind and solar electricity even tend to intensify with higher levels of wind infeed (indicated by the concave function), meaning that an increasing share of wind infeed tends to amplify the self-cannibalization problem.

Solar infeed is less pronounced than wind's, yet for high solar infeed levels the negative effect on the market values of wind and solar is comparable to (or even a bit more pronounced than) that of wind infeed. This is evidence that wind and solar cannibalize themselves, and that the effect is economically significant. While other empirical investigations (e.g. Lòpez Prol et al., 2021) already provided evidence supporting the theory of a self-cannibalization effect of renewables, our results are estimated from data on a significantly higher market penetration of wind and solar electricity (in Germany) and suggest that the self-cannibalization effects are indeed pronounced and non-linear. Without any political interference, variable renewable energy technologies may not survive on their own in the market.

Nonetheless, the good news for wind and solar installations is that an increasing carbon price counteracts the self-cannibalization effect. Figure 6 shows a perceptible increase in the market values of wind and solar power for an increase in the carbon price. A carbon price of 40 €/$tCo_2$ can – ceteris paribus – more than offset the negative influence of high wind infeed. However, the function is estimated to be concave, so that the positive effect of the carbon price on the market values of wind and solar tends to flatten out with carbon prices well beyond 40 €/$tCO_2$. One explanation may be that with high carbon prices, the marginal costs of fossil fuel technologies increase and thus, in the short run, get partly replaced by electricity imports from abroad. In such a scenario, the augmenting effect of higher marginal costs of fossil fuel technologies on the wholesale price of electricity would get compensated by a price-dampening effect of electricity imports (e.g. from France having a high share of cheap nuclear power).

Let us briefly discuss the influence of other right-hand-side variables on the predicted market values values, as presented in Appendix Figure A3. An increase in load significantly elevates the market values of wind and solar power. The effect turns out to be almost linear. More electricity generation from gas-fired power plants modestly increases wind and solar market values. Nuclear power generation has a modestly concave influence, thus decreasing RE market values for higher nuclear generation levels. An increase in the price of natural gas has a pronounced positive and almost linear impact on RE market values. An increase in net imports (which implies a decreasing electricity price) moderately lowers RE market values.

# 6 Discussion of countermeasures against the self-cannibalization problem

Mills and Wiser (2015) found that bulk power storage and geographic diversification of RE facilities can mitigate the self-cannibalization effect of RE. Lòpez Prol et al. (2021) argue that any measures to increase power system flexibility, such as energy storages, demand management, or geographically diverse interconnection lines, may also help mitigate the problem. Ruhnau (2022) finds that flexible load additions (e.g. from hydrogen electrolyzers) during times of low electricity prices is another countermeasure. Analogously, our models also yield that increasing electricity demand lifts the market values of renewables. Moreover, increasing input prices (e.g. the price of natural gas) result in higher market values of RE. Another important argument is that phasing out subsidy payments for fossil fuels, which are still prevalent in many countries around the globe, would create a level paying field between RE and fossil fuels (IRENA, 2021). Our finding that a carbon pricing can significantly offset the cannibalization effect, seems yet to be another promising policy measure to counteract RE's cannibalization and boost their competitiveness. This has several reasons.

First, many economists and policy makers may agree that subsidies for RE may be justified to overcome their infant-industry state. Once the RE's LCOE have fallen significantly (as may be the case already or in the near future; see, e.g. the discussion in López Prol and Schill, 2021) or once RE have reached a significant market share in a given country, it may be worthwhile to follow other market-based measures to tackle the emissions externality while at the same time meeting other second-order conditions, such as incentivizing investment in low-carbon electricity generation technologies. Hence, the introduction and intensification of carbon pricing may be a promising strategy that lives up to these goals. This is, for example, what the German Council of Economic Experts (CGEE, 2021) has recently declared as a promising avenue for Germany's near-future transition path.

Second, an increasing number of countries and regions have been adopting carbon pricing measures, either via carbon taxes or via cap-and-trade emissions certificate programs, or are planning on intensifying carbon pricing. Appendix Figure A1 visualizes carbon prices of several emission trading schemes around the globe, showing generally increasing price trends. In this respect, the EU ETS saw a drastic increase of its emissions allowances price since mid 2017, from a price as low as €5/$tCO_2$ (Haxhimusa and Liebensteiner, 2021) to currently 90 €/$tCO_2$[13] After

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[13] EUA price, as of 02 February 2022, obtained from the European Energy Exchange (EEX; https://www.eex.com/en/market-data/environmental-markets/spot-market).

Brexit and the consequent exit from the EU ETS, Great Britain has implemented an ambitious national emissions trading scheme, which currently yields higher carbon prices than the EU ETS. China's ETS has passed its three-years pilot phase by the end of 2020, and will likely see increasing allowance prices given that the emissions cap will be decreased every year. Another example is Canada's carbon tax, which is set to increase every year. As of 1 April 2021, the federal minimum tax is set at C$40 and set to be increased gradually to C$170 in 2030. It is thus reassuring that a high carbon price can significantly counteract the reduction of RE's market values for an increasing market penetration.

However the cure of carbon pricing to the self-cannibalization effect of RE has a limitation. Carbon pricing can only elevate RE's market values as long as there are $CO_2$-intensive production units in the electricity supply mix, for which the carbon price can lifts their marginal costs and consequently the spot price of electricity. Once the market is fully decarbonized (which will unlikely be the case in the near future, but at least serves as a benchmark scenario), a carbon price will ultimately have no impact on the electricity spot market any longer.

## 7 Conclusion

Many jurisdictions around the globe grant financial support payments for renewable energies in order to foster their market integration and to decarbonize the energy sector. Decreasing costs of RE have spurred the hopes that RE may eventually become economical and thus persist in the market independently of any support payments. However, RE feed into the system at zero marginal costs, and their infeed is geographically and temporarily clustered (due to weather conditions). Hence, during times of high wind and solar electricity production, wholesale electricity prices plummet, eroding RE's market values. This is coined as the "self-cannibalization effect" of renewables. It endangers the competitiveness of RE with conventional fossil power plants, undermines a potential market maturity of RE, reduces investment incentives into green technologies, and altogether may impede the energy transition.

In this study, we have investigated to what extent the market value of RE in the German energy market is affected by the cannibalization effect. As Germany is a pioneer in the field of the energy transition towards RE, this makes it a relevant case and can provide valuable lessons for other countries that seek to increase the share of renewable energy. Using a rich data set and a highly flexible econometric model, we find that the self-cannibalization effect of RE is pronounced, empirically confirming the theory of self-cannibalization. This is a concern, as it works against the intended self-sustaining survivability of RE in the market. Importantly, we provide compelling empirical evidence that carbon pricing – a first-best policy to the emissions externality according to the neoclassical economic theory – presents a promising countermeasure. We show that a carbon price of about 40 €/t$CO_2$ can, ceteris paribus, offset the self-cannibalization effect of a high RE infeed level. To the best of our knowledge, this is the first study to empirically investigate the effect of a high carbon allowance price (arising from the EU ETS) on RE's market values.

One important policy advice from this study is thus that a "sufficiently high" carbon price elevates the competitiveness of RE and may make them independent of subsidy payments. A downside of this advice is that if a state is reached in which power generation is completely decarbonized, the effect of carbon pricing will be extinguished. In such a case, the energy system will face new challenges and the market design will have to be rethought. One possible option could then be to switch from an energy-only to a capacity market.

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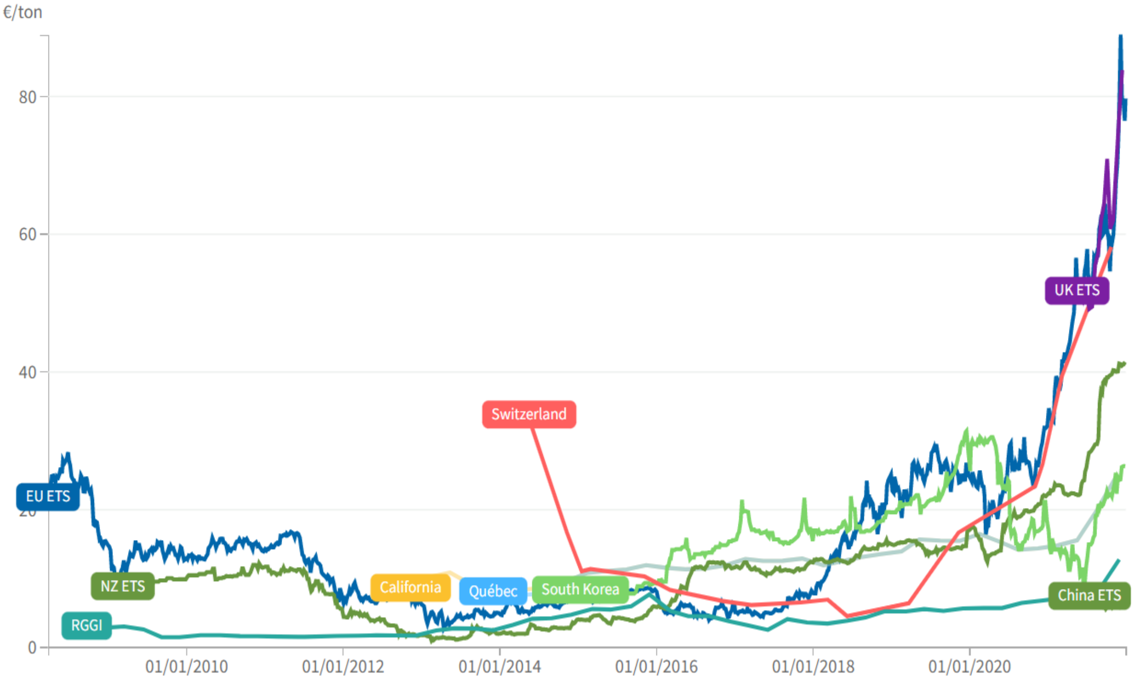
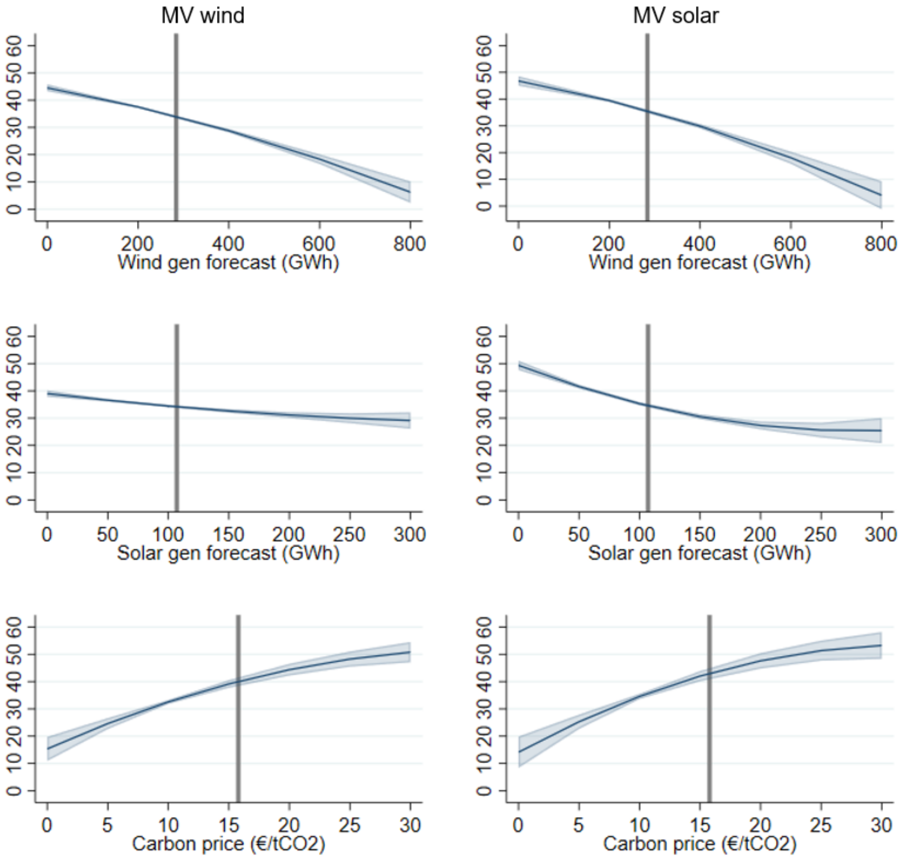
# Appendix

**Figure A1: Carbon prices from several ETSs**



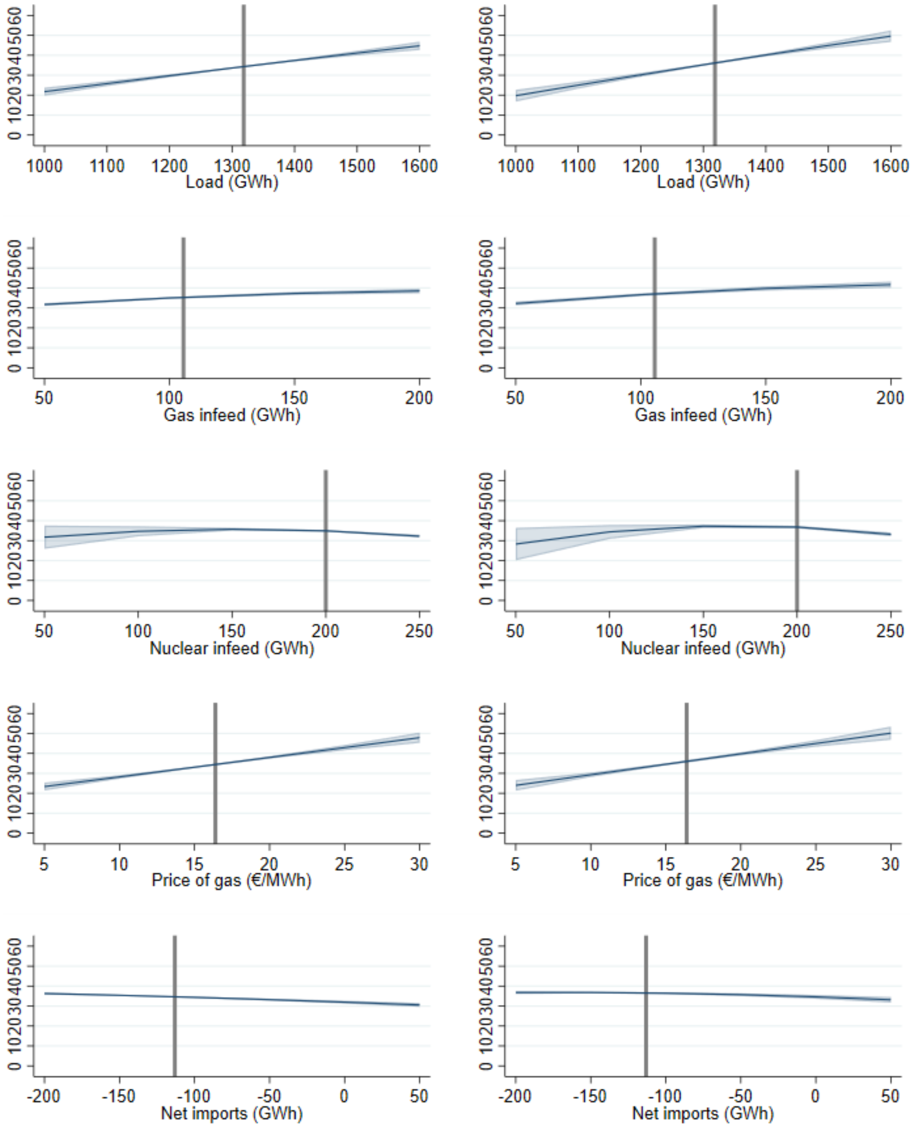
Source: screenshot of the International Carbon Action Partnership's Allowance Price Explorer; https://icapcarbonaction.com/en/ets-prices, 2 February 2022.

**Figure A2: Predicted values of market values of wind and solar (€/MWh). Restricted sample prior to COVID-19: 2015/01/01–2020/01/31**



The Figure shows predicted values of market values (MV) of wind and solar in €/MWh. Other variables are held constant at their sample means. Sample period restricted to 2015/01/01–2020/01/31. The maximum carbon price was €30/tCO$_2$, which is why we restricted the predictions accordingly. Vertical lines in gray indicate the sample mean of each independent variable. The 95% confidence intervals are based on heteroscedasticity and autocorrelation consistent standard errors.

**Figure A3: Predicted market values of renewable energies, additional right-hand-side variables (€/MWh)**



This figure extends Figure 6 by additional right-hand-side variables. The Figure shows predicted values of market values (MV) of RE in €/MWh. Other variables are held constant at their sample means. Predicted values are based on regression models 3 (for wind) and 4 (for solar). Vertical lines in gray indicate the sample mean of each independent variable. The 95% confidence intervals are based on heteroscedasticity and autocorrelation consistent standard errors.

# Unilateral Carbon Price Floor by a Country Engaged in Emissions Trading

Fabian Naumann*

**Abstract:** This paper examines if a country that is already part of an international emissions trading scheme may benefit from the additional implementation of a unilateral carbon price floor in the form of a carbon tax. Because permit prices in practice are often too weak to push real changes, unilateral policy-making to establish carbon taxes as a supplement to the cap-and-trade program has gained importance over the last years. This is closely related to the situation in the EU ETS where the United Kingdom and France imposed unilateral price floors. We provide a theoretical static two-country model with uncertainty about actual abatement costs to explain under which circumstances a unilateral price floor is desirable when the implementation of a (superior) bilateral price floor fails for political reasons. Our results indicate that a unilateral carbon price floor can indeed bring about a situation under which abatement of the domestic country exceeds the overall abatement target as under a cap-and-trade system, resulting in higher domestic welfare than in the absence of the price floor.

**Keywords:** Emissions trading schemes, Price floor, Unilateral policy, Uncertainty

**JEL Classification:** D62; H23; Q53

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*Technische Universität Kaiserslautern, fabian.naumann@wiwi.uni-kl.de

# 1 Introduction

In the presence of externalities, emissions trading has gained importance over the last two decades as a widely used policy instrument to regulate polluting industries. However, the thought is by no means new, as Pigou proposed the pricing of externalities in his famous work "*The Economics of Welfare*" in the 1920s (Pigou, 1920). As a result, the party creating the externality internalizes the external effect through government regulation. Coase (1960) demonstrates that well-defined property rights and subsequent negotiations can be one way to handle externalities. Together with the idea of tradable permits by Dales (1968), this lays the foundation of today's emissions trading systems. Moreover, Montgomery (1972) provides a mathematical foundation demonstrating that an abatement target can be achieved in a cost-efficient manner via permit trading. Its counterpart, an emissions tax, is often seen as a substitute instrument. While a quantity instrument allows for price fluctuation, the price instrument allows for quantity variation. Without uncertainties, both instruments are equally efficient, but this changes as soon as there is uncertainty (e.g., due to the curve shape of the benefit or cost function). There is a whole strand of literature that compares these instruments, pioneered by the seminal paper of Weitzman (1974), as each of these instruments has its own merits and drawbacks. Weitzman (1974) finds that a price (quantity) regulation is preferable when the benefit function has a more linear (non-linear) form[1]. Newell and Pizer (2003) go one step further and investigate this for a stock externality, analyzing the expected net benefits of a price-based and quantity-based instrument when there is cost uncertainty. They argue in favor of the price instrument and point out that integrating a price instrument into an existing quantity regulation could be beneficial.

If emissions permit prices are below expectations, the introduction of a price floor could be a policy option to counteract. Hybrid systems that integrate additional price regulation (e.g., a price floor, a price ceiling, or both) into emissions trading systems are becoming more popular and increase regulatory complexity. Nevertheless, hybrid instruments should not be seen as multiple measures (Hepburn, 2006). Price controls can strengthen abatement activities, which would otherwise also be insufficient, and set a long-term price signal for low-carbon technology investments. To create a well-functioning innovation policy, a high and durable market price for emissions that accurately reflects the external effect is a key factor (Nordhaus, 2011).

Roberts and Spence (1976) first introduced an approach that extends pollution licenses either by a subsidy or a penalty. With this hybrid system, uncertainties about the actual abatement costs are balanced by the combination of a price ceiling and a price floor. That a hybrid policy

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[1] A more linear (non-linear) form induces a relatively flat (steep) marginal benefit curve.

design may be a desirable alternative to pure price or quantity controls was shown by Pizer (2002) when purchasing additional allowances is possible at a fixed price. In addition, McKibbin and Wilcoxen (2002) argue in favor of a hybrid system to achieve efficiency under uncertainty, as they consider a pure emissions tax politically difficult to implement. Fell et al. (2012) analyze the effects of limited (soft) and unlimited (hard price collars) allowance reserve in cap and trade schemes controlling for uncertainty in baseline emissions and compliance costs. The results indicate that a more modest reserve provides the best cost and emissions control. Wood and Jotzo (2011) study possible price floor mechanisms in emission trading schemes, such as the repurchase of permit rights, an auction reserve price, and a price increase in the form of an extra fee or tax while emphasizing that the latter is an under-researched field. The authors further argue that an extra fee or extra tax on domestic emissions not only yields additional government revenues[2], but also represents the only price floor approach that has no effects on the tradability of allowances in the international trading scheme. Nonetheless, a combination of an emissions trading scheme and a price instrument does not always result in desirable effects and may undermine the price signal in the rest of the emissions market. Moreover, tighter environmental regulation in one country drives its investments into more expensive technologies compared to potential abatement technologies in countries without the additional policy (Fankhauser et al., 2010). It has been highlighted by Hoel (1991) that unilateral climate policies result in emissions leakage. As a consequence, subsequent international negotiations may result in higher emissions than without a unilateral climate policy in place. However, in our analysis, a unilateral measure supplements an existing emissions trading system.

A study that is more closely related to ours is Heindl et al. (2014), in which linking price-based and quantity-based instruments by implementing an additional tax on top of the market price is examined. Contrary to our analysis, the tax has to be paid in addition to the permit price. In times of high permit prices, this leads to an additional burden on the country that implements the unilateral tax. Wood and Jotzo (2011) argue that despite the certainty in government revenues, this is often politically undesirable and more difficult to enforce with emitters. By contrast, we apply a variable carbon tax that effectively establishes a unilateral price floor.

Our goal is to investigate if a country that is already part of an international emissions trading scheme may benefit from the additional implementation of carbon tax for its domestic firms, thereby establishing a (domestic) carbon price floor. We assume that, in order to avoid double charging, the permit price is subtracted from the price floor if the price floor is higher than the permit price so that domestic firms overall face a carbon price equal to the price floor. If the permit

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[2] For example, in times of a recession, these revenues can then be used to stimulate the economy.

price exceeds the price floor, domestic firms only pay the permit price. Even if the unilateral price floor established in this way is inferior to a uniform price floor in countries that participate in the cap-and-trade scheme, it may still be welfare-improving for the country that implements it.

This analysis is based on a static two-country model with symmetric cost uncertainty. We assume that the two countries participating in the emissions trading scheme are ex ante identical. Now, one country is introducing an additional climate policy, resulting in an asymmetry of countries. From the perspective of the social planner of one country, in the following referred to as country 1, and with regard to the resulting welfare effects, we analyze under which circumstances the implementation of a unilateral price floor is economically desirable. To the best of our knowledge, this question has not been analyzed in the literature.

We find that under uncertainty about actual abatement costs, there are situations in which additional unilateral price regulation, in the form of a price floor, is welfare-improving. A key difference to a top-up tax (Heindl et al., 2014) is that this additional burden only arises when abatement costs are overestimated and the emission price is low. In contrast, a top-up tax leads to an additional burden even in times of a high price (underestimation of abatement costs), which could then decrease the resulting welfare. When abatement costs are lower than expected, the introduction of a unilateral price floor allows to exploit cheap abatement options to some extent if the permit price is low, thereby generating additional environmental gains, that would otherwise (i.e., without the price floor) not be used. This is the case when abatement in the country that imposes the price floor exceeds the abatement target of the emissions trading system. A relatively loose emissions cap is a conceivable scenario, especially in the initial phase of an emissions trading system or when there is an allowance surplus in the market. The present paper further illustrates the interplay between emissions cap and abatement cost shock and its effect on the decision to introduce a unilateral price floor. Higher abatement cost shocks, in general, widen the range of welfare increasing unilateral price floors and supports its implementation.

The remainder of this article is organized as follows. Section 2 introduces the simple static two-country model and presents the effects of a unilateral price floor on abatements as well as the resulting emissions permit price. In Section 3, we turn to the welfare analysis to determine conditions for which the implementation of a unilateral price floor is beneficial. Finally, we present conclusions in Section 4.

## 2 Model

In our analysis, we compare the expected welfare of one of the two symmetric countries with and without a unilateral carbon price floor. In this section, we explain the underlying theoretical framework with which we conduct our analysis.

### Welfare function

We first define the welfare of a country $i \in \{1, 2\}$, which consists of three parts. First, the benefits to country $i$ of combined realized abatement are $B_i(\sum_i a_i)$. Hence, we assume that abatement activities in country 1 also have positive effects on country 2 and vice versa. Second, abatement activities in country $i$ result in respective abatement costs $C_i(a_i, \theta)$, which depend on a random cost shock variable $\theta$. Finally, the difference between received permits [3] ($\bar{e}$) and actual emissions ($e_i$) defines the quantity traded on the emissions permit market. Quantity traded multiplied with the market price for permits ($p$) generates revenues (costs) and increase (decrease) the welfare of country $i$. We assume that $\bar{e}$ (received permits per country) is an exogenous variable, whereas the market price for emissions $p$ is endogenously determined under the cap and trade system[4]. Thus, the welfare function of country $i$ reads:

$$W_i(a_i, a_{-i}) = B_i(a_i, a_{-i}) - C_i(a_i, \theta) + (\bar{e} - e_i) \cdot p, \quad for\ all\ i = 1, 2 \tag{1}$$

Realized emissions $e_i$ are the difference between emissions under "business as usual" $e_0$ and actual realized abatement $a_i$[5], resulting in the following welfare.

$$W_i(a_i, a_{-i}) = B_i(a_i, a_{-i}) - C_i(a_i, \theta) + (\bar{e} - (e_0 - a_i)) \cdot p, \quad for\ all\ i = 1, 2 \tag{2}$$

In the following subsections, we describe the components and variables of the welfare in more detail.

### Benefit and cost functions

In the literature, linear or quadratic benefit and cost functions are commonly used (e.g., Weitzman, 1974, 2014; Barrett, 1994; McGinty, 2007; Heindl et al., 2014). We assume a linear benefit function for each country depending on overall abatement $A$:

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[3] We assume that the permits are allocated equally to country 1 and 2. As a result, $2\bar{e}$ defines the overall emissions cap.

[4] A more thorough explanation will be presented in following of this section.

[5] Within the model, we allow only for positive or zero abatement activities ($a_i \geq 0$) — an emissions increase (negative abatement activities) is therefore not provided. The maximum emission level by a country is restricted to their "business as usual" emissions.

$$B_i(A) = \beta A, \quad with\ \beta > 0\ , \quad for\ all\ i = 1, 2 \tag{3}$$

The overall abatement $A$ is defined as the sum of abatement $a_i$ and $a_{-i}$ undertaken ($A = \sum_i a_i \quad , i \in \{1, 2\}$). As mentioned in the beginning, we assume that a country benefits not only from domestic but also from foreign abatement activities.

Following Weitzman (1974), we assume a quadratic and convex abatement cost function, which includes a disturbance term (random variable) $\theta$ that enters the linear part of the cost function and hits both countries equally. The random variable shifts the cost function upwards or downwards. It can either be seen as an unexpected (positive or negative) cost shock or an over- or underestimation of abatement costs. By assumption, the random variable $\theta$ has only two possible realizations, with an expected value of zero, $\mathrm{E}[\theta] = 0$.

$$\theta = \begin{cases} \overline{\theta} & \text{positive} \quad \text{with probability} \quad 0.5 \\ \\ \underline{\theta} & \text{negative} \quad \text{with probability} \quad 0.5 \end{cases} \tag{4}$$

The specification of the cost shock implies $\bar{\theta} = -\underline{\theta}$. Thus, the realized cost function reads:

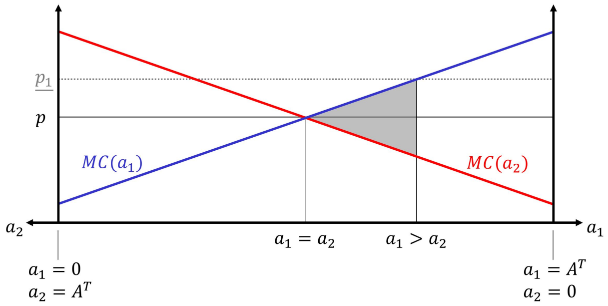
$$C_i(a_i, \theta) = (\gamma + \theta)a_i + \frac{\zeta}{2}a_i^2 \quad with\ \gamma > 0\ and\ \zeta > 0, \quad for\ all\ i = 1, 2 \tag{5}$$

The shock term $\theta$ is initially unknown to the social planner at the time when the price floor is implemented. Furthermore, we do not allow for negative marginal abatement cost so that $C_i'(a_i, \theta) \geq 0, \forall a_i$ is valid in our model. Thereby $\theta$ is restricted to $|\theta| \leq \gamma$.

**Unilateral price floor**

It has already been demonstrated by Montgomery (1972) that an emissions trading scheme delivers abatement in a cost-efficient way for a given abatement target. In optimum, resulting marginal abatement costs are equalized across participants via permit trading. As soon as a country implements an additional price regulation, such as a price floor or top-up tax, inefficiencies result. Firms in the country that implements the price floor do not only face the permit price but also the tax or fee burden. Thus, firms in that country react to the rising emissions price by increasing their abatement. As a result, permit trading does not lead to equalization of resulting marginal abatement costs anymore $MC(a_1) \neq MC(a_2)$. Figure 1 schematically illustrates the cost inefficiency that arises from a unilateral price floor in a simple framework of two symmetric countries. For a given abatement target $A^T = 2e_0 - 2\bar{e}$ implemented by the emissions trading scheme and without an additional unilateral policy implemented, the market price $p$ equalizes marginal abatement costs of both countries ($p = MC(a_1) = MC(a_2)$) – the same applies for asymmetric countries. If country 1 imposes a unilateral price floor $\underline{p_1}$, abatement in country 1 (country 2) increases (decreases) and $a_1 > a_2$, resulting in $MC(a_1) > MC(a_2)$. In doing so, the same abatement ($A^T$) is achieved at higher costs, which defines cost-inefficiency (the gray shaded area illustrates the inefficiency).[6] A bilateral price floor, however, induces $MC(a_1) = MC(a_2)$. Therefore, a unilateral price floor is never cost-efficient thus making a bilateral price floor preferable in any given case. Even if a unilateral price floor is cost inefficient for achieving an abatement target, its introduction can still be beneficial. This may be the case precisely once additional benefits are generated.

**Figure 1: Cost inefficiency of a unilateral price floor**



The graph depicts the cost inefficiency resulting from a unilateral price floor for emissions in country 1 , $\underline{p_1}$, in a setting with two symmetric countries. The horizontal axes show abatement activities in country 1 ($a_1$) and country 2 ($a_2$). The vertical axis represents marginal abatement costs in country 1 ($MC(a_1)$, blue) and country 2 ($MC(a_2)$, red). As marginal abatement costs are not harmonized under the additional regulation ($MC(a_1) > MC(a_2)$). Consequently, costs to meet the regulatory target increase which leads to cost inefficiency (gray shaded area).

Now we analyze how the implementation of a unilateral price floor affects a representative firm in country 1. A fix price floor $\underline{p_1}$ in country 1, which directly affects the emission costs (and indirectly the market price $p$), is designed as a unilateral tax in our model. If the market price $p$ falls below $\underline{p_1}$, then $p$ is subtracted from $\underline{p_1}$. Due to the unilateral price floor, the resulting emissions price in country 1, hereinafter referred to as $p_1$, can never drop below a certain value – the price floor $\underline{p_1}$. The price mechanism ensures that either the emissions market price $p$ or the price floor $\underline{p_1}$, whichever is the greater, must be paid for emissions

$$p_1 = \begin{cases} p & \text{if } p \geq \underline{p_1} \\ \underline{p_1} & \text{otherwise.} \end{cases} \tag{6}$$

---

[6] This holds for every abatement target.

We examine this model from the perspective of the social planner in the domestic country, who sets a price floor by imposing a unilateral tax. The social planner has no information about the actual value of the random abatement cost shock, and hence maximizes the *expected* welfare over the price floor. To obtain the ex ante optimal price floor, we follow Weitzman (1974) in determining the optimal price instrument.

### Abatements

Abatement activities can be derived according to the cost minimization problem of a representative price-taking firm in each country. For an emissions price, firms in both countries react by choosing their respective cost-minimizing abatement. A representative firm in country 1, which has imposed a unilateral price floor $\underline{p_1}$, minimizes its emission costs. The firm takes the emissions price $p_1$ as given and solves the following optimization problem:

$$\min_{a_1} \; p_1 \cdot (e_0 - a_1) + (\gamma + \theta) a_1 + \frac{\zeta}{2} a_1^2. \tag{7}$$

The first-order condition with respect to $a_1$ leads to the abatement level $a_1 = \frac{p_1 - \gamma - \theta}{\zeta}$. As the firm in country 1 only faces the price floor when the emissions market price $p$ is lower than the set price floor $\underline{p_1}$, the resulting abatement level is

$$a_1 = \begin{cases} 0 & \text{if } p \leq \gamma + \theta \\ \frac{p - \gamma - \theta}{\zeta} & \text{if } \underline{p_1} \leq p \\ \frac{\underline{p_1} - \gamma - \theta}{\zeta} & \text{otherwise.} \end{cases} \tag{8}$$

A representative firm in country 2 is not confronted with a price floor, but only with the emissions price and thus minimizing its emission costs accordingly, resulting in the abatement level

$$a_2 = \begin{cases} 0 & \text{if } p \leq \gamma + \theta \\ \frac{p - \gamma - \theta}{\zeta} & \text{otherwise.} \end{cases} \tag{9}$$

### Emissions market price

Throughout our analysis we assume a fully competitive emissions market and neglect transaction costs associated with permit trading. Otherwise, results could change (see, e.g., Hahn, 1984; Stavins, 1995). For an emissions market price $p$ and a price floor $\underline{p_1}$, firms in both countries react by choosing the abatement $a_1$ and $a_2$, respectively, as described above. The realization of the cost shock $\theta$ increases (decreases) abatement activities for negative (positive) values of the shock

$(\frac{\partial a_1}{\partial \theta} \leq 0$ and $\frac{\partial a_2}{\partial \theta} \leq 0)$.[7]

The market price for emissions $p$ can be determined by transforming the condition that overall emissions may not exceed the overall emissions cap, $\sum_i e_i = 2\bar{e}$, and therefore $\sum_i (e_0 - a_i) = 2\bar{e}$. We impose $p \geq 0$ throughout our analysis. Inserting the respective firms' reactions $a_1$ (Eq. (8)) and $a_2$ (Eq. (9)) and solving the equations for $p$ yields

$$p = \begin{cases} \zeta(e_0 - \bar{e}) + \gamma + \theta & \text{if } \underline{p_1} \leq \zeta(e_0 - \bar{e}) + \gamma + \theta \\ 2\zeta(e_0 - \bar{e}) - \underline{p_1} + 2\gamma + 2\theta & \text{if } \zeta(e_0 - \bar{e}) + \gamma + \theta < \underline{p_1} < 2\zeta(e_0 - \bar{e}) + \gamma + \theta \\ 0 & \text{otherwise.} \end{cases} \tag{10}$$

Figure 2 illustrates the effect of a unilateral price floor in country 1 on supply and demand of certificates on the emissions market as well as the resulting emissions price. The quantity supplied or demanded by country 1 is $Q_1 = \frac{p_1 - \gamma - \theta}{\zeta} - (e_0 - \bar{e})$ and by country 2 is $Q_2 = -\frac{p - \gamma - \theta}{\zeta} + (e_0 - \bar{e})$. The dashed line shows $Q_1 = \frac{p - \gamma - \theta}{\zeta} - (e_0 - \bar{e})$ for a unilateral price floor that is ineffective, $\underline{p_1} \leq \zeta(e_0 - \bar{e}) + \gamma + \theta$, representing the symmetric case ($Q_1 = -Q_2$). If the market price $p$ falls below the unilateral price floor $\underline{p_1}$, abatement in country 1 ($\frac{\underline{p_1} - \gamma - \theta}{\zeta}$) exceeds the abatement target $(e_0 - \bar{e})$ and thus $Q_1 = \frac{\underline{p_1} - \gamma - \theta}{\zeta} - (e_0 - \bar{e})$ becomes positive. A positive (negative) $Q_1$ indicates that country 1 is a seller (buyer) in the certificate market. For country 2 and $Q_2$, the same applies in reverse. Thus, for an effective price floor in country 1 ($\underline{p_1} > p$), the supply of permits of country 1 is $Q_1^S = \frac{\underline{p_1} - \gamma - \theta}{\zeta} - (e_0 - \bar{e})$ and the demand of country 2 is $Q_2^D = -\frac{p - \gamma - \theta}{\zeta} + (e_0 - \bar{e})$.

The supply of certificates of country 1 equals its initial endowment ($Q_1^S = \bar{e}$) if $\underline{p_1} \geq \zeta e_0 + \gamma + \theta$. For $p = \gamma + \theta$, the demand of country 2 is saturated ($Q_2^D = e_0 - \bar{e}$). This is precisely the case when $\underline{p_1} \geq 2\zeta(e_0 - \bar{e}) + \gamma + \theta$. We assume that another certificate offered by country 1 leads to a market price of zero since there is no further demand for it (see Figure 2b). Due to the resulting oversupply, companies in country 1 undercut each other until the price drops to zero. For $\bar{e} < e_0 - \bar{e}$, a unilateral price floor would never result in an oversupply. However, in our analysis we consider the case of an exogenous emissions cap, in which $\bar{e} \geq e_0 - \bar{e}$ holds, as $\bar{e} < e_0 - \bar{e}$ and consequently $\bar{e} < \frac{e_0}{2}$ would indicate a very tight emissions cap.[8] We obtain the following quantity supplied or demanded by country 1

$$Q_1 = \begin{cases} -(e_0 - \bar{e}) & \text{if } p_1 \leq \gamma + \theta \\ \frac{p_1 - \gamma - \theta}{\zeta} - (e_0 - \bar{e}) & \text{if } \gamma + \theta < p_1 < \zeta e_0 + \gamma + \theta \\ \bar{e} & \text{otherwise,} \end{cases} \tag{11}$$

---

[7] If abatement activity in country 2 is already 0, see Eq. (9), the effect of $\theta$ on abatement is also 0.

[8] $\bar{e} < \frac{e_0}{2}$ would represent an emissions trading scheme with an emissions reduction of over 50%.

and the following quantity supplied or demanded by country 2

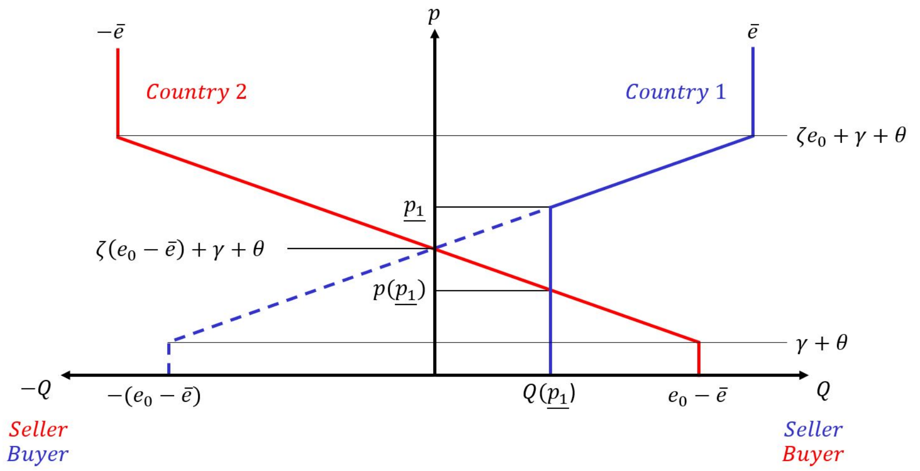
$$Q_2 = \begin{cases} e_0 - \bar{e} & \text{if } p \leq \gamma + \theta \\ (e_0 - \bar{e}) - \frac{p-\gamma-\theta}{\zeta} & \text{if } \gamma + \theta < p < \zeta e_0 + \gamma + \theta \\ -\bar{e} & \text{otherwise.} \end{cases} \tag{12}$$

Figure 3 presents the effect of a price floor on countries' abatement activities and the emissions market price for a negative (Figure 3a) and positive cost shock (Figure 3b) for an exemplary parameter setting. The market price for emissions without a unilateral price floor implemented by country 1 is $p = \zeta(e_0 - \bar{e}) + \gamma + \theta$, which indicates a critical value - in the following referred to as $CV1$. A price floor $\underline{p_1}$ less than $CV1$ would result in no price effect, as this would render the price floor ineffective (see Section 2), while the emissions market price and abatement choices both remain unchanged.

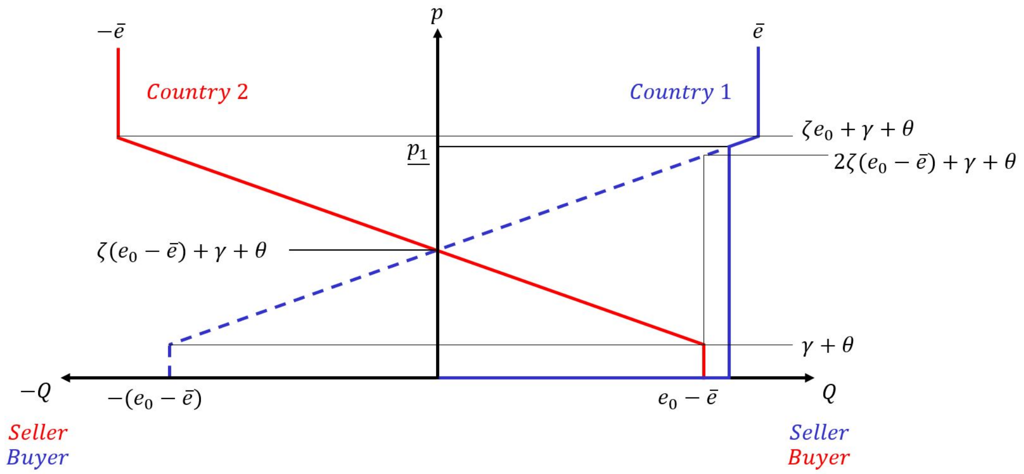
Thus, we now focus on a price floor greater than the market price for emissions, $\underline{p_1} > p$. In this case, abatement activities of country 1 depend on the level of the price floor (see Equation (8)). Equation (10) demonstrates that imposing a price floor $\underline{p_1}$ in country 1 affects the market price for emissions $p$, which in turn, influences the abatement choice in country 2, $a_2$ (Equation (9)). That is, the market price for emissions $p$ decreases as the price floor increases, $\frac{\partial p}{\partial \underline{p_1}} < 0$, for $\zeta(e_0 - \bar{e}) + \gamma + \theta < \underline{p_1} < 2\zeta(e_0 - \bar{e}) + \gamma + \theta$. As a result, the price fall reduces abatement activities in country 2 ($\frac{\partial a_2}{\partial p} > 0$, for $p > \gamma + \theta$) and leads to the so-called waterbed effect. Intuitively, for country 2 it is cost-effective to buy permit rights instead of undertaking abatement activities, as abatement activities of country 1 increase with the price floor $\frac{\partial a_1}{\partial \underline{p_1}} > 0$.

From the abatement choice of country 2 (Eq. (9)), we can conclude that for $p \leq \gamma + \theta$, abatement activities become zero. We obtain the price floor $\underline{p_1}$ for which the permit price equals or falls below $\gamma + \theta$ by solving the equation for the market price for $\underline{p_1}$. The resulting price floor, $\underline{p_1} = 2\zeta(e_0 - \bar{e}) + \gamma + \theta$, represents the next critical value - in the following referred to as $CV2$. Country 2 stops its abatement activities, $a_2 = 0$, for any price floor above this value because emissions certificates are now cheaper than any abatement activity. Inserting this critical value into the abatement decision of country 1, we obtain $a_1 = \frac{2\zeta(e_0-\bar{e})+\gamma+\theta-\gamma-\theta}{\zeta} = 2e_0 - 2\bar{e}$. We can see that country 1 is responsible for all the emissions reduction, since under cap and trade the total abatement target is defined as $2e_0 - 2\bar{e}$. If the imposed price floor is greater than this critical value, total abatement exceeds the defined abatement target and the market price for emissions drops to zero. To sum up, we obtain:

**Figure 2: Supply and demand on the emissions certificate market**



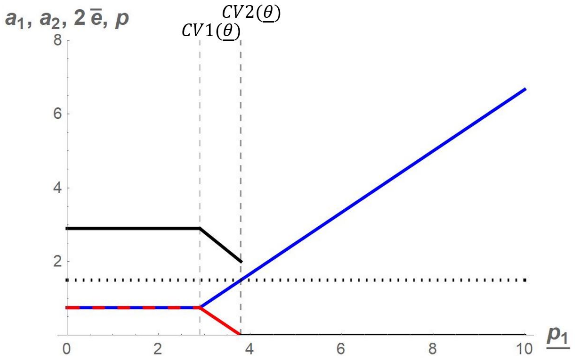
**(a) Positive emissions market price**



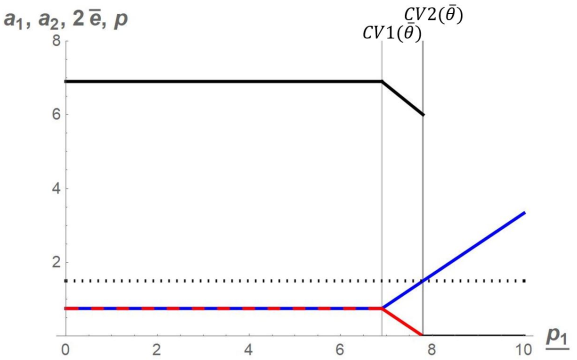
**(b) Emissions market price of zero**

The figure visualizes supply and demand of allowances on the emissions certificate market, using symmetry. The quantity of supplied or demanded permits ($Q$) is shown on the horizontal axis and the emissions market price $p$ and unilateral price floor $\underline{p_1}$ on the vertical axis. The dashed blue line represents the counterfactual scenario for country 1 in which no unilateral price floor is in place. A positive $Q$ indicates that country 1 (blue) is a seller and country 2 (red) is a buyer in the market. The same applies in reverse for a negative $Q$. For a low unilateral price floor the market price for emissions remains positive, whereas it falls to 0 for a high unilateral price floor.

**Figure 3: Effect of a unilateral price floor on abatement and the emissions market price**



**(a) Negative realization of the cost shock**



**(b) Positive realization of the cost shock**

The graph shows the ETS abatement target (dotted black), abatement in country 1 (blue) and 2 (red), and the permit price (black), depending on the unilateral price floor, for a positive and negative realization of the cost shock. This illustrates the interaction between a unilateral price floor and the effects of the cost shock. For example, a price floor may be effective if the cost shock is negative ($\underline{p_1} > CV1(\underline{\theta})$), but not if it is positive ($\underline{p_1} \leq CV1(\bar{\theta})$). The parameter settings are $\gamma = 4$, $\zeta = 1.2$, $e_0 = 10$, $\bar{e} = 9.25$, $\underline{\theta} = -2$, $\bar{\theta} = 2$.

$$\begin{aligned} CV1 &:= \zeta(e_0 - \bar{e}) + \gamma + \theta \\ CV2 &:= 2\zeta(e_0 - \bar{e}) + \gamma + \theta \end{aligned} \tag{13}$$

It holds that $CV1 < CV2$, resulting in the following effects:

1. $\underline{p_1} \leq$ CV1: The price floor is ineffective.

2. $\underline{p_1} >$ CV1: The price floor affects $a_1$ positively, $a_2$ and $p$ both negatively.

3. $\underline{p_1} \geq$ CV2: Country 2 does not abate emissions anymore ($a_2 = 0$) and country 1 is responsible for all the abatement. Now, country 1's abatement can even exceed the implemented abatement target of the cap and trade scheme ($a_1 \geq 2e_0 - 2\bar{e}$) and the emissions market price becomes zero ($p = 0$). In this case, the abatement target of the entire emissions trading system can be overachieved by country 1, thereby, generating additional environmental benefits. The actual levels of $CV1$ and

$CV2$ depend on the realization of the abatement cost shock $\theta$. In the following, we analyze how the realization of the abatement cost shock $\theta$, ceteris paribus, affects the optimality of introducing a unilateral price floor.

**Expected welfare**

By inserting the specific benefit (Eq. (3)) and cost function (Eq. (5)) into the welfare function (Eq. (2)), the welfare for country 1 reads

$$W_1 = \underbrace{\beta(a_1 + a_2)}_{\text{Benefits}} - \underbrace{(\gamma + \theta)a_1 - \frac{\zeta}{2}a_1^2}_{\text{Costs}} + \underbrace{(\bar{e} - e_0 + a_1) \cdot p}_{\text{Trading profits}}\,. \tag{14}$$

Again, the realization of the cost shock $\theta$ is initially unknown. For this reason, we specify the *expected* welfare. The *expected* welfare $\mathrm{E}[W_1]$ (Eq. (15)) consists of the realized welfare for each possible realization $\theta$ of $\theta$ multiplied with its probability of occurrence.

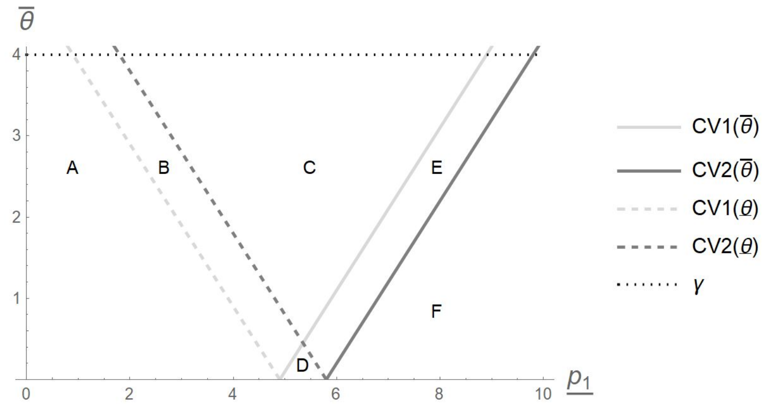
$$\mathrm{E}[W_1(\theta, \underline{p_1})] = \frac{1}{2} \cdot W_1(\theta = \bar{\theta}, \underline{p_1}) + \frac{1}{2} \cdot W_1(\theta = \underline{\theta}, \underline{p_1}) \tag{15}$$

From the perspective of the social planner of country 1, we maximize the *expected* welfare function over $\underline{p_1}$ to obtain the ex ante optimal price floor $\underline{p_1^*}$. In the following, we compare the resulting *expected* welfare of having a price floor (via the variable tax) imposed ($\mathrm{E}[W_1(\theta, \underline{p_1^*})]$) with its counter-factual scenario of having no price floor implemented ($\mathrm{E}[W_1(\theta, \underline{p_1} = 0])$). In general, a unilateral price floor is economically desirable from the perspective of the domestic social planner if, and only if, the *expected* welfare $\mathrm{E}[W_1(\theta, \underline{p_1^*})]$, with a unilateral ex ante optimal price floor $\underline{p_1^*}$, exceeds the *expected* welfare without unilateral price regulation, $\mathrm{E}[W_1(\theta, \underline{p_1} = 0)]$.

# 3 Welfare analysis

Although there are parameter realizations for which a unilateral price floor does not bring welfare improvements, in this paper we determine conditions for which a unilateral price floor is welfare-improving. To provide deeper insights into the model effects, Figure 4 presents the critical values (Eq. (13)), discussed in the Section 2, for an exemplary parameter setting in a theta-price floor diagram. The positive (solid lines) and negative realizations (dashed lines) of the random variable are illustrated in the graph. Therefore we solve the equations for the critical values for $\bar{\theta}$, using $\underline{\theta} = -\bar{\theta}$.

**Figure 4: Areas resulting from critical values**



The figure illustrates CV1 and CV2 for a positive (solid lines) and negative (dashed lines) cost shock realization and all resulting areas (Area A to F) in a $\bar{\theta}$-$\underline{p_1}$ diagram. The parameter settings are $\gamma = 4$, $\zeta = 1.2$, $e_0 = 10$, $\bar{e} = 9.25$.

| | Positive realization ($\bar{\theta}$) | Negative realization ($\underline{\theta}$) |
|---|---|---|
| CV1 | $\bar{\theta} = \underline{p_1} - \zeta(e_0 - \bar{e}) - \gamma$ | $\bar{\theta} = \zeta(e_0 - \bar{e}) + \gamma - \underline{p_1}$ |
| CV2 | $\bar{\theta} = \underline{p_1} - 2\zeta(e_0 - \bar{e}) - \gamma$ | $\bar{\theta} = 2\zeta(e_0 - \bar{e}) + \gamma - \underline{p_1}$ |

By plotting both realization possibilities in one graph, we can visualize all feasible theta-price floor combinations. Due to the restriction $|\theta| \leq \gamma$ from the cost shock definition in Section 2, realizations above the value of $\gamma$ become invalid.

Combinations of $\theta$ and $\underline{p_1}$ within **Area A** lie below $CV1(\underline{\theta})$ and $CV1(\bar{\theta})$. If the theta-price floor combination is below the CV1 for both realizations of the random variable, there is neither a unilateral price floor effect nor a welfare effect. This case equals the scenario of having no price floor implemented. Hence, abatement activities of both countries would remain unchanged by the price floor. From Section 2 we know that for $p \geq \underline{p_1}$ the resulting abatement activities are defined as $a_i = \frac{p-\gamma-\theta}{\zeta}$. Inserting the resulting price for emissions $p = \zeta(e_0 - \bar{e}) + \gamma + \theta$ into the abatement choices of countries $a$ and $b$, we obtain $a_1 = a_2 = e_0 - \bar{e}$ (emissions reductions are equalized between the countries 1 and 2). By inserting $a_1 = a_2 = e_0 - \bar{e}$ into the welfare function for country 1, we obtain the resulting welfare used for the comparative counter-factual scenario of having no unilateral price floor implemented. The welfare function for a positive realization reads

$$W_1^A(\bar{\theta}) = \beta(2e_0 - 2\bar{e}) - (\gamma + \bar{\theta})(e_0 - \bar{e}) - \frac{\zeta}{2}(e_0 - \bar{e})^2 \tag{16}$$

and for a negative realization

$$W_1^A(\underline{\theta}) = \beta(2e_0 - 2\bar{e}) - (\gamma + \underline{\theta})(e_0 - \bar{e}) - \frac{\zeta}{2}(e_0 - \bar{e})^2. \tag{17}$$

The expected welfare in Area A is thus defined as benefits minus costs (Eq. (18)), because realizations of the cost shock offset each other.

$$\mathrm{E}[W_1^A(\theta)] = \beta(2e_0 - 2\bar{e}) - \gamma(e_0 - \bar{e}) - \frac{\zeta}{2}(e_0 - \bar{e})^2 \tag{18}$$

There is no trading of emission rights between countries, as abatement is identical and equal to the national abatement target implemented by the cap and trade system ($a_1 = a_2 = e_0 - \bar{e}$). To be more precise, each country uses exactly the emissions rights received ($e_0 - a_1 = e_0 - a_2 = \bar{e}$).[9] It becomes clear that the emission cap per country $\bar{e}$ is a key parameter for the welfare level in Area A.

## 3.1 Price floor is only effective for a negative realization of the shock

A price floor is only intended to counteract a certificate price that is too low, which occurs in the event of a negative realization ($\theta = \underline{\theta}$). We focus our formal analysis on areas in which the $\underline{p_1}$-$\theta$ combinations do not exceed the $CV1(\bar{\theta})$. That is Area B and C in Figure 4. For the $\underline{p_1}$-$\theta$ combinations a positive realization of the random variable renders the price floor ineffective. It reflects the idea of a unilateral price floor that only functions as a price floor for abatement costs lower than expected (negative abatement cost shock). The unilateral price floor is not intended to completely make the emissions trading scheme obsolete, but merely to support it in the event of a negative abatement cost shock and low emissions prices through an increased price signal. While the resulting welfare for a positive realization of the random variable ($\theta = \bar{\theta}$) remains unchanged, we are interested in the welfare for a negative realization ($\theta = \underline{\theta}$). This is the main difference from a top-up tax – only in the event of a low emissions price, the additional price regulation intervenes. In contrast, a top-up tax leads to an additional burden in the country that implements it for both realization of the abatement cost shock, even if the emissions price is higher than expected (positive realization of the cost shock).

If the *expected* welfare $\mathrm{E}[W_1(\theta, \underline{p_1^*})]$ with an ex ante welfare maximizing unilateral price floor $\underline{p_1^*} > p$, exceeds the *expected* welfare without unilateral price regulation, $\mathrm{E}[W_1(\theta, \underline{p_1} = 0)]$, the unilateral price floor is economically desirable from the perspective of the domestic social planner.

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[9] In this case, the volume of traded emission rights becomes zero. Inserting $a_1 = a_2 = e_0 - \bar{e}$ and $p = \zeta(e_0 - \bar{e}) + \gamma + \theta$ into the trading part of the welfare function $(\bar{e} - e_0 + a_1) \cdot p$, we obtain $(\bar{e} - e_0 + e_0 - \bar{e}) \cdot (\zeta(e_0 - \bar{e}) + \gamma + \theta) = 0$.

**Table 1: Partial effects on the welfare in Area A**

| **Partial derivatives** | **Signs** |
|---|---|
| $\frac{\partial W_1^A(\underline{\theta})}{\partial \beta} = 2(e_0 - \bar{e})$ | $> 0$ |
| $\frac{\partial W_1^A(\underline{\theta})}{\partial \gamma} = -(e_0 - \bar{e})$ | $< 0$ |
| $\frac{\partial W_1^A(\underline{\theta})}{\partial (\underline{\theta})} = -(e_0 - \bar{e})$ | $< 0$ |
| $\frac{\partial W_1^A(\underline{\theta})}{\partial \zeta} = -\frac{1}{2}(e_0 - \bar{e})^2$ | $< 0$ |
| $\frac{\partial W_1^A(\underline{\theta})}{\partial \bar{e}} = -2\beta + \gamma + \underline{\theta} + \zeta(e_0 - \bar{e})$ | $\begin{cases} > 0 & \text{if } 2\beta < \gamma + \underline{\theta} + \zeta(e_0 - \bar{e}) \\ = 0 & \text{if } 2\beta = \gamma + \underline{\theta} + \zeta(e_0 - \bar{e}) \\ < 0 & \text{otherwise.} \end{cases}$ |

That would be the case if the welfare for a negative realization of the random variable, $\theta = \underline{\theta}$ , is greater with than without a unilateral price intervention in form of a price floor:

$$W_1(\underline{\theta}, \underline{p_1} > p) > W_1(\underline{\theta}, \underline{p_1} \leq p) = W_1^A(\underline{\theta}) \tag{19}$$

Table 1 lists partial effects of the model parameters on the welfare in Area A for a negative realization of the abatement cost shock ($\theta = \underline{\theta}$). It is quite intuitive that higher benefits from abatement ($\beta$) increase, whereas higher cost parameters ($\gamma$, $\underline{\theta}$, $\zeta$) decrease the resulting welfare. If it is beneficial to abate emissions ($2\beta > \gamma + \underline{\theta} + \zeta(e_0 - \bar{e})$) a tighter emissions cap per country $\bar{e}$ enhances welfare, as it induces higher abatement.

### Area B – constant overall abatement

As soon as the price floor exceeds $CV1(\underline{\theta})$, unilateral price regulation affects the market price for emissions $p$, abatement activities $a_1$ and $a_2$ as well as the resulting welfare. A higher price floor $\underline{p_1}$ in general leads to greater abatement activities in country 1 ($\frac{\partial a_1}{\partial \underline{p_1}} = \frac{1}{\zeta} > 0$). As a result, country 1 trades more emission rights to country 2. The market price for emissions $p$ decreases ($\frac{\partial p}{\partial \underline{p_1}} = -1 < 0$) due to an increasing supply of emission rights ($\frac{\partial(\bar{e} - e_0 + \frac{\underline{p_1} - \gamma - \underline{\theta}}{\zeta})}{\partial \underline{p_1}} = \frac{1}{\zeta} > 0$). Consequently, abatement activities in country 2 decline with the permit price ($\frac{\partial a_2}{\partial p} = \frac{1}{\zeta} > 0$). Costs for purchasing emission rights fall, to a certain extend, below the equivalent abatement costs, resulting in the waterbed effect. As abatement in country 1 increases by $\frac{1}{\zeta}$, abatement in country 2 decreases by $-\frac{1}{\zeta}$, thus offsetting each others' effects.

For a price floor $\underline{p_1}$ in Area B ($CV1(\underline{\theta}) < \underline{p_1} < CV2(\underline{\theta})$ and $\underline{p_1} \leq CV1(\bar{\theta})$), Inequality (19) in general form reads $W_1^B(\underline{\theta}, \underline{p_1}) > W_1^A(\underline{\theta})$. We obtain the following welfare function for a negative realization of the random variable which consists of benefits from abatement, abatement costs and trading profits from emissions trading:

$$\begin{aligned} W_1^B(\underline{\theta},\underline{p_1}) = & \underbrace{\beta(2e_0-\bar{E})+\frac{\delta}{2}(2e_0-\bar{E})^2}_{\text{Benefits}} \\ & \underbrace{-(\gamma+\underline{\theta})(\frac{\underline{p_1}-\gamma-\underline{\theta}}{\zeta})-\frac{\zeta}{2}(\frac{\underline{p_1}-\gamma-\underline{\theta}}{\zeta})^2}_{\text{Abatement costs}} \\ & +\underbrace{(\bar{e}-e_0+\frac{\underline{p_1}-\gamma-\underline{\theta}}{\zeta})}_{\text{Supply of emissions rights}}\cdot\underbrace{(2\zeta(e_0-\bar{e})-\underline{p_1}+2\gamma+2\underline{\theta})}_{\text{Emissions market price}}. \end{aligned} \tag{20}$$

Because benefits remain constant compared to Area A, $B_1^B(\underline{\theta}) = B_1^A(\underline{\theta})$, $\underline{p_1}$ only affects trading profits and abatement costs. Maximizing the welfare with respect to the price floor $\underline{p_1}$ leads, after rearranging, to:

$$\underline{p_1^*} = \zeta(e_0-\bar{e})+\gamma+\underline{\theta} = CV1(\underline{\theta}) \tag{21}$$

The welfare maximizing price floor $\underline{p_1^*}$ equals $CV1(\underline{\theta})$ – the emissions market price without an effective price floor – and thus represents a counter solution. In this case, the unilateral price floor is ineffective and we obtain the identical welfare (and abatement activities) as within Area A. Consequently, it can be concluded that a price floor which lies in Area B is never welfare-improving, as the welfare function is strictly concave $\frac{\partial^2 W_1^B(\underline{\theta})}{\partial \underline{p_1}^2} = -\frac{3}{\zeta} < 0$.

Intuitively speaking, the waterbed effect leads to a situation in which total abatement remains constant and marginal benefits of abatement for an increasing price floor become 0. Thus, country 1 has identical benefits from abatement as without the price floor but at higher abatement costs. The permit market price decreases from $p = MC(a_1) = MC(a_2)$ with an increasing price floor, which results in $p < MC(a_1)$. The costs of additional abatement outweigh trading profits from the sale of additional allowances to country 2. Consequently, imposing a unilateral price floor never improves welfare. This leads to Proposition 1.

**Proposition 1** *A price floor* $\underline{p_1}$ *for which* $CV1(\underline{\theta}) < \underline{p_1} < CV2(\underline{\theta})$ *and* $\underline{p_1} \leq CV1(\bar{\theta})$ *holds is never welfare-improving. Thus, the social planner in country 1 has no incentive in imposing a price floor in this scenario, which leads to* $\underline{p_1^*} = 0$. *This applies for Area B.*

### Area C – greater overall abatement

Imposing a price floor $\underline{p_1}$ in Area C ($CV2(\underline{\theta}) \leq \underline{p_1} \leq CV1(\bar{\theta})$) causes a cessation of abatement activities in country 2, $a_2 = 0$, due to a resulting market price drop. As the emissions market

**Table 2: Partial effects on the welfare in Area C**

| Partial derivatives | Signs |
|---|---|
| $\frac{\partial W_1^C(\underline{\theta},\underline{p_1})}{\partial \beta} = \frac{\underline{p_1}-\gamma-\underline{\theta}}{\zeta}$ | $> 0$ |
| $\frac{\partial W_1^C(\underline{\theta},\underline{p_1})}{\partial \gamma} = -\frac{\beta}{\zeta} + \frac{\gamma+\underline{\theta}}{\zeta}$ | $< 0$ |
| $\frac{\partial W_1^C(\underline{\theta},\underline{p_1})}{\partial \underline{\theta}} = -\frac{\beta}{\zeta} + \frac{\gamma+\underline{\theta}}{\zeta}$ | $< 0$ |
| $\frac{\partial W_1^C(\underline{\theta},\underline{p_1})}{\partial \zeta} = -\beta\frac{\underline{p_1}-\gamma-\underline{\theta}}{\zeta^2} + (\gamma+\underline{\theta})\frac{\underline{p_1}-\gamma-\underline{\theta}}{\zeta^2} + \frac{1}{2}(\frac{\underline{p_1}-\gamma-\underline{\theta}}{\zeta})^2$ | $< 0$ |
| $\frac{\partial W_1^C(\underline{\theta},\underline{p_1})}{\partial \underline{p_1}} = \frac{\beta}{\zeta} - \frac{\underline{p_1}}{\zeta}$ | $\begin{cases} > 0 & \beta > \underline{p_1} \\ = 0 & \beta = \underline{p_1} \\ < 0 & \text{otherwise.} \end{cases}$ |

price becomes zero, so do trading profits. Now, emissions reduction in country 1 can also exceed the defined abatement target via the cap and trade system $a_1 \geq 2e_0 - 2\bar{e}$.[10] This generates additional environmental gains, that would otherwise (i.e., without the price floor) not be utilized ($\frac{\partial B_1(\underline{p_1})}{\partial \underline{p_1}} > 0$). In general, a price floor only is welfare increasing if $W_1^C(\underline{\theta},\underline{p_1}) > W_1^A(\underline{\theta})$ holds. The welfare function in Area C reads:

$$W_1^C(\underline{\theta},\underline{p_1}) = \beta(\frac{\underline{p_1}-\gamma-\underline{\theta}}{\zeta}) - (\gamma+\underline{\theta})(\frac{\underline{p_1}-\gamma-\underline{\theta}}{\zeta}) - \frac{\zeta}{2}(\frac{\underline{p_1}-\gamma-\underline{\theta}}{\zeta})^2 \tag{22}$$

Table 2 presents partial effects of the model parameters on the welfare in Area C for a negative realization of the abatement cost shock ($\theta = \underline{\theta}$). As in Area A, higher benefits (costs) increase (decrease) the resulting welfare in this area. If the benefit parameter $\beta$ is greater than the unilateral price floor $\underline{p_1}$, increasing the unilateral price floor results in a higher welfare. However, an increment of the unilateral price floor $\underline{p_1}$ in case of $\beta < \underline{p_1}$ leads to a welfare reduction. It is already apparent that the welfare maximizing unilateral price floor is $\underline{p_1^*} = \beta$. In case of an interior solution, welfare maximization ($\frac{\partial W_1^C(\underline{\theta},\underline{p_1})}{\partial \underline{p_1}} \overset{!}{=} 0$) leads to

$$\underline{p_1^*} = \beta. \tag{23}$$

Inserting the welfare maximizing price floor $\underline{p_1^*} = \beta$ into the welfare function (Eq. 22) and rearranging yields

$$W_1^C(\underline{\theta},\underline{p_1^*} = \beta) = \frac{(\beta-\gamma-\underline{\theta})^2}{2\zeta}. \tag{24}$$

This leads to the following Proposition.

**Proposition 2** *If and only if the conditions* $W_1^C(\underline{\theta},\underline{p_1^*}) > W_1^A(\underline{\theta})$ *and* $CV2(\underline{\theta}) \leq \underline{p_1^*} \leq CV1(\bar{\theta})$

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[10] Inserting $\underline{p_1} \geq CV2(\underline{\theta}) = 2\zeta(e_0 - \bar{e}) + \gamma + \underline{\theta}$ into the abatement function $a_1 = \frac{\underline{p_1}-\gamma-\underline{\theta}}{\zeta}$ yields $a_1 \geq 2e_0 - 2\bar{e}$.

*hold, we obtain an interior solution. The implementation of a unilateral price floor in country 1,* $p_1^* = \beta$*, is thus welfare increasing. However, if condition* $CV2(\underline{\theta}) \leq \underline{p_1^*} \leq CV1(\bar{\theta})$ *does not hold, but* $W_1^C(\underline{\theta}, \underline{p_1}) > W_1^A(\underline{\theta})$ *holds, this results in a corner solution. In this case, if* $\beta < CV2(\underline{\theta})$*,* $\underline{p_1^*} = CV2(\underline{\theta}) = 2\zeta(e_0 - \bar{e}) + \gamma + \underline{\theta}$ *and otherwise* $\underline{p_1^*} = CV1(\bar{\theta}) = \zeta(e_0 - \bar{e}) + \gamma + \bar{\theta}$*, maximizes the welfare and results in a welfare improvement. Otherwise, a price floor in country 1 is never desirable. This leads to Equation* (25)*.*

$$p_1^* = \begin{cases} \beta & \text{if } W_1^C(\underline{\theta}, \underline{p_1} = \beta) > W_1^A(\underline{\theta}) \text{ and } CV2(\underline{\theta}) \leq \beta \leq CV1(\bar{\theta}) \\ 2\zeta(e_0 - \bar{e}) + \gamma + \underline{\theta} & \text{if } W_1^C(\underline{\theta}, \underline{p_1}) > W_1^A(\underline{\theta}) \text{ and } \beta < CV2(\underline{\theta}) \\ \zeta(e_0 - \bar{e}) + \gamma + \bar{\theta} & \text{if } W_1^C(\underline{\theta}, \underline{p_1}) > W_1^A(\underline{\theta}) \text{ and } \beta > CV1(\bar{\theta}) \\ 0 & \text{otherwise} \end{cases} \tag{25}$$

**Numerical example Area C**

Since the interpretation of results of a general analytical study of Area C is very limited due to the large number of variables and constraints, we illustrate the effects for a specific parameter setting: Benefit parameter $\beta = 5$, cost parameters $\gamma = 4$ and $\zeta = 1.2$, emissions business as usual $e_0 = 10$ and an emissions cap per country $\bar{e} = 9.25$. Thus, the cap represents an emissions reduction target of 7.5%. Also the parameter setting fulfills $W_1^A(\underline{\theta}) > 0$ and $W_1^A(\bar{\theta}) > 0$, ensuring that the implemented emissions cap is beneficial for both realizations of the cost shock. As a consequence, the emissions trading scheme initially never results in a negative welfare of a country, making the initial implementation of the joint system desirable. The parameters leads to the following benefit (Eq. (26)) and cost function (Eq. (27)).

$$B_i(A) = 5A \tag{26}$$

$$C_i(a_i, \underline{\theta}) = (4 + \underline{\theta})a_i + \frac{6}{10}a_i^2 \tag{27}$$

In this case, the resulting emissions market price reads

$$p = \begin{cases} 4.9 + \theta & \text{if } \underline{p_1} \leq 4.9 + \theta \\ 9.8 - \underline{p_1} + 2\theta & \text{if } 4.9 + \theta < \underline{p_1} < 5.8 + \theta \\ 0 & \text{otherwise.} \end{cases} \tag{28}$$

We obtain the following critical values:

$$\begin{aligned} CV1(\underline{\theta}) &= 4.9 - \underline{\theta} \\ CV2(\underline{\theta}) &= 5.8 - \underline{\theta} \\ CV1(\bar{\theta}) &= 4.9 + \bar{\theta} \end{aligned} \tag{29}$$

Using the specific benefit and cost functions, we now focus on the difference between the counterfactual welfare of having no price floor implemented (Eq. (30), Area A) and welfare obtained in Area C (Eq. (31)).

$$W_1^A(\underline{\theta}) = \frac{333}{80} - \frac{3}{4}\underline{\theta} \tag{30}$$

$$W_1^C(\underline{\theta}) = \frac{5}{12}(-\underline{p_1} + 4 + \underline{\theta})(\underline{p_1} - 6 + \underline{\theta}) \tag{31}$$

If the welfare in Area C exceeds the welfare in Area A, the welfare difference $\Delta_{W_1^C(\underline{\theta}),W_1^A(\underline{\theta})}$ (Eq. (32)) becomes positive and the implementation of a unilateral price floor becomes beneficial in Area C.

$$\Delta_{W_1^C(\underline{\theta}),W_1^A(\underline{\theta})} = W_1^C(\underline{\theta}) - W_1^A(\underline{\theta}) = \frac{1}{240}\left(-3399 - 100(-10 + \underline{p_1})\underline{p_1} + 20\underline{\theta}(-1 + 5\underline{\theta})\right) \tag{32}$$

For welfare to increase in Area C and solutions to be in line with parameter and area restrictions, the following conditions must be met:

1. $-4 \leq \underline{\theta} < 0$. The abatement cost shock $\underline{\theta}$ must not be lower than $-\gamma$ to avoid negative abatement costs.

2. $\frac{29}{5} + \theta < \underline{p_1} \leq \frac{49}{10} - \underline{\theta}$. The unilateral price floor $\underline{p_1}$ must exceed $CV2(\underline{\theta})$, but not $CV1(\bar{\theta})$.

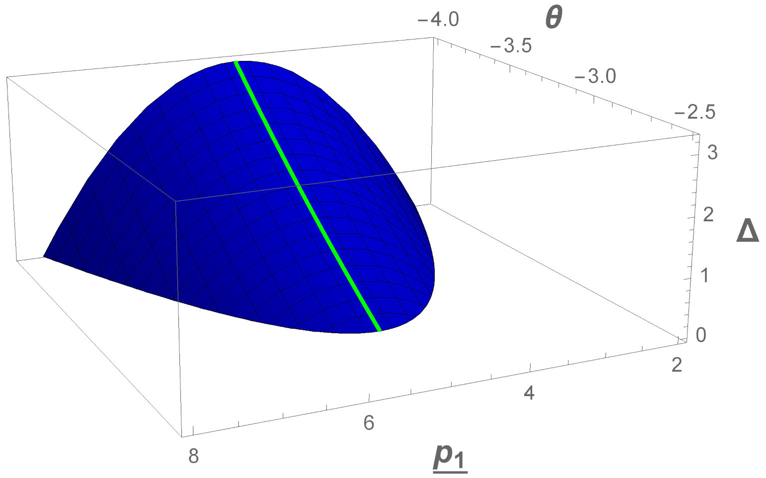
3. $\Delta_{W_1^C(\underline{\theta}),W_1^A(\underline{\theta})} > 0$. Resulting welfare in Area C must be higher than in the counterfactual scenario of having no unilateral price floor implemented (Area A).

Solving the inequalities for the specific parameter setting leads to the following results.

- If and only if conditions $\frac{1}{10}(50 - \sqrt{781}) < \underline{p_1} < \frac{1}{10}(50 + \sqrt{781})$ and $-4 \leq \underline{\theta} < \frac{1}{10} - \sqrt{34 - 10\underline{p_1} + \underline{p_1}^2}$ hold, the implementation of a unilateral price floor $\underline{p_1}$ in country 1 is beneficial in Area C.

- If and only if the stronger condition $-4 \leq \underline{\theta} < -\frac{29}{10}$ also holds, the welfare maximizing price floor $\underline{p_1^*} = \beta = 5$ is located in Area C. Otherwise, the welfare maximum is obtained at $\underline{p_1^*} = \frac{49}{10} - \underline{\theta}$, which represents the right boundary this Area ($CV1(\bar{\theta})$).

**Figure 5: Welfare difference for different $\underline{p_1}$ and $\underline{\theta}$ levels**

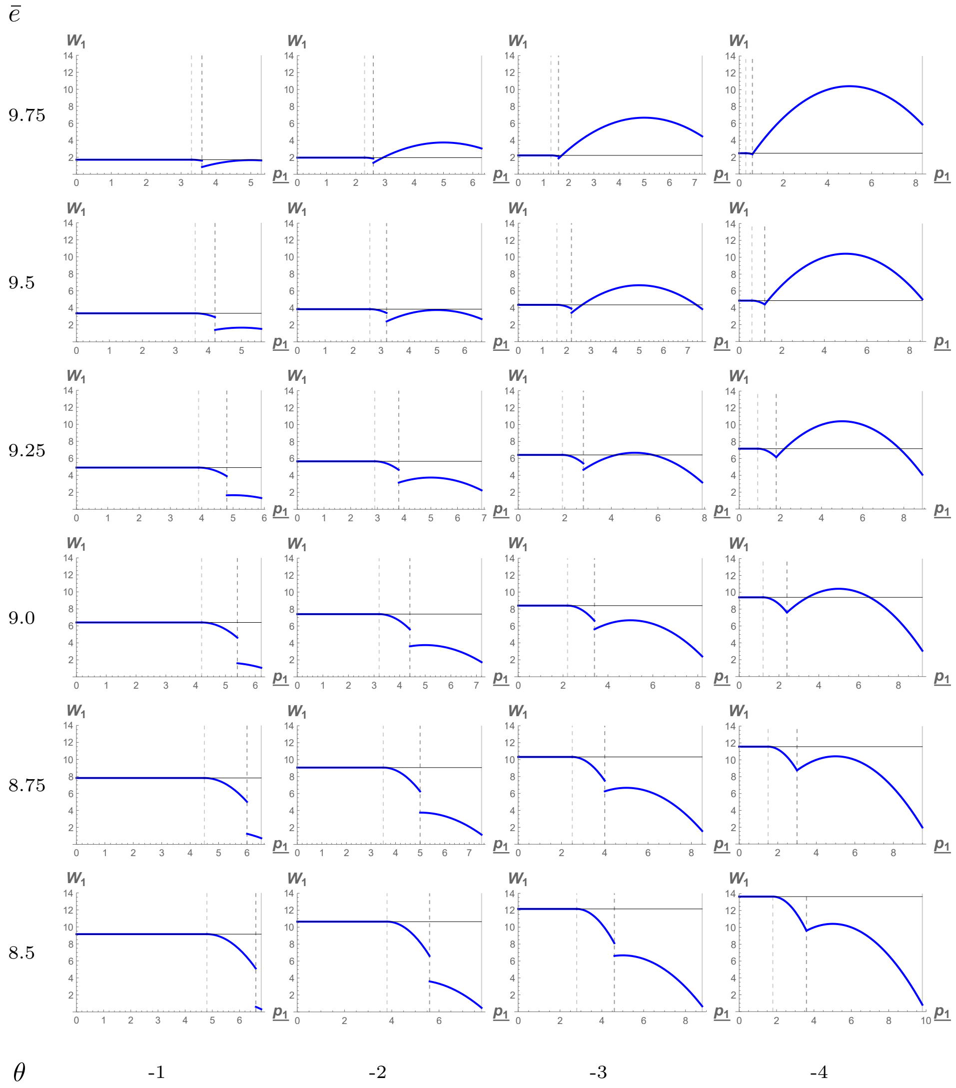


The graph visualizes the difference between the welfare in Area A and C ($\Delta_{W_1^C(\underline{\theta}),W_1^A(\underline{\theta})}$), depending on the price floor $\underline{p_1}$ and the realized cost shock $\underline{\theta}$. A larger cost shock $\underline{\theta}$ leads to a larger number of price floors that are welfare enhancing. In green, the optimal price floor for each shock level is highlighted which is $\underline{p_1^*} = \beta = 5$. The parameter settings are $\beta = 5, \gamma = 4$, $\zeta = 1$, $e_0 = 10$, $\bar{e} = 9.25$.

Figure 5 depicts the welfare difference as a function of $\underline{p_1}$ and $\underline{\theta}$ allowing to identify all parameter constellations that lead to a welfare increase (i.e., where $\Delta_{W_1^C(\underline{\theta}),W_1^A(\underline{\theta})} > 0$). The abatement cost shock must be large enough for the welfare difference to be positive, otherwise it is negative. The graph also illustrates the quadratic effect of $\underline{p_1}$ on the difference $\Delta_{W_1^C(\underline{\theta}),W_1^A(\underline{\theta})}$ (via its quadratic effect on the welfare in Area C $W_1^C(\underline{\theta})$). Here the green line highlights the maximal difference – the welfare maximum in Area C – for different $\theta$ values. As analytically derived, $\underline{p_1^*} = \beta = 5$ maximizes the welfare in Area C. Furthermore, the range of price floors that enhance welfare in Area C widens with a more pronounced abatement cost shock.

As the exogenous emissions cap per country $\bar{e}$ is another key parameter, we analyze the effect of a variation in the emissions cap per country $\bar{e}$ for emission reduction targets between 2.5% ($\bar{e} = 9.75$) and 15% ($\bar{e} = 8.5$) in 2.5% intervals, for different cost shock realizations $\underline{\theta} = \{-1, -2, -3, -4\}$. Figure 6 shows the welfare in country 1 (blue) in Area B and C, compared to the counterfactual scenario of having no price floor implemented (Area A, black horizontal line), for the specified parameter variations. It becomes obvious that a price floor in Area B, the part that lies between $CV1(\underline{\theta})$ (dashed gray) and $CV2(\underline{\theta})$ (dashed dark-gray), is never welfare-improving. This is consistent with our analytical results in Area B. However, there are parameter combinations for which the unilateral price floor in country 1 leads to welfare improvements in Area C (between $CV2(\underline{\theta})$ (dashed dark-gray) and $CV1(\bar{\theta})$ (solid gray)). This may already be achieved via a unilateral price floor in Area C, in the case of a relatively loose emissions cap per country and a relatively small abatement cost shock. Here, cheap abatement options are used to generate additional benefits. Of

**Figure 6: Welfare of country 1 for different emission caps, cost shock realizations and price floor levels**



The figure illustrates the realized welfare (blue) for different negative cost shocks ($\theta = \underline{\theta}$) and emission caps per country ($\bar{e}$), depending on the price floor level ($\underline{p_1}$), for a specific parameter setting ($\beta = 5$; $\gamma = 4$; $\zeta = 1.2$; $e_0 = 10$). In the figure, the black horizontal line represents the counterfactual welfare of having no price floor implemented (Area A). The part between $CV1(\underline{\theta})$ (dashed gray) and $CV2(\underline{\theta})$ (dashed dark-gray) specifies Area B and the part between $CV2(\underline{\theta})$ (dashed dark-gray) and $CV1(\bar{\theta})$ (solid gray) defines Area C.

course, a more pronounced abatement cost shock makes the unilateral price floor increasingly advantageous. However, the more stringent the emissions cap, the larger the shock in abatement costs must be to generate additional welfare gains. For very ambitious emission caps, the abatement cost shock may never lead to an improvement in welfare relative to the counterfactual scenario. In this case, abatement options have been exhausted and the costs of additional abatement exceed the additional benefits in country 1. Thus, the numerical example highlights the interaction between the abatement cost shock $\theta$ and the unilateral price floor $\underline{p_1}$, but also demonstrates the effect of the emissions cap per country $\bar{e}$, on the advantage of such a unilateral price floor.

## 4 Conclusion

The research presented here seeks to explore insights about unilateral environmental policy-making of a country (via the introduction of a domestic price floor in the form of a carbon tax). We provide a simple theoretical two-country model with uncertainty in abatement costs to explain under which circumstances a unilateral price floor is desirable when the implementation of a (superior) bilateral price floor fails for political reasons. Our analysis has shown that as soon as the market price for emissions drops below the set price floor, the unilateral price floor affects the market price for emissions, abatement activities as well as the resulting welfare. A higher price floor in general leads to greater (less) abatement activities in the domestic (foreign) country. Consequently, additional benefits from overall pollution abatement may increase the welfare of the country that unilaterally implements the price floor in addition to the cap-and-trade scheme, in situations where the permit price is low. This is precisely the case for a negative realization of the abatement cost shock.

The key finding from this analysis is that imposing a unilateral price floor can be welfare-increasing for several parameter settings. A positive realization of the abatement cost shock may result in a market price for emissions above the price floor. In this case, the price floor is not binding because the unilateral price floor falls short of the permit price. By contrast, under a negative realization of the random variable, abatement costs are lower than expected and the market price for emissions can fall below the price floor. Depending on the parameter settings, this can lead to a situation in which the abatement of the domestic country exceeds the total abatement target implied by the cap-and-trade scheme, so that additional environmental benefits are generated. We have demonstrated that an additional unilateral policy can lead to higher domestic welfare than in the absence of the price floor, in spite of a reduction of the abatement activities of the foreign firms (carbon leakage). If a relatively loose abatement target is implemented in the emissions trading scheme, the additional unilateral price regulation in form of a price floor may become beneficial.

This may be the case in particular if an emissions trading system is introduced or if there is a surplus of allowances on the market. A more pronounced cost shock favors the introduction of a unilateral price floor by leading to cheap abatement options that would otherwise not be used. This would be the case, for example, in the event of an unexpected reduction or an initial overestimation of abatement costs. Under these circumstances, a country may introduce this additional unilateral price regulation to implement a more stringent environmental policy and ensure that all cheap abatement opportunities are utilized, should they exist.

The simple model could serve as a basis for assessing the effects of, for example, i) an endogenous emissions cap ii) heterogeneous countries iii) a dynamic setting iv) a wider value range and independent realizations of the abatement cost shock, or v) a cancellation mechanism of free allowances. Although these extensions will increase the model's complexity, they may provide deeper insights into unilateral policy-making and represent a subject for further research.

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# Emissions Trading Schemes: Negotiations on the Emissions Cap

Fabian Naumann* Tom Rauber †

**Abstract:** Setting a sufficiently stringent emissions cap is a key factor in ensuring that an emissions trading system can effectively tackle climate change. The crucial question therefore becomes: what cap is implemented? In this paper, we consider an alternating-offers model in which two asymmetric countries have already committed to jointly implement an emissions trading scheme. We investigate whether bargaining over the emissions cap can result in the social emissions optimum and the reasons for deviations. We show that an initial endowment of emission rights based on historic emissions never results in the social optimum. However, other permit allocations exist which lead to the social optimum. In this case, the initial endowment can, to some extent, function relatively similar to a side payment, allowing efficiency and distribution to be separated. If the negotiating countries are too different, no allocation of allowances can lead to the socially optimal emissions level.

**Keywords:** Nash bargaining solution, Emissions trading schemes, Emissions cap

**JEL Classification:** C71; D62; H23; Q53

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[*] Technische Universität Kaiserslautern (TUK), fabian.naumann@wiwi.uni-kl.de

[†] Technische Universität Kaiserslautern (TUK), tom.rauber@wiwi.uni-kl.de

# 1 Introduction

The ongoing climate change and its immense impact, which poses tremendous challenges to humanity, highlights market failure in the provision of global public goods.

Market failure in the presence of externalities is a well-studied problem in the literature. Coase (1960) shows that, once property rights are clearly defined, bargaining can lead to an efficient market outcome. This holds even in the presence of externalities and regardless of the initial allocation of property rights. First economic approaches to tackle the decline in environmental quality go back to the 1960s when Dales (1968) proposes a charging scheme in his seminal work. The suggested scheme limits the number of rights to pollute, issued by the government, thereby restricting environmental damages, such as to water and the atmosphere. Together with the theoretical foundation of markets in licenses and its cost efficiency by Montgomery (1972), this lays the theoretical basis for emissions trading systems as they are implemented nowadays. In light of the modern research that was built on that foundation, our paper can be viewed in the larger context of three strands of literature, namely *allowance choices* as well as *public good provision from a political perspective* and *linking emissions trading schemes.*

In a more recent paper, Helm (2003) shows that endogenous *allowance choices* by countries do not automatically result in lower pollution levels, as environmentally more (less) concerned countries choose to pollute less (more) and thus environmental efforts offset. It becomes clear that a transnational problem requires cooperation between countries. Smead et al. (2014) analyze a game, where agents bargain over their share of the fixed emission total including learning dynamics. They find that negotiations tend to fail if too many agents are faced with an under-proportional emissions share, making the initial demand a key factor for a successful negotiation.

Segendorff (1998) is the first to consider delegates in the context of international environmental agreements and represents the *public good provision from a political perspective.*[1] He finds that authorities choose delegates who misrepresent their preferences.[2]. Loeper (2017) analyzes international cooperation, where policymakers are elected by a country's population. Strategic behavior by voters leads to the election of policymakers who under-represent interests. A key finding is that the type of public good is relevant and a more convex demand function enhances the provision of a public good. Arvaniti and Habla (2021) also contribute to the "strategic delegation" literature, showing that delegates who misrepresent preferences lead to a situation in which it is not clear if and for whom cooperation is beneficial. Although we also explore how countries cooperate, in

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[1] See also Siqueira (2003).

[2] For further contributuins on misrepresentation of preferences see also Crawford and Varian (1979), Jones (1989), and Burtraw (1992, 1993).

our case to define the emission cap in a cap and trade system, we abstract from situations where delegates falsely represent their countries preferences.

If national emissions trading systems have already been implemented, the question arises as to whether *linking existing systems* is advantageous. It becomes more advantageous the higher the jurisdictions' size and shock variances, while a higher correlation of shocks and sunk costs of linking show the opposite effect (Doda and Taschini, 2017). Flachsland et al. (2009) analyze from an economic, political, and regulatory perspective the benefits and disadvantages of linking, such as reduced volatility, strengthening the multilateral commitment versus expanded emission caps to obtain permit trade benefits and abatement targets that are not in line with a burden-sharing approach and decline in a country‘s regulatory power. Doda et al. (2019) find that multilateral linking can lead to tremendous efficiency gains which arise equally from effort and risk-sharing. However, Habla and Winkler (2018) demonstrate that strategic delegation hinders the linking of emissions trading schemes.

The paper closest in spirit to ours is Dijkstra and Nentjes (2020), which compares the Exchange-Matching-Lindahl (EML) solution (a bottom-up mechanism) and the Nash Bargaining solution (a top-down mechanism) for the provision of a public good. As the EML is lesser-known, we only briefly summarize this cooperation mechanism, as used by Dijkstra and Nentjes (2020). Under EML there is an exchange rate offered to countries, which specifies the ratio of global to national abatement. Now, given this exchange rate, countries declare their respective supply and demand for emissions reduction. They find a Pareto-efficient equilibrium, in which countries' demands are identical due to different exchange rates. Their results indicate that i) in a setting with two agents both mechanisms are equivalent, ii) in a setting with more than two agents, EML is beneficial for agents with high benefit and low costs, and iii) lower side payments under the EML mechanism.

In contrast to the existing literature, we analyze a negotiation in which the total cap of the emissions trading scheme is the outcome of the bargaining while the division of the total cap among the countries' is fixed. Our study is based on a two-country model, where we assume that asymmetric countries have already committed to jointly introduce a cap and trade system.[3] Using a model with alternating offers, we investigate under which conditions this bargaining process leads to a socially optimal emissions quantity and why it can deviate from it.

Our results show that the bargaining process can bring about a situation in which the negotiated emissions level equals the social optimum. If allowances are allocated based on historical emissions, the socially optimal level of emissions can never be achieved in our model environment. However,

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[3] In a larger context, this could also be seen as two countries agreeing to link their emissions trading system and negotiate the overall cap.

the outcome of the bargaining may result in the social optimum if the allocation differs. In this case, the allocation of permits might be used as a compensation mechanism between countries. Furthermore, we find that if countries are too different, the redistribution of allowances reaches its limit and no allocation can lead to the social optimum. Nevertheless, we demonstrate that bargaining can result in a better solution compared to national emission trading schemes with national emission caps. Our work, thus, identifies reasons why the socially optimal emissions cap is not implemented in an emissions trading scheme. Although we made some strong assumptions, the model helps understand the reasons why emissions trading schemes might not set tight emission caps. In addition, the model can be extended to represent more realistic scenarios, such as an outside option or a risk of a breakdown in the bargaining process.

The paper is organized as follows. In the following section, we introduce the simple two-country model and provide basic insights about abatements as well as the emissions market price. Section 3 defines two benchmark scenarios, namely the social optimal emissions cap and national emission caps, for the welfare analysis. In Section 4 we analyze the cap negotiation, using an alternating-offers model, and compare results with the defined benchmarks. Finally, Section 5 concludes.

## 2 Model and Basic Insights

We briefly introduce the underlying theoretical framework in this section, deployed to describe a cap and trade system. Later, we endogenize the cap in this model by allowing the countries to negotiate.

### Welfare Function

We define the welfare of a country $i \in [1, 2]$ as benefits of overall abatement $B(\sum_i a_i)$, assuming a positive externality (country $i$ benefits from the abatement made by country $-i$), minus costs of abatement in a country $C(a_i)$. Because countries are linked through a cap and trade system, emissions trading results in either additional revenue or costs, depending on whether a country is a buyer or seller of permits. A country is a buyer (seller) of permits if actual emissions, $e_i$, are higher (lower) than its initial endowment of permits, $\bar{e}_i$, where $p$ is the endogenous permit market price. For the emissions cap of the scheme $\bar{E}$ it holds that $\bar{E} = \bar{e}_1 + \bar{e}_2 = \mu\bar{E} + (1-\mu)\bar{E}$, where $\mu$ defines the permit share allocated to country 1.[4] Putting the components together the welfare function reads:

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[4] We take $\mu$ as given. It could, for instance, be determined by emissions under business as usual, by a certain historical tradition, or by previous negotiations.

$$W_i(a_i, a_{-i}) = B_i(a_i, a_{-i}) - C_i(a_i) + (\bar{e}_i - e_i) \cdot p, \quad for\ all\ i = 1, 2 \tag{1}$$

As realized emissions $e_i$ are emissions under "business as usual" $e_{i,0}$ minus actual realized abatement $a_i$:[5], we can re-write the welfare function as follows.

$$W_i(a_i, a_{-i}) = B_i(a_i, a_{-i}) - C_i(a_i) + (\bar{e}_i - (e_{i,0} - a_i)) \cdot p, \quad for\ all\ i = 1, 2 \tag{2}$$

**Benefit and Cost Function**

In the literature, linear or quadratic functions are often assumed for abatement benefits and costs, see, for instance, Weitzman (1974, 2014), Barrett (1994) and McGinty (2007). We assume a quadratic benefit function (3) and cost function (4) for each country, where the total abatement $A$ is defined as $A \coloneqq \sum_i a_i$.

$$B_i(A) = \beta_i A - \frac{\delta_i}{2} A^2, \quad where\ \beta_i > 0\ and\ \delta_i > 0, \qquad for\ all\ i = 1, 2 \tag{3}$$

$$C_i(a_i) = \frac{\zeta_i}{2} a_i^2, \qquad where\ \zeta_i > 0, \qquad for\ all\ i = 1, 2. \tag{4}$$

In our analysis, we want to focus on the case that provides the most insights, where the two countries have different characteristics and, therefore, different goals in the reduction of emissions. Let country 1 have *i*) small emissions under "business as usual", *ii*) high benefits, but also *iii*) high costs from abatement. Country 1 can be thought of as a country with a relatively small GDP, but rather higher exposure to the negative consequences of the emissions, e.g. because of geographical factors like a long coast line. County 2, on the contrary, has *i*) high emissions under "business as usual", *ii*) low benefits, but also *iii*) low costs from abatement. This is an adequate representation of a country with a high GDP that is less affected by the negative consequences of the emissions. To reflect this in our model, we assume that $\zeta_1 > \zeta_2$, $\beta_1 > \beta_2$ while $\delta \coloneqq \delta_1 = \delta_2$, and $e_{2,0} = \kappa \cdot e_{1,0}$ where $\kappa > 1$.

Furthermore, in the main part of the paper, we focus on the most realistic scenarios where the countries' optimal caps are greater than zero, i.e., where complete decarbonization is never optimal. Formally, this requires $W_i(a_i, a_{-i})$ to be a concave function with its maximum greater than zero. As we see below, this is ensured for any given allocation $\mu$ by the following technical assumptions that we impose about the relation between the model parameters. These assumptions

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[5] We assume $a_i \geq 0$. A country cannot increase its emissions above the initial level, the emissions "business as usual".

moreover determine how the allocation $\mu$ changes country $i$'s optimal cap, which allows us to avoid tedious case distinctions and focus on the cases where compelling results are obtained.

i) $\zeta_2 \left( \frac{\zeta_1}{\zeta_1+\zeta_2} \right)^2 < \delta$.

ii) $\frac{3\zeta_1+\zeta_2}{\zeta_1+3\zeta_2} < \kappa$,[6]

iii) $\frac{\beta_1}{e_{1,0}} < \frac{1}{2}\left[\delta + \frac{\zeta_1\zeta_2(2\zeta_1+\zeta_2)}{(\zeta_1+\zeta_2)^2}\right] + \frac{\kappa}{2}\left[\delta - \zeta_1\left(\frac{\zeta_2}{\zeta_1+\zeta_2}\right)^2\right]$.

**Abatements**

We start by deriving some basic insights concerning the realized emission price and the abatement activities within an existing cap and trade system. As firms under regulation minimize their abatement costs, the minimization problem of a representative price-taking firm in each country reads

$$\min_{a_i} p \cdot (e_{i,0} - a_i) + \frac{\zeta_i}{2} a_i^2. \tag{5}$$

The corresponding FOC for a representative firm in country $i$ reads as

$$a_i = \frac{p}{\zeta_i}, \tag{6}$$

and determines the optimal abatement activities carried out in that country. Since maximum emissions in total are limited to the overall emissions cap $\bar{E}$, market clearing in the emission permits market requires that $\sum_i (e_{i,0} - a_i) = \bar{E}$, where $e_{2,0} = \kappa e_{1,0}$. Inserting the abatements per country leads the emissions market price $p$:

$$p = \frac{\zeta_1\zeta_2}{\zeta_1+\zeta_2}\left((\kappa+1)e_{1,0} - \bar{E}\right). \tag{7}$$

The resulting abatement activities are:

$$a_1 = \frac{\zeta_2}{\zeta_1+\zeta_2}\left[(\kappa+1)e_{1,0} - \bar{E}\right], \tag{8}$$

$$a_2 = \frac{\zeta_1}{\zeta_1+\zeta_2}\left[(\kappa+1)e_{1,0} - \bar{E}\right], \tag{9}$$

$$A = a_1 + a_2 = (\kappa+1)e_{1,0} - \bar{E}. \tag{10}$$

Since country 2 represents the country with lower abatement costs ($\zeta_1 > \zeta_2$), this country also contributes more to total abatement ($a_2 > a_1$). This is in accordance with emissions trading and

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[6] Note that this is a rather weak assumption, for $\zeta_2 \approx \zeta_1$ we get that $1 < \kappa$, while we get for $\zeta_2 \ll \zeta_1$ that $3 < \kappa$.

rather intuitive. Because emission permits can be traded, an international emissions trading scheme leads to emissions abatement in the most cost-effective way by equalizing marginal abatement costs.

# 3 Benchmarks

We define two benchmark scenarios with the help of which we can then evaluate the bargaining results of our model. In the first scenario, a *centralized* cap definition carried out by a social planner is analyzed, before investigating the *decentralized* processes in subsequent sections. In particular, analyzing the benchmarks allows us to compare the social welfare generated through bargaining to the welfare generated in those scenarios.

## 3.1 Social Optimum

Let us first assume that there exists a social planner who maximizes the welfare of both countries involved, which is $W(\bar{E}) = W_1(\bar{E}) + W_2(\bar{E})$. It is apparent that, from a centralized perspective, trading activities between the countries offset each other. Hence, the overall welfare optimized by the social planner only consists of benefits and costs and reads as:

$$W(\bar{E}) = B_1(A(\bar{E})) - C_1(a_1(\bar{E})) + B_2(A(\bar{E})) - C_2(a_2(\bar{E})). \tag{11}$$

The socially optimal cap satisfies the FOC, which is

$$W'(\bar{E}) = \left[B_1'(A(\bar{E})) + B_2'(A(\bar{E}))\right] \frac{\partial A}{\partial \bar{E}} - C_1'(a_1(\bar{E}))\frac{\partial a_1}{\partial \bar{E}} - C_2'(a_2(\bar{E}))\frac{\partial a_2}{\partial \bar{E}} = 0. \tag{12}$$

Intuitively, the abatement activities induced by the welfare maximizing cap $\bar{E}_S^*$ balance the marginal cost of abatement with the overall marginal benefit of abatement. Using (8)–(10) the FOC can be rewritten as

$$C_i'(a_i(\bar{E})) = B_1'(A(\bar{E})) + B_2'(A(\bar{E})) \quad i \in [1, 2]. \tag{13}$$

Since both countries benefit from a marginal increase in the abatement irrespectively where the emissions have been saved, we obtain the sum of the marginal benefits on the right-hand side of Equation (13). Since emissions rights can be traded, it leads to a situation where marginal abatement costs of participating countries equalize, i.e., $C_1'(a_1(\bar{E})) = C_2'(a_2(\bar{E}))$, and ultimately determine the resulting price on the certificate market. In general, emission trading schemes thereby ensure that the emissions target is met at lowest cost, which makes it an efficient policy instrument to regulate pollution.[7] Hence, a marginal increase in the abatement induces costs at the level represented on the left-hand side of Equation (13). The welfare is maximized at the socially optimal emissions level $\bar{E}_S^*$ where total marginal benefit is equal to marginal cost. For the specified benefit and cost functions, cf. (3) and (4), we can explicitly solve for the socially optimal cap, which is

$$\bar{E}_S^* = (\kappa + 1)e_{1,0} - \frac{\beta_1 + \beta_2}{2\delta + \frac{\zeta_1\zeta_2}{\zeta_1+\zeta_2}}. \tag{14}$$

The second term of Equation (14) can be interpreted as the abatement target implemented via the cap and trade system, which is subtracted from total emissions under business as usual. In our notation, we define the socially optimal welfare generated by $\bar{E}_S^*$ as

$$W_S^* \coloneqq W\left(\bar{E}_S^*\right). \tag{15}$$

## 3.2 National Caps

Now, we turn to a decentralized scenario, in which countries do not participate in a joint emissions trading scheme but instead deploy national regulations, in form of national cap and trade systems. Because each country implement its own emissions cap, the corresponding abatements for the countries are

$$a_1 = e_{1,0} - \bar{e}_1, \tag{16}$$

$$a_2 = \kappa e_{1,0} - \bar{e}_2. \tag{17}$$

Given the cap of country $-i$, country $i$ chooses its own cap to maximize its welfare, i.e., as solution to

$$\max_{\bar{e}_i} B_i(A(\bar{e}_i, \bar{e}_{-i})) - C_i(a_i(\bar{e}_i)) \tag{18}$$

Hence, the solution to (18) defines a reaction function of the form $\bar{e}_i(\bar{e}_{-i})$ for each country. Solving this system of equations leads to the Nash equilibrium, where

$$\bar{e}_{1,C}^* = e_{1,0} - \frac{\zeta_2\beta_1 + \delta(\beta_1 - \beta_2)}{\zeta_1\zeta_2 + \delta(\zeta_1 + \zeta_2)}, \tag{19}$$

$$\bar{e}_{2,C}^* = \kappa e_{1,0} - \frac{\zeta_1\beta_2 - \delta(\beta_1 - \beta_2)}{\zeta_1\zeta_2 + \delta(\zeta_1 + \zeta_2)}. \tag{20}$$

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[7] This holds true in absence of transaction costs and imperfect competition (e.g., Hahn, 1984; Stavins, 1995).

Intuitively, the cap $e^*_{i,C}$ chosen by county $i$ is the optimal response to the cap $e^*_{-i,C}$ chosen by country $-i$ such that no country has an incentive to deviate. To capture the global effect that those caps have on the overall emissions, we define $\bar{E}^*_C$ as sum of the individual caps, representing the resulting overall emissions level in the two country setting. Summing up Equation (19) and (20) and rearranging leads to

$$\bar{E}^*_C = \bar{e}^*_{1,C} + \bar{e}^*_{1,C} = (\kappa + 1)e_{1,0} - \frac{\zeta_2\beta_1 + \zeta_1\beta_2}{\zeta_1\zeta_2 + \delta(\zeta_1 + \zeta_2)} \tag{21}$$

Again, the second summand of Equation (19) can be interpreted as total abatement that is implemented via the decentralized CAPs. Similarly to the socially optimal welfare, the overall welfare generated by national caps is defined as

$$W^*_C \coloneqq W_1(\bar{e}^*_{1,C}) + W_2(\bar{e}^*_{2,C}). \tag{22}$$

# 4 Cap Negotiations

Now, we turn to the case where the countries have already agreed to commit in a cap and trade system and explore how they endogenously set the cap via negotiating.

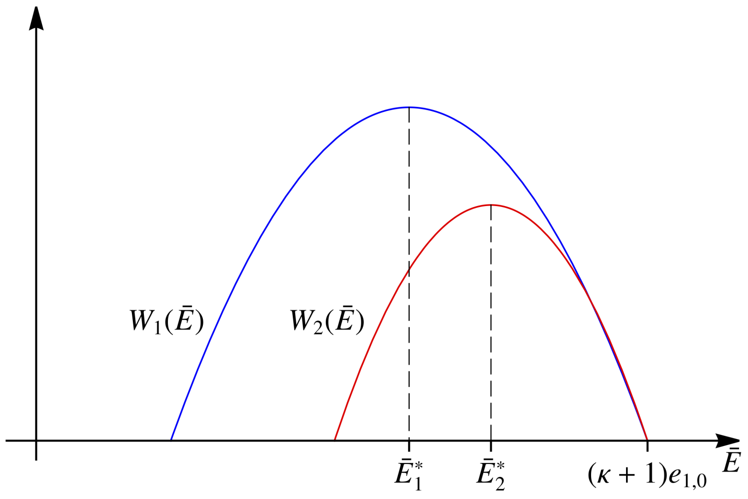
## 4.1 Basic Insights

To begin with, we specify the set of potential bargaining solutions and the effect of the model parameters. We, therefore, determine how each country $i$ would optimally set the global cap $\bar{E}^*_i$. Since each country wants to maximize its welfare, the FOC of Equation (2) determines each country's desired cap. After simplifying the FOC writes as

$$B'_i(A(\bar{E})) = \mu_i C'_i(a_i(\bar{E})) + \left(\mu_i\bar{E} - e_{i,0} + a_i(\bar{E})\right) C''_i(a_i(\bar{E}))\frac{\partial a_i}{\partial \bar{E}}, \quad \textit{for all } i = 1, 2, \tag{23}$$

where $\mu_1 = \mu$ and $\mu_2 = 1 - \mu$. The right-hand side of Equation (23) captures two marginal effects, a cost effect (first summand on the right-hand side) and a trading effect (second summand on the right-hand side). In optimum, these two effects equal marginal benefit (left-hand side of Eq. (23)). If a country is a seller (buyer) of certificates, the trading effect is positive (negative). Explicitly

**Figure 1: Optimal caps for county 1 and 2.**



solving Equation (23) for each country $i$ leads to

$$\bar{E}_1^* = e_{1,0}(\kappa+1) - \frac{e_{1,0}\left[(\kappa+1)\mu - 1\right] + \frac{\zeta_1+\zeta_2}{\zeta_1\zeta_2}\beta_1}{2\mu + \frac{\zeta_1+\zeta_2}{\zeta_1\zeta_2}\left[\delta - \zeta_1\left(\frac{\zeta_2}{\zeta_1+\zeta_2}\right)^2\right]} \tag{24}$$

$$\bar{E}_2^* = e_{1,0}(\kappa+1) - \frac{e_{1,0}\left[1 - (\kappa+1)\mu\right] + \frac{\zeta_1+\zeta_2}{\zeta_1\zeta_2}\beta_2}{2(1-\mu) + \frac{\zeta_1+\zeta_2}{\zeta_1\zeta_2}\left[\delta - \zeta_2\left(\frac{\zeta_1}{\zeta_1+\zeta_2}\right)^2\right]} \tag{25}$$

We immediately find that $\bar{E}_1^* < \bar{E}_2^*$ for $\kappa$ sufficiently large or for $\beta_1$ sufficiently greater than $\beta_2$. Intuitively, if country 1 has rather low emissions under "business as usual" or if its benefits from abatement are rather high compared to country 2, then country 1 advocates a lower cap, i.e., stronger abatement activities. Figure 1 illustrates each country's welfare dependent on the cap $\bar{E}$ in the case where $\bar{E}_1^* < \bar{E}_2^*$. As it can be seen, the set of Pareto efficient caps is given by the interval $[\bar{E}_1^*, \bar{E}_2^*]$. Since bargaining results in a Pareto efficient outcome, the bargaining solution is located in this closed interval. Moreover, if the countries agree to keep the current level of emission, i.e., a cap of $(\kappa+1)e_{1,0}$, both countries obtain a welfare of zero by the construction of the cost and benefit function. In general, the set of Pareto efficient caps, $\mathscr{P}$, from which we determine the Pareto efficient bargaining outcome, is given by the interval $[\min\{\bar{E}_1^*, \bar{E}_2^*\}, \max\{\bar{E}_1^*, \bar{E}_2^*\}]$.[8] The effect that the allocation of the certificates among the countries has on the optimal caps is specified in Lemma 1. For the proof see Appendix A.

**Lemma 1** *If the share of country 1's certificates, $\mu$, increases, then country 1's optimal cap decreases, $\frac{\partial \bar{E}_1^*}{\partial \mu} < 0$, while country 2's optimal cap increases, $\frac{\partial \bar{E}_1^*}{\partial \mu} > 0$.*

---

[8] Note that in the trivial case where $\min\{\bar{E}_1^*, \bar{E}_2^*\} = \max\{\bar{E}_1^*, \bar{E}_2^*\}$ no conflict of interests arises, and the countries agree upon a cap which is socially optimal.

Intuitively, since its emissions are significantly lower, country 1 wants to reduce the total amount of certificates to reduce the total emissions and to be able to sell its excess of certificates at a higher price if its share of certificates increases. By contrast, country 2 wants to compensate a lower share of certificates allocated to it by increasing the total amount of certificates and thereby reducing the market price.

## 4.2 Nash Bargaining Solution

One of the simplest ways to model a cap negotiation[9] is according to Rubinstein's (1982) alternating-offers model. Country $i$ proposes a cap. Then country $-i$ can either accept this offer and the game ends or reject the offer and make a counter offer after $\Delta > 0$ time units. In case of rejection, it is $i$'s turn to decide whether to accept the counteroffer or to make a counter-counteroffer. This process continues until one country accepts the proposed cap.[10] A prominent result in bargaining theory is that the subgame perfect equilibrium in the Rubinstein model converges to Nash's (1950) bargaining solution if the absolute magnitudes of the frictions in the bargaining process are small (Binmore et al., 1986; Binmore, 1987). Evidently, this is in accordance with our set-up as the bargaining process is substantially faster than climate change. Hence, even if the bargaining is extended by $\Delta$ due to the rejection of an offer almost the same benefits and costs can be reached through an agreement in the next round. For simplicity, we assume that the counties have the same discount rate such that we can apply the (symmetric) Nash bargaining solution.[11]

### 4.2.1 Definition

In our setting the Nash bargaining solution is defined as the solution of the following maximization problem:

$$\max_{\bar{E} \in \mathscr{P}} W_1\left(\bar{E}\right) \cdot W_2\left(\bar{E}\right), \tag{26}$$

where $W_1 \cdot W_2$ is referred to as Nash product. To facilitate exposition, we exploit the relation to the first-order condition specified in Lemma 2. For the proof see Appendix B.

**Lemma 2** *The Nash bargaining solution $\bar{E}_N^*$ is unique and satisfies the first-order condition of the Nash product.*

---

[9] See Osborne and Rubinstein (1990) and Muthoo (1999) for textbook treatments of bargaining theory.

[10] Note that this standard version of the alternating-offers model does not incorporate the possibility of opting out of the bargaining. In our set-up, the interpretation is that while the counties have already agreed on creating a cap and trade system, they only bargain about the implemented cap.

[11] Different discount rates would shift bargaining power in favour of country $i$ that possess a lower discount rate which in turn leads to a bargaining outcome that is close to $\bar{E}_i^*$.

Using Lemma 2, we obtain that $\bar{E}_N^*$ satisfies

$$W_1'\left(\bar{E}\right) + \frac{W_1\left(\bar{E}\right)}{W_2\left(\bar{E}\right)} \cdot W_2'\left(\bar{E}\right) = 0. \tag{27}$$

After inserting, rearranging and simplifying the FOC reads as follows:

$$C_1'(a_1(\bar{E}))\left[\mu + (1-\mu)\theta(\bar{E})\right] = B_1'(A(\bar{E})) + \theta(\bar{E})B_2'(A(\bar{E})) + x_{12}\frac{\zeta_1\zeta_2}{\zeta_1+\zeta_2}\left(1-\theta(\bar{E})\right), \tag{28}$$

$$\textit{where } x_{12} = \mu\bar{E} - (e_{1,0} - a_1(\bar{E})) \textit{ and } \theta(\bar{E}) = \frac{B_1(A(\bar{E})) - C_1(a_1(\bar{E})) + x_{12}C_1'(a_1(\bar{E}))}{B_2(A(\bar{E})) - C_2(a_2(\bar{E})) - x_{12}C_1'(a_1(\bar{E}))}.$$

$x_{12}$ denotes the amount of certificates country 1 sells to country 2. In fact, $x_{12}$ can also be negative implying that country 1 buys the corresponding amount of certificates from country 2. Hence, $\theta$ represents the ratio of country 1's welfare to country 2's welfare.

### 4.2.2 Comparison to the Social Optimum

Now we seek to explore the question whether the bargaining solution is socially optimal. It is worth emphasizing that each total abatement in the cap and trade system is achieved with the optimal cost structure, namely with equal marginal cost in each country. Hence, if $\bar{E}_N^* = \bar{E}_S^*$ then this automatically implies that the bargaining solution is socially optimal. Comparing the FOCs, leads to Lemma 3 for the proof see Appendix C.

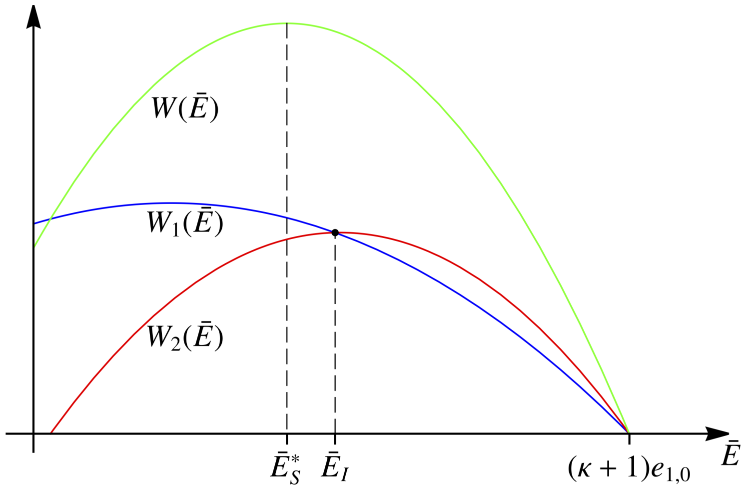
**Lemma 3** *Bargaining implements the efficient cap if and only if* $\theta(\bar{E}_N^*) = 1$.

Intuitively, if $\bar{E}_N^*$ satisfies that $W_1\left(\bar{E}_N^*\right) = W_2\left(\bar{E}_N^*\right)$, then Equation (27) coincides with the the FOC for the socially optimal cap. Although the countries are different in terms of cost- and benefit structures, bargaining can only lead to a socially optimal outcome, if the bargaining solution generates the same welfare for both countries. As we investigate next, this is only satisfied for particular combinations of costs, benefits, emissions, and distribution of the certificates.

In our model it is reasonable to assume that the countries' cost and benefit structures as well as the emissions under "business as usual" are exogenously given and cannot be changed. The allocation of the certificates, however, is determined among the countries before the negotiation takes place. Therefore, the interesting question is, whether a allocation $\mu_S^*$ exists such that the consecutive bargaining results in the socially efficient outcome given the other parameters. Proposition 1 establishes the definition of the allocation $\mu_S^*$. For the proof see Appendix D.

**Proposition 1** *Bargaining implements the socially optimal cap,* $\bar{E}_N^* = \bar{E}_S^*$, *if and only if the allocation of shares is* $\mu_S^*$, *where*

**Figure 2: Distribution of Welfare for $\beta_1 > \overline{\beta}_1$.**



$$\mu_S^* = \frac{e_{1,0}\left[2\delta(\zeta_1+\zeta_2)+\zeta_1\zeta_2\right] - \delta\frac{(\zeta_1+\zeta_2)^2}{\zeta_1\zeta_2}(\beta_1-\beta_2) - \frac{1}{4}\left[(3\zeta_1+5\zeta_2)\beta_1 - (\zeta_1-\zeta_2)\beta_2\right]}{(\kappa+1)e_{1,0}\left[2\delta(\zeta_1+\zeta_2)+\zeta_1\zeta_2\right] - (\zeta_1+\zeta_2)(\beta_1+\beta_2)}. \tag{29}$$

Hence, if the ex-ante determined allocation of the certificates is $\mu_S^*$, the bargaining then results in the socially optimal cap. For any other distribution of the certificates, the countries agree on a cap that is not optimal for the overall welfare. Furthermore, note that the numerator of Equation (29) is decreasing in $\beta_1$, this leads us to Corollary 1.

**Corollary 1** *There exists a $\overline{\beta}_1$ such that $\mu_S^* = 0$, and $\mu_S^*$ is strictly decreasing for $\beta_1 \in [\beta_2, \overline{\beta}_1]$. For $\beta_1 > \overline{\beta}_1$ bargaining cannot implement $\bar{E}_S^*$.*

For the proof see Appendix E. Graphically, the mechanism is as follows, Equation (27) implies that bargaining leads to a socially optimal solution whenever $\bar{E}_I$, the cap for which $W_1$ and $W_2$ intersect, equals the socially optimal cap $\bar{E}_S^*$. As illustrated in Figure 2, if $\beta_1 > \overline{\beta}_1$, then we have that $\bar{E}_I > \bar{E}_S^*$ for $\mu = 0$. According to Lemma 1 an increase in $\mu$ shifts the maximum of $W_1$ up and to the left while the opposite effect occurs for $W_2$. Hence, increasing $\mu$ increases $\bar{E}_I$ while it has no effect on $\bar{E}_S^*$. $\beta_1 > \overline{\beta}_1$ therefore implies that $\bar{E}_I > \bar{E}_S^*$ for all possible distributions of certificates $\mu \in [0,1]$.

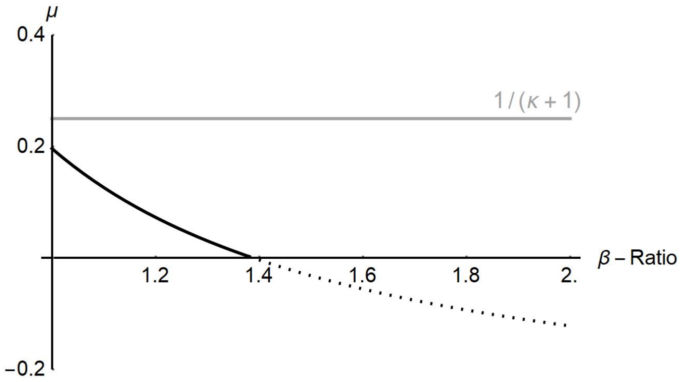
Intuitively, if $\beta_1$ is increased then country 1 benefits more from abatement. Hence, a lower cap is optimal for both, country 1 as well as for the total welfare. Country 2 needs to be compensated to agree on that lower cap in a bargaining. This compensation works via an increased share of certificates for country 2 (and therefore a lower share for country 1). Hence, as indicated by (Buchholz et al., 2005), the allocation of permits is used for implicit side payments in an emissions trading system. As a result, a country has to purchase fewer certificates or receive additional revenue for selling the certificates, depending on whether the country is a buyer or seller of allowances. If country 2 receives all the certificates, i.e., $\mu_S^* = 0$, then the entire scope for compensating country 2 is used. A further increase in $\beta_1$ would decrease the socially optimal cap, but this cap could not be implemented by the bargaining because there is no means for further compensating country 2. In particular, if the benefits for country 1 are too high, then there is no distribution of certificates among the countries that provides both countries with the same welfare. Consequently, bargaining does not lead to a socially optimal outcome in the case where the countries are strongly dissimilar, i.e., where the countries substantially differ in emission ($\kappa$ sufficiently high) and benefits ($\beta_1 - \beta_2$ is sufficiently large).

Proposition1 together with Corollary 1 implies the following for the optimal allocation of certificates among the countries which is proved in Appendix F:

**Corollary 2** *For the optimal allocation of certificates, it holds that* $\mu_S^* < 1/(\kappa+1)$ *for all* $\beta_1 \in [\beta_2, \overline{\beta}_1]$ .

Hence, allocating the certificates based on historical emissions, i.e., according to the proportion of the emissions under business as usual, does never lead to a socially optimal bargaining solution, see Figure 3. To ensure a welfare maximizing bargaining outcome the allocation of certificates needs to take not only the distribution of the emissions but also cost and benefit structures into account.

**Figure 3: Optimal $\mu$ for $\kappa = 3$.**

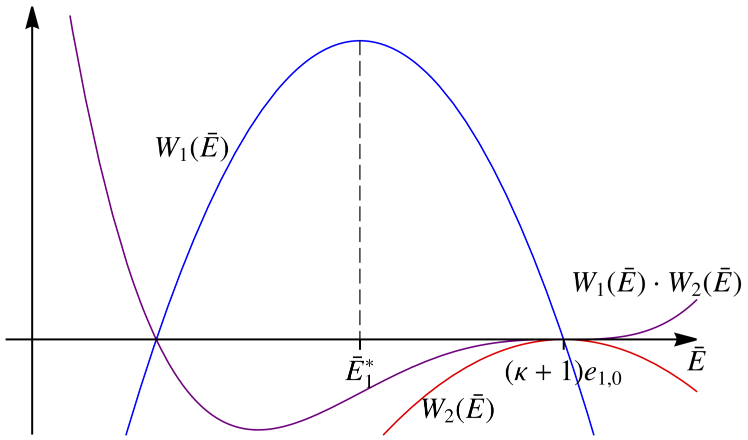


Parameter setting: $\zeta_1 = 0.9$, $\zeta_2 = 0.1$, $e_{1,0} = 100$, $\delta = 0.1$, $\beta_1 = 30$.

### 4.2.3 Comparison to the National Caps

Next, we compare the bargaining solution to the decentralized outcome where both countries deploy national caps. The welfare induced by the bargaining solution relies crucially on $\mu$, i.e., the allocation of the certificates among the countries. As we have seen above, for $\beta_1 \in [\beta_2, \overline{\beta}_1]$

**Figure 4: Optimal caps for county 1 and 2.**



bargaining can result in the socially optimal solution, if $\mu = \mu_S^*$. In that case, we obtain that $W_N^* = W_S^*$. However, there also exists a $\mu_i^0$ such that country $i$'s optimal cap equals the total emissions under "business as usual". Interestingly, country $i$ can enforce that cap in bargaining, i.e., the bargaining leads to $\bar{E}_N^* = (\kappa+1)e_{1,0}$. According to Equations (8) and (9) this leads to zero abatement activities, which, in turn, induces a welfare of zero, $W_N^* = 0$. See Figure 4 for a graphical representation of the case where country 2 enforces the total emissions under "business as usual" as bargaining outcome. The intuition is as follows: since the distribution of certificates is in favour of $-i$, country $i$ has nothing to gain in the bargaining. In fact, perpetually rejecting every offer made by $-i$ leaves country $i$ better off, except for the offer of a cap that equals the emissions under "business as usual", which makes country $i$ indifferent between accepting and rejecting the offer.[12]

Using Equations (24) and (25), we can explicitly solve $E_i^* = (\kappa+1)e_{1,0}$ for $\mu_i^0$, which yields

$$\mu_1^0 = \frac{1 - \left(\frac{\zeta_1+\zeta_2}{\zeta_1\zeta_2}\frac{\beta_1}{e_{1,0}}\right)}{\kappa+1}, \tag{30}$$

$$\mu_2^0 = \frac{1 + \left(\frac{\zeta_1+\zeta_2}{\zeta_1\zeta_2}\frac{\beta_2}{e_{1,0}}\right)}{\kappa+1}. \tag{31}$$

The finding that the bargaining results in emissions under "business as usual" and a welfare of zero, both individually and socially, immediately carries over to the case where a country demands a cap higher than "business as usual", $\bar{E}_i^* > (\kappa+1)e_{1,0}$. Lemma 4 summarizes these results:

**Lemma 4** *For $\mu \in [0,1]$ the welfare generated by the bargaining solution is $W_S^* \geq W_N^* \geq 0$. If*

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[12] In fact, the subgame perfect equilibrium in the Rubinstein alternating-offers is not unique in this case. Therefore, it is neither guaranteed that an agreement is struck in round 1 nor that it is reached at all. In terms of welfare, however, it is irrelevant whether countries remain in the status quo because they have agreed on it or because they permanently disagree on how to change the status quo.

*$\mu \leq \mu_1^0$ or $\mu \geq \mu_2^0$ bargaining results in $\bar{E}_N^* = (\kappa + 1)e_{1,0}$ and $W_N^* = 0$.*

For *national CAPs*, however, each country obtains a welfare greater than zero. By definition of a Nash equilibrium country $i$'s cap is the optimal response to the cap chosen by the other country $-i$. If country $i$ deviates and chooses $\bar{e}_i = e_{i,0}$, i.e., zero abatement $a_i = 0$, instead of $\bar{e}_i = \bar{e}_{i,C}^*$ then this leads to a strictly reduced welfare for country $i$. But even this deviation generates welfare $W_i \geq 0$ since $\bar{e}_{-i,C}^* \leq e_{-i,0}$ because country $i$ still benefits from the abatement of county $-i$ but does not experience any costs. Therefore, we obtain that $W_{i,C}^* > 0$ and $W_C^* = W_{1,C}^* + W_{2,C}^* > 0$.

As might be reasonably expected, the counter factual leads to a lower welfare compared to the social optimum, since the social planner takes the costs and benefits of both countries into account, whereas in the counterfactual scenario each country optimizes separately without considering cross-border benefits and cheap abatement options. This leads to two different effects.

First, the overall cap is *higher* in the counter factual scenario, i.e., the total abatement activities are lower. More precisely, using Equations (14) and (21), we can calculate the difference to the optimal cap as

$$\bar{E}_C^* - \bar{E}_S^* = \frac{\beta_1 + \beta_2}{2\delta + \frac{\zeta_1\zeta_2}{\zeta_1+\zeta_2}} \left[ 1 - \frac{1 + \frac{\delta}{\delta + \frac{\zeta_1\zeta_2}{\zeta_1+\zeta_2}}}{2 + \frac{(\zeta_1-\zeta_2)(\beta_1-\beta_2)}{\zeta_2\beta_1+\zeta_1\beta_2}} \right] > 0. \tag{32}$$

For $\beta_1 > \beta_2$, the difference is positive and increasing in $\beta_1$, which implies that the higher the difference $\beta_1 - \beta_2$, the higher the difference from the overall abatement activities in the counter factual scenario to the socially optimal abatement. Intuitively, since its benefits are increased country 1 sets a lower national cap $\bar{e}_{1,C}^*$ to implement higher national abatement. Country 2, on the contrary, can free ride on this abatement activities by setting a higher nationally cap $\bar{e}_{2,C}^*$ thereby reducing its cost. As a result, the total cap increases less than it would be socially optimal.

Second, the abatement activities induced by the $\bar{E}_C^*$ are *inefficient*, i.e., the same total abatement could be implemented with lower costs. A certain overall abatement is implemented efficiently if the abatement activities are distributed among the countries such that their marginal costs are equal. The cap and trade system provides the efficient distribution, where we have that

$$\frac{a_1}{a_2} = \frac{\zeta_2}{\zeta_1}. \tag{33}$$

For national CAPs, however, we obtain the following distribution among the countries:

$$\frac{a_1}{a_2} = \frac{\zeta_2\beta_1 + \delta(\beta_1 - \beta_2)}{\zeta_1\beta_2 - \delta(\beta_1 - \beta_2)} \tag{34}$$

For $\beta_1 > \beta_2$, country 1 abates too much, while country 2 abates too little. Moreover, this ratio is increasing in $\beta_1$, i.e., the higher difference $\beta_1 - \beta_2$ the higher the inefficiency. Lemma 5 summarizes the results for national CAPs.

**Lemma 5** *The overall welfare of national CAPs, $W_C^*$, is greater than zero but smaller than the socially optimal, i.e., $0 < W_C^* < W_S^*$. The difference to the social optimum, $W_S^* - W_C^*$, increases in $\beta_1$.*

Combining Lemma 4 and Lemma 5 yields the following proposition.

**Proposition 2** *For $\mu \in [0, 1]$ and $\beta_1 \in [\beta_2, \overline{\beta}_1]$, we have that $W_N^* > W_C^*$ if $\mu$ is sufficiently close to $\mu_S^*$ and $W_N^* < W_C^*$ if $\mu$ is sufficiently close to either $\mu_1^0$ or $\mu_2^0$.*

This is particularly the case, when the countries' benefit structures differ substantially, i.e., $\beta_1$ close to $\overline{\beta}_1$. National CAPs then lead to a significantly lower welfare compared to the social optimum due to *i*) substantial deviations from the optimal abatement *ii*) highly inefficient distribution of the abatement activities among the countries. Therefore, bargaining also leads to a significantly better outcome than national caps, if the ex-ante determined allocation of certificates is significantly close to zero.

# 5 Conclusion

In our two-country model, countries have already committed to jointly implement an emissions trading scheme and bargain over the total emissions cap. We model the cap negotiation as an alternating-offers model, following Rubinstein (1982), and show that even for moderate differences in baseline emissions the initial endowment of permit rights based on historical emissions never leads to the social optimum. However, we can determine allocations that lead to the optimum, where the allocation of allowances can be seen as a form of compensation payment between countries. In this case, the country with high emissions but low benefits and costs of abatement receives a higher share of allowances, resulting in a more stringent emissions cap. This compensation mechanism is only possible to a certain extent and depends on the countries' benefit functions.

If the countries' benefit structures of abatement are too different ($\beta_1 > \bar{\beta}_1$) we cannot find an allocation of allowances between countries that implements the social optimum. This results from the fact that the redistribution of the initial endowment is limited, as a country cannot receive more than the total quantity of allowances.

Although it is not always possible to achieve the socially optimal level of emissions, from a global perspective, bargaining can lead to a better solution than having national emission trading schemes with a national emissions cap instead.

We are aware that we have made a strong modeling assumptions, namely the countries have already agreed to implement a joint emissions trading system in a sense that they cannot opt out of the bargaining. Further research is necessary to verify our results in extensions of the alternating-offers model that allow the bargaining to end without an agreement. The most plausible approach is by allowing the parties to strategically opt out of the bargaining such that national caps are implemented. Integrating this outside option still allows to exploit the relation between the subgame perfect equilibrium in the alternating-offers model and the Nash bargaining solution. Merely the set of feasible caps for an agreement is weakly smaller, since these caps must not only be element of $\mathscr{P}$ but also ensure that each country gets a weakly higher welfare than in the case of national caps (Binmore, 1985; Muthoo, 1999).

Another alternative approach for allowing for the collapse of the bargaining is the integration of the risk of a random breakdown in the sense that one party gets suddenly fed up and leaves the negotiating table such that national caps are implemented [13]. Again, it is possible to exploit the relation to the Nash bargaining solution, where the Nash product now takes the form $(W_1 - d_1) \cdot (W_2 - d_2)$. In this setting, the disagreement point $(d_1, d_2)$ is calculate from the countries welfare in case of national caps and the arrival rates of the breakdown (Binmore et al., 1986; Muthoo, 1999).

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[13] Essentially this can be seen as an "agreement to disagree", which is plausible in behavioural settings (Binmore et al., 1986), while it is inconsistent for rational agents with common knowledge (Aumann, 1976).

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# Appendix

## A Proof of Lemma 1

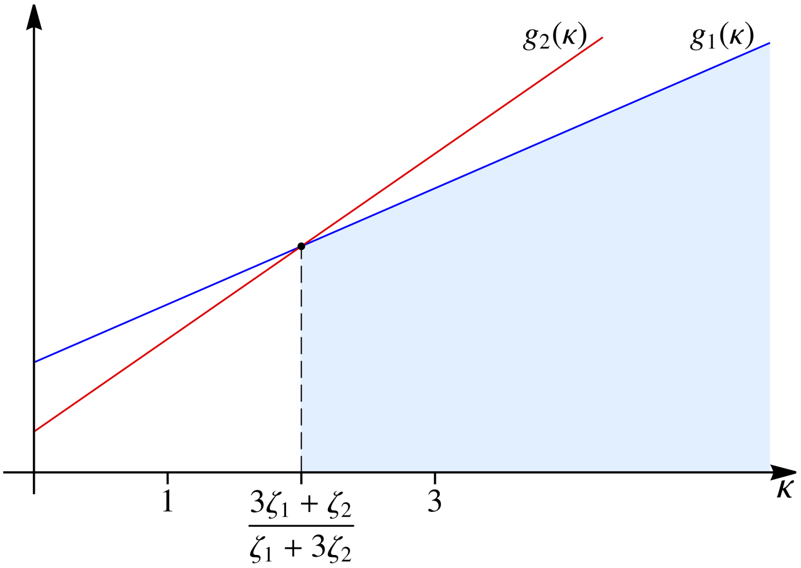
Differentiating (24) and (25) with respect to $\mu$ yields

$$\frac{\partial \bar{E}_1^*}{\partial \mu} > [<] 0 \iff \frac{\beta_1}{e_{1,0}} > [<] \overbrace{\frac{1}{2}\left[\delta + \frac{\zeta_1\zeta_2(2\zeta_1+\zeta_2)}{(\zeta_1+\zeta_2)^2}\right] + \frac{\kappa}{2}\left[\delta - \zeta_1\left(\frac{\zeta_2}{\zeta_1+\zeta_2}\right)^2\right]}^{g_1(\kappa):=} \tag{35}$$

$$\frac{\partial \bar{E}_2^*}{\partial \mu} > [<] 0 \iff \frac{\beta_2}{e_{1,0}} < [>] \overbrace{\frac{1}{2}\left[\delta - \zeta_2\left(\frac{\zeta_1}{\zeta_1+\zeta_2}\right)^2\right] + \frac{\kappa}{2}\left[\delta + \frac{\zeta_1\zeta_2(\zeta_1+2\zeta_2)}{(\zeta_1+\zeta_2)^2}\right]}^{g_2(\kappa):=}. \tag{36}$$

The light blue area in Figure 5 shows the set of feasible $\beta_1/e_{1,0}$ given Assumptions (*ii*) and (*iii*). Hence, we have that $\partial \bar{E}_1^*/\partial \mu < 0$. Since we additional get for $\kappa > (3\zeta_1+\zeta_2)/(\zeta_1+3\zeta_2)$ that $g_2(\kappa) > g_1(\kappa) > \beta_1/e_{1,0} > \beta_2/e_{1,0}$, we can immediately conclude that $\partial \bar{E}_2^*/\partial \mu > 0$.

**Figure 5: Feasible parameter sets of $\beta_1/e_{1,0}$.**



□

## B Proof of Lemma 2

Let us first consider the case where $\bar{E}_1^* < \bar{E}_2^* < (\kappa+1)e_{1,0}$, see Figure 1. Evaluating the derivative of the Nash product at the lower bound of $\mathscr{P}$, we obtain, by definition of $\bar{E}_1^*$, that

$$W_1'\left(\bar{E}_1^*\right) \cdot W_2\left(\bar{E}_1^*\right) + W_1\left(\bar{E}_1^*\right) \cdot W_2'\left(\bar{E}_1^*\right) = W_1\left(\bar{E}_1^*\right) \cdot W_2'\left(\bar{E}_1^*\right) > 0. \tag{37}$$

By contrast, evaluating the derivative of the Nash product at the upper bound of $\mathscr{P}$, we obtain, by definition of $\bar{E}_2^*$, that

$$W_1'\left(\bar{E}_2^*\right) \cdot W_2\left(\bar{E}_2^*\right) + W_1\left(\bar{E}_2^*\right) \cdot W_2'\left(\bar{E}_2^*\right) = W_1'\left(\bar{E}_2^*\right) \cdot W_2\left(\bar{E}_2^*\right) < 0. \tag{38}$$

The INTERMEDIATE VALUE THEOREM implies that a solution to the FOC exists. Moreover, we have that $W_1'\left(\bar{E}\right) \cdot W_2\left(\bar{E}\right)$ as well as $W_1\left(\bar{E}\right) \cdot W_2'\left(\bar{E}\right)$ are decreasing for $\bar{E} \in \mathscr{P}$, such that the Nash product is strictly concave on that interval. Thus, the FOC has a unique solution for $\bar{E} \in \mathscr{P}$

which constitutes a global maximum.
Next consider the case where $\bar{E}_1^* < (\kappa+1)e_{1,0} \leq \bar{E}_2^*$, see Figure 4. In that case, we have that

$$W_1'\Big((\kappa+1)e_{1,0}\Big)\cdot W_2\Big((\kappa+1)e_{1,0}\Big) + W_1\Big((\kappa+1)e_{1,0}\Big)\cdot W_2'\Big((\kappa+1)e_{1,0}\Big) = 0. \tag{39}$$

Furthermore, by construction, the Nash product is zero for $(\kappa+1)e_{1,0}$ and strictly negative for all other $\bar{E} \in \mathscr{P}$. Hence, $(\kappa+1)e_{1,0}$ constitutes the unique global maximum for $\bar{E} \in \mathscr{P}$ and it satisfies the FOC.
For the cases where $\bar{E}_2^* < \bar{E}_1^* < (\kappa+1)e_{1,0}$ and $\bar{E}_2^* < (\kappa+1)e_{1,0} \leq \bar{E}_1^*$, the same arguments apply only the indices are reversed.[14] □

# C Proof of Lemma 3

First, note that $\bar{E}_S^*$ and $\bar{E}_N^*$ are unique by Equation 14 and Lemma 2, respectively. According to Lemma 2, the Nash bargaining solution satisfies

$$\begin{aligned} &C_1'(a_1(\bar{E}_N^*))\left[\mu + (1-\mu)\theta(\bar{E}_N^*)\right] \\ &= B_1'(A(\bar{E}_N^*)) + \theta(\bar{E}_N^*)B_2'(A(\bar{E}_N^*)) + x_{12}\frac{\zeta_1\zeta_2}{\zeta_1+\zeta_2}\left(1-\theta(\bar{E}_N^*)\right), \end{aligned} \tag{40}$$

while it holds for the efficient cap that

$$C_1'(a_1(\bar{E}_S^*)) = B_1'(A(\bar{E}_S^*)) + B_2'(A(\bar{E}_S^*)). \tag{41}$$

If we have that $\theta(\bar{E}_N^*) = 1$, then Equation (40) simplifies to

$$C_1'(a_1(\bar{E}_N^*)) = B_1'(A(\bar{E}_N^*)) + B_2'(A(\bar{E}_N^*)). \tag{42}$$

Comparing to Equation 41 immediately yields that $\bar{E}_S^* = \bar{E}_N^*$. Now, consider the opposite direction. If we have that $\bar{E}_S^* = \bar{E}_N^*$, then Equation 41 implies that

$$C_1'(A(\bar{E}_N^*)) = B_1'(A(\bar{E}_N^*)) + B_2'(A(\bar{E}_N^*)).$$

A comparison to Equation 40 directly reveals that we must have $\theta(\bar{E}_N^*) = 1$. □

# D Proof of Proposition 1

First, we establish a relation that we will use throughout the proof:

$$x_{12} = \mu\bar{E} - (e_{1,0} - a_1(\bar{E})) = -(1-\mu)\bar{E} + (\kappa e_{1,0} - a_2(\bar{E})). \tag{43}$$

Now we start the proof by using the definition of $\theta(\bar{E}) = 1$ if and only if $\bar{E}_S^* = \bar{E}_N^*$. Inserting the definition of $\theta(\bar{E})$ yields

$$\frac{B_1(A(\bar{E}_N^*)) - C_1(a_1(\bar{E}_N^*)) + x_{12}C_1'(a_1(\bar{E}_N^*))}{B_2(A(\bar{E}_N^*)) - C_2(a_2(\bar{E}_N^*)) - x_{12}C_1'(a_1(\bar{E}_N^*))} = 1. \tag{44}$$

Rearranging this expression and using the functional forms of $B_i(A(\bar{E}))$ and $C_i(a_i(\bar{E}))$ leads to

$$-\frac{(\zeta_1+\zeta_2)(\beta_1-\beta_2)}{2\zeta_1\zeta_2} - \frac{\left[(\kappa+1)e_{1,0} - \bar{E}_N^*\right](\zeta_1-\zeta_2)}{4(\zeta_1+\zeta_2)} = x_{12}. \tag{45}$$

Inserting Equation (43) and rearranging for $\mu$ yields

$$1 + \frac{a(\bar{E}_N^*) - \kappa e_{1,0}}{\bar{E}} - \frac{(\zeta_1+\zeta_2)(\beta_1-\beta_2)}{2\zeta_1\zeta_2\bar{E}_N^*} - \frac{\left[(\kappa+1)e_{1,0} - \bar{E}_N^*\right](\zeta_1-\zeta_2)}{4(\zeta_1+\zeta_2)\bar{E}_N^*} = \mu. \tag{46}$$

---

[14] Note that the cases where $(\kappa+1)e_{1,0} \leq \bar{E}_1^* \leq \bar{E}_2^*$ and $(\kappa+1)e_{1,0} \leq \bar{E}_2^* \leq \bar{E}_1^*$ cannot occur in our model due to the quadric structure of benefits and costs.

Since we have that $\bar{E}_N^* = \bar{E}_S^*$, we can insert Equation (14). Simplifying finally leads to the desired result:

$$\mu_S^* = \frac{e_{1,0}\left[2\delta(\zeta_1+\zeta_2)+\zeta_1\zeta_2\right] - \delta\frac{(\zeta_1+\zeta_2)^2}{\zeta_1\zeta_2}(\beta_1-\beta_2) - \frac{1}{4}\Bigg[(3\zeta_1+5\zeta_2)\beta_1 - (\zeta_1-\zeta_2)\beta_2\Bigg]}{(\kappa+1)e_{1,0}\left[2\delta(\zeta_1+\zeta_2)+\zeta_1\zeta_2\right] - (\zeta_1+\zeta_2)(\beta_1+\beta_2)}. \tag{47}$$

□

# E Proof of Corollary 1

First, we turn to $\overline{\beta}$. Note that the numerator of (29) is decreasing in $\beta_1$. Hence, $\mu_S^* = 0$ if and only if

$$e_{1,0}\left[2\delta(\zeta_1+\zeta_2)+\zeta_1\zeta_2\right] - \delta\frac{(\zeta_1+\zeta_2)^2}{\zeta_1\zeta_2}(\beta_1-\beta_2) - \frac{1}{4}\Bigg[(3\zeta_1+5\zeta_2)\beta_1 - (\zeta_1-\zeta_2)\beta_2\Bigg] = 0 \tag{48}$$

Solving Equation (48) for $\beta_1$ leads us to

$$\overline{\beta}_1 = \frac{4\zeta_1\zeta_2 e_{1,0}\left[2\delta(\zeta_1+\zeta_2)+\zeta_1\zeta_2\right] + \beta_2\left[4\delta(\zeta_1+\zeta_2)^2 + \zeta_1\zeta_2(\zeta_1-\zeta_2)\right]}{\zeta_1\zeta_2(3\zeta_1+5\zeta_2) + 4\delta(\zeta_1+\zeta_2)^2} \tag{49}$$

Second, note that the denominator of (29) is positive if only if:

$$\frac{\beta_1+\beta_2}{e_{1,0}} < (\kappa+1)\left(2\delta + \frac{\zeta_1\zeta_2}{\zeta_1+\zeta_2}\right) \tag{50}$$

Since we have that

$$\begin{aligned}
\frac{\beta_1+\beta_2}{e_{1,0}} &< 2\frac{\beta_1}{e_{1,0}} \\
&< \left[\delta + \frac{\zeta_1\zeta_2(2\zeta_1+\zeta_2)}{(\zeta_1+\zeta_2)^2}\right] + \kappa\left[\delta - \zeta_1\left(\frac{\zeta_2}{\zeta_1+\zeta_2}\right)^2\right] \\
&= \left[\delta + \zeta_2\left(\frac{\zeta_1}{(\zeta_1+\zeta_2)}\right)^2 + \frac{\zeta_1\zeta_2}{(\zeta_1+\zeta_2)}\right] + \kappa\left[\delta - \zeta_1\left(\frac{\zeta_2}{\zeta_1+\zeta_2}\right)^2\right] \\
&< \left[2\delta + \frac{\zeta_1\zeta_2}{(\zeta_1+\zeta_2)}\right] + \kappa\left[\delta - \zeta_1\left(\frac{\zeta_2}{\zeta_1+\zeta_2}\right)^2\right] \\
&< (\kappa+1)\left(2\delta + \frac{\zeta_1\zeta_2}{\zeta_1+\zeta_2}\right),
\end{aligned}$$

Inequality (50) holds and we must have that the denominator of (29) is always positive. Because $g_1(\kappa)$ is increasing in $\kappa$, cf. Appendix A while $\overline{\beta}_1/e_{1,0}$ is independent of $\kappa$ we must necessarily have that $\overline{\beta}_1/e_{1,0} < g_1(\kappa)$ for $\kappa$ sufficiently large. In other words, for $\kappa$ sufficiently large, we obtain feasible ratios $\beta_1/e_{1,0}$ where $\mu_S^* < 0$.

To determine $\partial\mu_S^*/\partial\beta_1$ we need to apply the quotient rule. The sign of the derivative, however, is determined by sign of the numerator of the resulting quotient. Hence, we get that

$$\begin{aligned}
\frac{\partial\mu_S^*}{\partial\beta_1} \overset{\text{sign}}{=} &-\left[\frac{\delta(\zeta_1+\zeta_2)^2}{\zeta_1\zeta_1} + \frac{1}{4}(3\zeta_1+5\zeta_2)\right]\Bigg[(\kappa+1)\eta - (\zeta_1+\zeta_2)(\beta_1+\beta_2)\Bigg] \\
&+ \Bigg[(\zeta_1+\zeta_2)\Bigg]\left[\eta - \frac{\delta(\zeta_1+\zeta_2)^2}{\zeta_1\zeta_2} - \frac{1}{4}\left[(3\zeta_1+5\zeta_2)\beta_1 - (\zeta_1-\zeta_2)\beta_2\right]\right]
\end{aligned} \tag{51}$$

where we defined $\eta = e_{1,0}[2\delta(\zeta_1+\zeta_2)+\zeta_1\zeta_2]$. Now, note that the r.h.s. of 51 is linear in $\beta_1$, i.e. it has a single root. Hence, we can conclude that $\mu_S^*$ is decreasing in $\beta_1$ on the entire interval $[\beta_2, \overline{\beta}_1]$, if we have that $\partial\mu_S^*/\partial\beta_1 < 0$ for $\beta_1 \to \beta_2$ and for $\beta_1 \to \overline{\beta}_1$.[15] First, we turn to $\beta_1 \to \overline{\beta}_1$. By definition of $\overline{\beta}_1$, we get that

$$\lim_{\beta_1 \to \overline{\beta}_1} \frac{\partial \mu_S^*}{\partial \beta_1} \overset{\text{sign}}{=} -\left[\frac{\delta(\zeta_1+\zeta_2)^2}{\zeta_1\zeta_1} + \frac{1}{4}(3\zeta_1 + 5\zeta_2)\right]\left[(\kappa+1)\eta - (\zeta_1+\zeta_2)(\overline{\beta}_1 + \beta_2)\right] < 0. \tag{52}$$

Second, let us analyze $\beta_1 \to \beta_2$, where we obtain that

$$\begin{aligned}\lim_{\beta_1 \to \beta_2} \frac{\partial \mu_S^*}{\partial \beta_1} \overset{\text{sign}}{=} & -\left[\frac{\delta(\zeta_1+\zeta_2)^2}{\zeta_1\zeta_1} + \frac{1}{4}(3\zeta_1 + 5\zeta_2)\right]\left[(\kappa+1)\eta - (\zeta_1+\zeta_2)2\beta_2\right] \\ & + \left[(\zeta_1+\zeta_2)\right]\left[\eta - \frac{\delta(\zeta_1+\zeta_2)^2}{\zeta_1\zeta_2} - \frac{7}{4}\zeta_1\beta_2 - \frac{1}{4}\zeta_2\beta_2\right].\end{aligned} \tag{53}$$

To establish the negative sign, it is sufficient to show that the factors in the first line in 53 are greater than the factors in the second line. For the first factor, we obtain that

$$\begin{aligned}\frac{\delta(\zeta_1+\zeta_2)^2}{\zeta_1\zeta_1} + \frac{1}{4}(3\zeta_1 + 5\zeta_2) &> \zeta_1 + \frac{1}{4}(3\zeta_1 + 5\zeta_2) \\ &= \frac{7}{4}\zeta_1 + \frac{5}{4}\zeta_2 \\ &> \zeta_1 + \zeta_2.\end{aligned} \tag{54}$$

Comparing the second factors leads to

$$(\kappa+1)\eta - (\zeta_1+\zeta_2)2\beta_2 > \eta - \frac{\delta(\zeta_1+\zeta_2)^2}{\zeta_1\zeta_2} - \frac{7}{4}\zeta_1\beta_2 - \frac{1}{4}\zeta_2\beta_2, \tag{55}$$

which can be rearranged to

$$\frac{4\,\kappa\,\eta}{\zeta_1 + 7\zeta_2} + \frac{\delta(\zeta_1+\zeta_2)^2}{\zeta_1\zeta_2(\zeta_1+7\zeta_2)} > \beta_2. \tag{56}$$

To see that Inequality 56 is indeed always satisfied, note that

$$\begin{aligned}\frac{4\,\kappa\,\eta}{\zeta_1 + 7\zeta_2} + \frac{\delta(\zeta_1+\zeta_2)^2}{\zeta_1\zeta_2(\zeta_1+7\zeta_2)} &> \frac{4\,\kappa\,\eta}{\zeta_1 + 7\zeta_2}, \\ &= 4\,\kappa\,e_{1,0}\left[2\delta\,\frac{\overbrace{(\zeta_1+\zeta_2)}^{>\frac{1}{4}}}{\zeta_1+7\zeta_2} + \frac{\zeta_1\zeta_2}{\zeta_1+7\zeta_2}\right], \\ &> \frac{e_{1,0}}{2}\left[4\delta\,\kappa + 8\kappa\frac{\zeta_1\zeta_2}{\zeta_1+7\zeta_2}\right],\end{aligned} \tag{57}$$

which we can further estimate downwards, since $\kappa > 1$, to

$$\begin{aligned}&> \frac{e_{1,0}}{2}\left[2\delta\,\kappa + \delta + \zeta_2\left(\frac{\zeta_1}{\zeta_1+\zeta_2}\right)^2 + \frac{\zeta_1\zeta_2}{\frac{1}{8}\zeta_1 + \frac{7}{8}\zeta_2}\right], \\ &> \frac{e_{1,0}}{2}\left[\kappa\left[\delta - \zeta_1\left(\frac{\zeta_2}{\zeta_1+\zeta_2}\right)^2\right] + \delta + \zeta_2\left(\frac{\zeta_1}{\zeta_1+\zeta_2}\right)^2 + \frac{\zeta_1\zeta_2}{\zeta_1+\zeta_2}\right], \\ &= \frac{e_{1,0}}{2}\left[\delta + \frac{\zeta_1\zeta_2(2\zeta_1+\zeta_2)}{(\zeta_1+\zeta_2)^2} + \kappa\left[\delta - \zeta_1\left(\frac{\zeta_2}{\zeta_1+\zeta_2}\right)^2\right]\right], \\ &> \beta_1 = \beta_2.\end{aligned}$$

Hence, we have that

$$\lim_{\beta_1 \to \beta_2} \frac{\partial \mu_S^*}{\partial \beta_1} < 0,$$

which implies that $\mu_S^*$ is decreasing in $\beta_1$ on the entire interval $[\beta_2, \overline{\beta}_1]$. □

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[15] We focus on the interesting case where $\overline{\beta}_1$ is feasible, i.e. where $\overline{\beta}_1/e_{1,0} < g_1(\kappa)$.

# F Proof of Corollary 2

Since we have already established that $\frac{\partial \mu_S^*}{\partial \beta_1} < 0$ for $\beta_1 \in [\beta_2, \overline{\beta}_1]$, we need to show now that

$$\lim_{\beta_1 \to \beta_2} \mu_S^* < \frac{1}{\kappa + 1}. \tag{58}$$

Taking the limits and rearranging leads us to

$$\frac{3\zeta_1 + \zeta_2}{\zeta_1 + 3\zeta_2} < \kappa \tag{59}$$

Which is satisfied according to our assumptions. □

# G Proof of Lemma 5

Using the Envelope Theorem, we get for $W_S^*$ that

$$\frac{\partial W_S^*}{\partial \beta_1} = (\kappa + 1)\, e_{1,0} - \bar{E}_S^*. \tag{60}$$

By contrast, differentiating and simplifying yields for $W_C^*$ that

$$\frac{\partial W_C^*}{\partial \beta_1} = (\kappa + 1)\, e_{1,0} - \bar{E}_C^* - \frac{\zeta_2 \beta_1 [\zeta_1 \zeta_2 + 2\delta(\zeta_1 + \zeta_2)] + \delta^2 (\beta_1 - \beta_2)(\zeta_1 + \zeta_2)}{[\zeta_1 \zeta_2 + \delta(\zeta_1 + \zeta_2)]^2}. \tag{61}$$

Subtracting (61) from (60) then leads to

$$\frac{\partial W_S^*}{\partial \beta_1} - \frac{\partial W_C^*}{\partial \beta_1} = \bar{E}_C^* - \bar{E}_S^* + \frac{\zeta_2 \beta_1 [\zeta_1 \zeta_2 + 2\delta(\zeta_1 + \zeta_2)] + \delta^2 (\beta_1 - \beta_2)(\zeta_1 + \zeta_2)}{[\zeta_1 \zeta_2 + \delta(\zeta_1 + \zeta_2)]^2}. \tag{62}$$

Since we have already established in (32) that $\bar{E}_C^* - \bar{E}_S^* > 0$, we can immediately conclude that

$$\frac{\partial W_S^*}{\partial \beta_1} - \frac{\partial W_C^*}{\partial \beta_1} > 0, \tag{63}$$

or, in other words, that the difference $W_S^* - W_C^*$ is increasing in $\beta_1$. □

# Conclusion

The papers presented in this dissertation have contributed to relevant topics in empirical energy economics and theoretical environmental economics. Articles within the field of energy economics mainly concentrated on the adverse effects of subsidized renewables on the energy system. The articles in environmental economics focused on the introduction of a unilateral price floor in emissions trading systems and the negotiation process for the emissions cap. However, the research in these two fields should not be considered separately, as both research directions address efficient emissions reduction and carbon pricing as well as closely related issues.

The first article empirically quantified the adverse effect of subsidies for renewables on the profitability of energy storages. The research found that renewables may lower investment incentives into energy storages by eroding their profits, while also presenting a potential remedy in the form of intensifying carbon pricing.

The second article concentrated on the self-cannibalization effect of renewables. Based on regression estimations, the analysis showed the dampening effect of renewables on their own market value. This revealed another adverse effect of subsidized renewables. A higher carbon price which boosts the market value of renewables has been demonstrated as a solution.

These two empirical contributions provide deeper insights about *non-market-based* state interventions in form of subsidies for renewables and the resulting undesirable market distortions in the energy sector. The analyses were conducted for the German (or German-Austrian) energy market, which is characterized by a vast share of renewable energies. This is particularly distressing, as it may impede the energy transition towards zero-carbon technologies. Lower energy storage profitability leads to lower investment and ultimately lower capacity increases. However, energy storages present a key technology for balancing the fluctuations of renewable energy infeed (Dunn et al., 2011; Zerrahn et al., 2018). Thus, the technology is essential to integrate vast shares of renewables into an energy system, maintain the security of electricity supply (Braff et al., 2016; Carson and Novan, 2013) and achieve an effective transition towards zero-carbon technologies (López Prol and Schill, 2021; Sinn, 2017). In addition to the expansion of balancing capacities, it is vital that market values and thus investment incentives for renewable energies remain high. This becomes a problem for the competitiveness of renewables versus conventional power plant types should the fall in market value exceed the reduction in costs (c.f. Lòpez Prol et al., 2021; Zipp, 2017). As a contribution to the "general theory of second-best" (Lipsey and Lancaster, 1956), the two empirical papers presented examples for undesirable efficiency losses due to a *non-market-based* approach, i.e. subsidies for renewables. In this context, the findings emphasized the advantage of a *market-based* approach in form of carbon pricing.

The transition to zero-carbon energy markets poses challenges for the energy system. Germany, with its pioneering role in renewable energies, represents a highly relevant case to analyze the effects of the high feed-in from renewable energies on the energy sector. The results are also of great political import for other countries aiming at a high share of renewable energies. If potential negative effects are already considered and addressed during the implementation of state interventions, it can increase efficiency and accelerate the energy transition. The empirical analyses are limited to the German and German-Austrian energy markets. Therefore, the results and implications are not universally applicable. Since the power plant park, the feed-in profile of renewables, and the environmental regulation differ from country to country, the results may vary. It is left for future research to investigate the issues for other energy markets and feed-in profiles of renewable energies. This can support a smooth transition of the energy sector to renewable energies and the reduction of emissions from energy generation.

The third article examined whether a unilateral price floor could be beneficial as a supplement to an existing emissions trading system by providing a theoretical model with abatement cost uncertainty. The model identified the conditions under which the unilateral price floor leads to additional abatement during periods of low prices, and thus to an additional benefit. It became apparent that a more pronounced cost shock widens the range of welfare-improving unilateral price floors and a relatively loose emissions cap favors the implementation of the additional unilateral policy.

The design of *market-based* mechanisms plays a decisive role in how well a system functions and abates emissions. If an externality is not priced correctly, it leads to inefficiencies Pigou (1920). That is, if the price is too low (high), there is an over (under) provision of the good causing the external effect. Due to uncertainties, emissions trading systems can lead to price fluctuations and unintended price signals (see, e.g., Fell et al., 2012; McKibbin and Wilcoxen, 2002; Roberts and Spence, 1976; Wood and Jotzo, 2011). As a result, the abatement level can be insufficient in times of low prices – due to ongoing climate change, this case is particularly unintended. For this reason, the design of the systems and price control measures to strengthen abatement activities represent an important area of research. If the integration of a price floor into an emissions trading system fails (e.g., for political reasons), the analysis of a unilateral price floor is particularly relevant.

Since the established model is based on a static setting with two homogeneous countries and identical shock for both countries, it might serve as the starting point for future extensions. Regarding the third article, this could include i) an endogenous emissions cap ii) heterogeneous countries iii) a dynamic model environment iv) different abatement cost shock distributions or v) a cancellation mechanism of allowances.

The theoretical analysis of emissions cap negotiations in emissions trading systems was subject of the fourth article. The research demonstrated that if countries are rather dissimilar or the permit allocation is based on historical emissions, negotiations never result in the social optimal emissions cap. However, it has been shown that the allocation of permits can to a certain extent be used to achieve the socially optimal emissions cap.

To ensure a sufficient emissions abatement, the externality has to be fully internalized. In emissions trading systems, it depends on the implemented emissions cap. Countries that have agreed to jointly implement or link an emissions trading system then set the emissions cap (the number of allowances). If a loose cap is set, this will result in little abatement and a low market price which does not internalize the externality correctly. Since the endogenous choice of the emissions level by each country may not lead to a reduction (Helm, 2003), the investigation of negotiation processes is an important issue. Negotiations between countries with different characteristics lead to contrasting objectives regarding the emissions cap. The important question becomes: can the negotiation process result in the social optimal emissions cap? The lessons learned from these negotiations can help better understand and design emissions trading systems. This is essential for the successful implementation of an emission trading scheme and the resulting emissions reduction, thus highlighting the importance of research in this field.

A strong assumption in this model is that countries have already agreed to jointly implement an emissions trading system. Consequently, negotiations in this model framework cannot fail. In addition, we do not consider the strategic behavior of delegates in our model. The presented model could be extended by i) allowing countries to opt out ii) integrating the risk of a breakdown or iii) including strategic delegations.

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# Curriculum Vitae

## Fabian Dominik Naumann

## Education

| | |
|---|---|
| 11/2017 - 12/2022 | **Chair or Environmental Economics, University of Kaiserslautern**<br>PhD Student |
| 10/2015 - 10/2017 | **University of Ulm**<br>M.Sc. in Sustainable Management |
| 09/2012 - 09/2015 | **Baden-Württemberg Cooperative State University Karlsruhe**<br>B.Sc. in Business Informatics |