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Complementing carbon prices with Carbon Contracts for Difference in the presence of risk - When is it beneficial and when not?

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Abstract

Deep decarbonisation requires large-scale irreversible investments throughout the next decade. Policymakers propose Carbon Contracts for Differences (CCfDs) to incentivise such investments in the industry sector. CCfDs are contracts between a regulator and a firm that pay out the difference between a guaranteed strike price and the actual carbon price per abated emissions by an investment. We develop an analytical model to assess the welfare effects of CCfDs and compare it to other carbon pricing regimes. In our model, a regulator can offer CCfDs to risk-averse firms that decide upon irreversible investments into an emission-free technology in the presence of risk. Risk can originate from the environmental damage or the variable costs of the emission-free technology. We find that CCfDs can be beneficial policy instruments, as they hedge firms' risk, encouraging investments when firms' risk aversion would otherwise inhibit them. In contrast to mitigating firms' risk by an early carbon price commitment, CCfDs maintain the regulator's flexibility to adjust the carbon price if new information reveals. However, as CCfDs hedge the firms' revenues, they might safeguard production with the emission-free technology, even if it is ex-post socially not optimal. In this case, regulatory flexibility can be welfare superior to offering a CCfD.

Keywords: Climate policy, carbon pricing, risk, Carbon Contracts for Difference
JEL classification: H23, L51, O31, Q55, Q58

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1. Introduction

The decarbonisation of the industrial sector requires substantial investments throughout the next decade (IEA, 2021). These investments are typically irreversible decisions that firms have to take in the presence of risk. The risk of an investment's profitability in a decarbonising world mainly stems from two sources:

First, the profitability of investments in low-carbon or emission-free technologies depends on carbon prices. These technologies are only competitive with conventional technologies if the carbon price throughout the asset's economic life reaches a certain level. However, carbon prices may feature risk. One reason is that the expected carbon damage may change as new scientific evidence on climate change emerges.[1] Another reason is the potentially changing public valuation of carbon damage, shown by court rulings on climate policy in 2021 in Germany (Economist, 2021; Bundesverfassungsgericht, 2021). Both circumstances create a *damage risk*. Firms facing irreversible investments are exposed to such a damage risk as the regulator may adjust the carbon price according to these changes. In fact, Chiappinelli et al. (2021) report that four out of five firms state that the lack of effective and predictable carbon pricing mechanisms is a major barrier to low-carbon investments. López Rodríguez et al. (2017) or Dorsey (2019) provide further empirical analysis that firms reduce their investments due to environmental regulation-related risks.

Second, there is a *variable cost risk*. Variable costs of low-carbon technologies are not fully known, as adopting innovative production processes may involve novel input factors. The markets for some of these input factors are highly immature, the most prominent example being green hydrogen. The production costs of hydrogen might vary depending, e.g., on the costs of electricity or transport (Brändle et al., 2021). Additionally, there is an active and ongoing market ramp-up involving multiple stakeholders to facilitate technological learning (Schlund et al., 2021). Hence, the market for hydrogen is still at the beginning of organising itself (IEA, 2019).

Firms' possibilities to hedge against these risks are limited or prohibitively costly.[2] For instance, in the European Emission Trading System (EU ETS), the availability of futures contracts with a maturity longer than three years is low (Newbery et al., 2019).[3] Similarly, there are limited hedging possibilities against variable cost risk from novel input factors traded on immature markets (OEIS, 2021). The described risks and the missing hedging possibilities deter firms from investing, which, in turn, poses a challenge to decarbonisation.

To nevertheless facilitate and incentivise large-scale investments in the presence of such risks, the European Commission's Hydrogen Strategy and the reform proposal for a *Fit for 55* package, suggest Carbon Contracts for Differences (CCfDs) as a support scheme for firms in the industry sector (European Commission, 2021a). CCfDs are contracts between the government and a firm that pay out the difference between a guaranteed price, the so-called *strike price*, and the actual carbon price, per tonne of emission reduction delivered by the firm through a low-carbon project. The contracts can be interpreted as a short position in a forward on emission permits. Therefore, CCfDs are effectively a hedging instrument to reduce the firms'

[1] For instance, the Sixth Assessment Report of the Intergovernmental Panel on Climate Change concludes that the climate system is warming faster than previously estimated (IPCC, 2021). Furthermore, OECD (2021) highlight the risks to predict the environmental damage due to the complex climate dynamics.

[2] If markets were complete, a perfect hedge of all relevant factors determining an investment's profitability would always be possible (Arrow and Debreu, 1954). Thereby, the profitability of abatement investments would not be volatile, and investments would be made as long as they are profitable in expectation without the impact of risk.

[3] There are several reasons why forward markets for emission allowances are incomplete (e.g. Tietjen et al., 2020, for a survey).

risk when making investment decisions. Besides their hedging properties, CCfDs may contain a subsidy for decarbonisation investments.[4] Such subsidies may be justified by, e.g., positive externalities. In this paper, we do not consider such externalities, and, hence, CCfDs mainly serve as hedging instrument in our setup. So far, there is only a limited understanding of how regulators should design such instruments and under which circumstances the introduction of CCfDs is welfare-enhancing.

In this paper, we analyse how different sources of risk affect the efficiency of CCfDs and when these contracts are preferable to other policies, like committing to a carbon price early on or a flexible carbon pricing regime. We develop an analytical model in which a regulator sequentially interacts with a continuum of risk-averse firms. These firms can either supply the market with a conventional technology, which causes carbon emissions subject to carbon pricing, or invest in an emission-free technology. The valuation of environmental damage from carbon emissions and the variable costs of the emission-free technology may be subject to risk. The firms are heterogeneous regarding their investment costs when adopting the emission-free technology. Firms invest if they increase their expected utility by adopting the emission-free technology. The regulator maximises social welfare by choosing one out of three carbon pricing regimes: 1) setting a carbon price flexibly after the actual damage or costs are revealed (*Regulatory Flexibility*), 2) committing to a carbon price early (*Commitment*)[5], and 3) a hybrid policy regime containing a CCfD and flexible carbon pricing (*CCfD*). We compare these three carbon pricing regimes against the social optimum.

We find that under perfect foresight, i.e. in the absence of risk, all carbon pricing regimes result in the social optimum. In all regimes, the carbon price equals the marginal environmental damage of production. The marginal firm investing in the emission-free technology balances the marginal costs and the marginal benefit of abatement. This finding arises from two effects: First, because the regulator has perfect foresight, she can set the optimal carbon price level at any time. Second, firms do not face a risk in profits. Any risk would hamper firms' willingness to invest if they are risk averse.

We then assess the effect of risk and risk aversion on the performance of the three carbon pricing regimes. In a first setup, we assume that production of the emission-free technology is always socially optimal given the actual damage and variable costs. In these cases, offering a CCfD results in the social optimum irrespective of the source of risk. The regulator can incentivise socially optimal investments via the CCfD and adjust the carbon price according to the actual damage valuation. In contrast, both *Regulatory Flexibility* and *Commitment* fall short of reaching the social optimum. Which of the two regimes is welfare-superior depends on the source of risk. In case of damage risk, the welfare ranking is ambiguous and depends on the level of the firms' risk aversion (with high risk aversion favouring *Commitment*) and the elasticity of demand (with high elasticity favouring *Regulatory Flexibility*). In contrast, committing to a carbon price is welfare-superior to *Regulatory Flexibility* in settings with variable cost risk, as the regulator can incentivise additional investments under *Commitment*.

Lastly, we assess the effects of emission-free production that is potentially welfare reducing given the actual damage and variable costs. In this case, we find that offering a CCfD does not reach the social optimum. If the regulator offers a CCfD, the firms' production decision does not depend on the actual carbon price. Thereby, the regulator safeguards emission-free production even if it is socially not optimal

[4]This is the case for the German and EU Hydrogen Strategy, as well as 'Fit for 55' package.

[5]Literature suggests that regulators may have an incentive to deviate from announced carbon prices ex-post, implying regulators may not be able to credibly commit (e.g. Helm et al., 2003).

ex-post. The same holds for *Commitment*. In contrast, under *Regulatory Flexibility*, the firm faces a carbon price equal to the social costs of carbon, such that it does not distort the production decision. Depending on the level of risk aversion and the probability of ex-post socially not optimal production, either *Regulatory Flexibility* or offering a CCfD is welfare superior.

Our paper contributes to two broad streams of literature in the context of irreversible investments in low-carbon technologies in the presence of risk.

The first literature stream focuses on policy options when firms face irreversible decisions. Baldursson and Von der Fehr (2004) analyse policy outcomes in a model in which firms choose between an irreversible long-term investment in abatement under risk and a short-term abatement option after the risk resolves. In the presence of risk aversion, the authors show that committing to a carbon tax ex-ante outperforms flexible carbon prices stemming from tradable permits because the latter increase the firms' risk exposure. Jakob and Brunner (2014) show that regulators can combine the advantages of flexibility and commitment by not committing to a specific climate policy level but a transparent adjustment strategy in response to climate damage shocks. In reality the regulator may need to address not only the optimal level of an irreversible investment decision but also the optimal consumption level. Höffler (2014) points out that regulators should address each target with a separate instrument. Therefore, a hybrid policy, i.e. the combination of two policies may be necessary. Offering a CCfD in addition to carbon prices constitutes a hybrid policy in the sense that the CCfD targets the firms' investment decisions while the complementary carbon price targets the optimal consumption level. Closely linked to our paper, Christiansen and Smith (2015) extend the analysis of Baldursson and Von der Fehr (2004) to hybrid policy instruments. The authors analyse a sequential setting in which firms initially have to decide on an investment in a low-carbon technology under risk and subsequently adjust output after the risk resolves. If a carbon tax commitment is the only instrument, the regulator sets the tax higher than the expected damage to incentivise more appropriate investments.[6] Supplementing the carbon tax with a state-contingent investment subsidy increases welfare as it allows for incentivising investment without setting a carbon tax that is too high. In a similar vein, Datta and Somanathan (2016) analyse a carbon tax and a permit system and examine the role of research and development (R&D) subsidies. They conclude that using only one instrument cannot be welfare-optimal if the regulator aims to address two targets - the internalisation of external effects from R&D and carbon damage. This is in line with our finding that a hybrid policy, in our case a CCfD, can improve welfare in a setting with an irreversible investment decision.

The second literature stream examines the role of hedging instruments for incentivising investments in low-carbon technologies under risk. Within this literature stream, the introduction of hedging instruments are found to increase investments in the presence of risk aversion. Borch (1962), who analyses reinsurance markets, demonstrates that players are willing to share risks according to their level of risk aversion by trading reinsurance covers which act as hedging instruments. This finding is supported by Willems and Morbee (2010), who examine investments in energy markets. The authors find that the availability of hedging opportunities increases investments of risk-averse firms and welfare. Habermacher and Lehmann (2020) analyse the interaction between a regulator aiming to maximise welfare and firms facing an investment

[6] This result resembles the insights from the real options literature where risk, combined with investment irreversibility, gives rise to an option value of waiting, e.g., Dixit et al. (1994). Chao and Wilson (1993) find an option value for emission allowances. Purchases of emission allowances provide flexibility to react to risk in a way that irreversible investments do not. The price of emission allowances may therefore exceed the marginal cost of abatement.

decision in low-carbon technologies. Similar to our paper, the authors assess carbon damage and variable costs risk. They find that the introduction of stage-contingent payments which partly hedge the risks of the regulator and the firm improve welfare compared to committing to carbon price or setting it flexibly. Those findings are in line with our result that a CCfD as an instrument for firms to hedge their risk leads to more investment and may increase welfare. Furthermore, hedging instruments may improve welfare even in the absence of risk aversion. An early example is Laffont and Tirole (1996), who show that the introduction of options solves the problems arising from strategic behaviour between the regulator and a firm.[7] If the regulator faces incomplete information, Unold and Requate (2001) show that offering options in addition to permits is welfare-enhancing. In contrast to this stream of literature, Quiggin et al. (1993) find that hedging instruments may also be welfare-deterring, as they may foster undesired behaviour. This result resembles our findings in the case of potentially ex-post welfare-reducing production in section 4.

CCfDs combine the effects of a hybrid policy and a hedging instrument. They recently gained attention from academic literature. Richstein (2017) focuses on the optimal combination of CCfDs and investment subsidies to lower policy costs and support investment decisions under risk and risk aversion. However, the study does not include the regulator's decision on the carbon price regime. To the best of our knowledge, Chiappinelli and Neuhoff (2020) provide the only study that explicitly analyses CCfDs in the context of multiple carbon pricing regimes. The authors model firms which face an irreversible investment decision and behave strategically, which influences the regulator's decision on the carbon price. In this setup, higher investments in abatement technologies lead to lower carbon prices so that firms strategically under-invest to induce higher carbon prices. Offering CCfDs can alleviate such a hold-up problem. We build on the model developed in Chiappinelli and Neuhoff (2020) but change the focus of analysis. We analyse a setup with a large number of small firms in a competitive market. Chiappinelli and Neuhoff (2020) show how CCfDs can alleviate the hold-up problem that results from regulation and, hence, mitigate regulatory risk. In contrast, we focus on the impact of CCfD in an environment of risks that are outside the control of regulator and firms, i.e., damage and variable cost risk. We also present the first paper in this literature stream to point out that CCfDs can cause a lock-in in technologies that are ex post not socially optimal.

2. Carbon pricing regimes in the absence of risk

This section introduces the model setup to analyse the effects of CCfDs. In the model, we assess the interactions between a regulator and firms in the absence of risk. The regulator can apply three carbon pricing regimes to reduce emissions while firms face an irreversible investment decision to abate emissions during production.

2.1. Model framework in the absence of risk

We model the market for a homogeneous good G in which three types of agents participate - namely, consumers, firms, and a regulator. Consumers have an elastic demand $Q(p_G)$ for the good at a market price p_G. Demand decreases in the good's price, i.e., $Q'(p_G) < 0$.

A continuum of firms supplies the good in a competitive market. Each firm produces one unit. Initially, all firms produce the good with a conventional technology. Using the conventional technology to produce

[7] This type of expropriation game constitutes a type of climate policy risk but mainly includes strategic behaviour.

one unit of G induces constant marginal production costs ($c_0 \geq 0$) that are identical among all firms. The production process emits one unit of carbon emission. The emission causes constant marginal environmental damage d, which lowers the overall welfare and is subject to a carbon price ($p \geq 0$). The resulting total marginal costs of the conventional technology equal $c_c = c_0 + p$.[8]

Firms can invest in an emission-free technology to produce G at carbon costs of zero. Investing implies that firms adopt new production processes within their existing production sites. As a result, the production capacity of the firms remains unaffected by an investment.[9] The investment decision is irreversible and induces investment costs as well as higher marginal production costs. We assume firms face heterogeneous investment costs, similar to the approach in Harstad (2012) or Requate and Unold (2003).[10] This heterogeneity may stem from several sources, e.g., because firms can adopt different technologies, have different access to resources, or have different R&D capacities. In our model, firms are ranked from low to high investment costs, such that they can be placed within an interval ranging from $[0, \chi_{max}]$.[11] We assume the firm-specific investment costs to be the product of the firm-specific position on the interval χ and a positive investment cost parameter c_i that is identical among firms. Hence, the investment costs of the firm positioned at χ equal $C_i(\chi) = \chi c_i$. Firms invest if they increase their profit by adopting the emission-free technology. Otherwise, they produce conventionally. We identify the firm which is indifferent between the two technologies by $\overline{\chi}$. As $C_i'(\chi) > 0$, all firms with $\chi \leq \overline{\chi}$ invest. In other words, $\overline{\chi}$ refers to the marginal firm investing in the emission-free technology. The position of a firm on the interval χ not only defines the firm-specific investment costs but also corresponds to the cumulative production capacity of all firms facing investment costs lower than the respective firm. In consequence, $\overline{\chi}$ defines the emission-free production capacity. In the following, we refer to $\overline{\chi}$ interchangeably either as the emission-free production capacity or as the marginal firm.

Emission-free production has additional marginal production costs c_v. This technology may, for instance, require more expensive input factors compared to the conventional technology. Hence, the total marginal production costs of firms using the emission-free technology equal $c_f = c_0 + c_v$. In section 2 and 3, we assume the marginal production costs of the emission-free technology to be lower than the carbon price (i.e., $c_v < p$). We alleviate the assumption in section 4. Additionally, we adopt the normalisation $c_0 = 0$. Considering investment and production costs, the profit of investing in the emission-free technology equals $\pi(\chi) = p_G - (c_0 + c_v + c_i\chi)$.

The regulator aims at maximising the welfare resulting from the market for G. For this, the regulator can choose among the three different carbon pricing regimes. Firstly, she can opt for *Regulatory Flexibility* (short: *Flex*), in which she sets the carbon price flexibly after the investment decisions of the firms took place. Secondly, she can make a *Commitment* (short: *Com*) and commit to a carbon price before the investment takes place. The third option *CCfD* is a hybrid policy of offering CCfDs to the firms before the investments take place and setting the carbon price afterwards. The CCfD sets a strike price p_s that safeguards firms against carbon price volatility. If the carbon price, which realises after the investments,

[8]We discuss the implication of assuming constant marginal damage in chapter 5.

[9]This does not exclude market entry of new firms; however, we do not model entry or exit decisions explicitly, as adopting new processes in established installations is likely less costly then investing in new installations.

[10]Empirical evidence shows that firms differ with respect to their costs of investing in pollution abatement Blundell et al. (2020).

[11]χ_{max} represents the production capacity of all firms and is assumed to exceed the demand $Q(p_G)$ for all possible values of p_G.

is lower than the strike price, the regulator pays the difference $(p_s - p)$ to the firm. If the carbon price is higher than the strike price, firms have to pay the difference to the regulator.

Before introducing the sequence of actions, we discuss the model approach and its main assumptions. First, a price-elastic demand, a competitive market structure, and the provision of homogeneous goods resemble many industries for which CCfDs are proposed, e.g., steel and chemicals (e.g. European Commission, 2021b; Fernandez, 2018; OECD, 2002). Second, these industries likely face a discrete, irreversible investment decision to decarbonise the production in combination with increased marginal production costs of the low-carbon technology. Currently, a switch of production processes from the coal- and coke-based blast furnace to hydrogen-based direct reduction is seen as the most promising way to decarbonise the primary steel sector (e.g. IEA, 2021). This switch in the production process induces a shift in input factors from coal to more expensive hydrogen (Vogl et al., 2018). Hence, our model captures many characteristics of industries, for which policymakers propose the use of CCfDs.

The agents in our model can take actions in four stages, namely the Early Policy stage t_1, the Investment stage t_2, the Late Policy stage t_3, and the Market Clearing stage t_4. Figure 1 depicts these stages. The sequence of actions differs between the carbon pricing regimes that we analyse in this paper. We subsequently discuss the agents' actions during the various stages of the game. As we derive the sub-game perfect Nash equilibrium by backward induction, we begin by presenting the last stage of the game.

	Firms	**Regulator** *Com*	**Regulator** *Flex*	**Regulator** *CCfD*	**Social Planner** *Opt*
Early Policy (t_1)		Sets p		Sets p_s	
Investment (t_2)	Invest up to $\overline{\chi}$				Sets $\overline{\chi}$
Late Policy (t_3)			Sets p	Sets p	Sets p
Market Clearing (t_4)	$p_G^* = p$ & $Q(p_G^*) = Q(p)$				

T

Figure 1: Sequence of actions in the different carbon pricing regimes.

Market Clearing stage: In t_4, the market clearing takes place. Firms produce the good with the respective technologies and serve the demand. In this stage, the carbon price p and the resulting emission-free production capacity $\overline{\chi}$ are already determined.

Late Policy stage: In t_3, the regulator sets the carbon price under *Regulatory Flexibility* and *CCfD*, given the previously determined production capacity of the emission-free technology.

Investment stage: In t_2, the firms decide whether to invest in the emission-free technology or not.

Firms with $\chi \leq \overline{\chi}$ invest as they increase their profit by adopting the emission-free technology, while the others ($\chi > \overline{\chi}$) maintain the conventional technology.

Early Policy stage: In t_1, the regulator can take actions in two of the three carbon pricing regimes. Under *Commitment*, she announces and commits to a carbon price for the subsequent stages. Under *CCfD*, the regulator offers firms CCfDs and determines the strike price.

In contrast to the other stages, the market clearing in t_4 is independent of the carbon pricing regime, such that we present the result upfront. We assume the investment costs to be sufficiently high compared to the demand, such that investments in the emission-free capacity cannot supply the overall demand, i.e., $\overline{\chi} < Q(p_G)$. This assumption implies that the demand for the good is partially served by firms that invested in the emission-free technology and by firms producing conventionally.[12] As demand exceeds the emission-free production capacity and marginal production costs of the emission-free technology are lower than of the conventional technology, the latter sets the market price. Due to the normalisation of $c_0 = 0$, the market price is defined by $p_G = p$ and the demand is equal to $Q(p_G) = Q(p)$, i.e., the carbon price fully determines the product price. Figure 2 illustrates the market clearing.

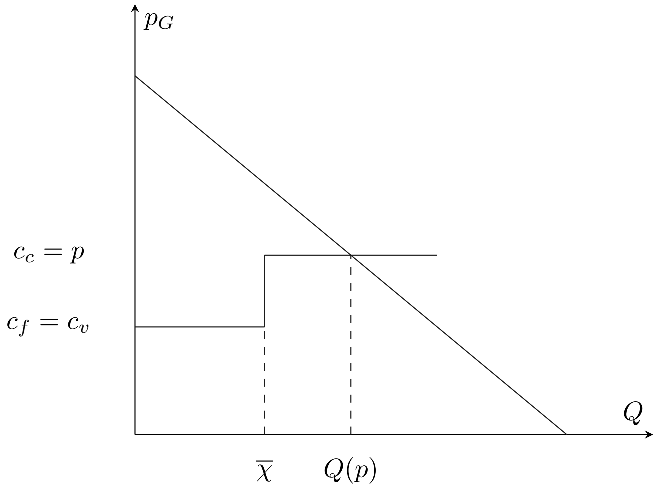


Figure 2: Market clearing.

Firms producing the good with the conventional technology do not generate profits as marginal revenue equals marginal costs, which are constant. The marginal profit of production of the firms investing in the emission-free technology equals $p - c_v$.

To evaluate the carbon pricing regimes, we compare the respective outcomes to the social optimum (short: *Opt*). In this hypothetical benchmark, a social planner sets the socially optimal investment in t_2 and the carbon price level in t_3. The social planner's objective is, identical to the regulator, to maximise social welfare stemming from the market for the product G. Social welfare comprises four elements: 1) net consumer surplus (CS), 2) producer surplus, 3) environmental damage, and 4) policy costs/revenues from carbon pricing and the CCfD.

[12]We discuss this assumption in section 5, as it is crucial for the outcome of the market clearing and the resulting incentives to invest in the emission-free technology.

The producer surplus is defined as the margin between marginal revenue and marginal costs. It differs before and after the irreversible investment. Before the investment, i.e., in t_1 and t_2, the marginal costs comprise investment and marginal production costs. After the investment, i.e., in t_3 and t_4, the investment costs are sunk, such that the marginal costs only comprise the marginal production costs. (1) displays the welfare before the investment takes place. The welfare representation after the investment takes place does not contain the investment costs $\int_0^{\overline{\chi}}(c_i z)dz$.

$$
\begin{aligned}
\mathcal{W}^{Flex/Com/Opt} &= \underbrace{\int_p^{\infty} Q(z)dz}_{\text{consumer surplus}} + \underbrace{\int_0^{\overline{\chi}}(p - c_v - c_i z)dz}_{\text{producer surplus}} - \underbrace{d\big[Q(p) - \overline{\chi}\big]}_{\text{environmental damage}} + \underbrace{p\big[Q(p) - \overline{\chi})\big]}_{\text{revenues from carbon pricing}} \\
\mathcal{W}^{CCfD} &= \underbrace{\int_p^{\infty} Q(z)dz}_{\text{consumer surplus}} + \underbrace{\int_0^{\overline{\chi}}(p_s - c_v - c_i z)dz}_{\text{producer surplus}} - \underbrace{d\big[Q(p) - \overline{\chi}\big]}_{\text{environmental damage}} + \underbrace{p\big[Q(p) - \overline{\chi})\big]}_{\text{revenues from carbon pricing}} - \underbrace{(p_s - p)\overline{\chi}}_{\text{CCfD payment}}
\end{aligned}
\tag{1}
$$

Payments arising from the CCfD do not affect the overall welfare as they only shift payments between firms and the regulator.[13] Hence, we can simplify welfare with and without CCfDs before investment to:

$$
\mathcal{W} = \int_p^{\infty} Q(z)dz + (p - d)Q(p) + \int_0^{\overline{\chi}}(d - c_v - c_i z)dz \tag{2}
$$

This simplified representation illustrates that welfare can be grouped into two elements. On the one hand, welfare is defined by consumption, the associated environmental damage, and the carbon pricing revenue. On the other hand, welfare stems from the level of emission-free production capacity $\overline{\chi}$ and the related costs and benefits from abatement.

2.2. Policy ranking in the absence of risk

In the following, we derive the optimal emission-free production capacity $\overline{\chi}$ and the optimal carbon price p in the absence of risks (i.e., under perfect foresight) under the assumption of a social planner. The solution serves as a hypothetical benchmark for the three carbon pricing regimes. To solve the optimisation of the social planner, we derive the first-order conditions of the welfare function:

$$
\begin{aligned}
\max_{\overline{\chi},p} \mathcal{W} &= \int_p^{\infty} Q(z)dz + (p - d)Q(p) + \int_0^{\overline{\chi}}(d - c_v - c_i z)dz \\
\frac{\partial \mathcal{W}}{\partial \overline{\chi}} &= (d - c_v - c_i\overline{\chi}) \longrightarrow \overline{\chi}^{Opt} = \frac{d - c_v}{c_i} \\
\frac{\partial \mathcal{W}}{\partial p} &= -Q(p) + Q(p) + Q'(p)(p - d) \longrightarrow p^{Opt} = d
\end{aligned}
\tag{3}
$$

The social planner chooses the emission-free production capacity such that the abatement costs (i.e., the investment and production costs) of the marginal firm ($\overline{\chi}^{Opt}$) equal the damage avoided by the investment in and the utilisation of the emission-free technology. The optimal carbon price (p^{Opt}) equals the marginal

[13]Note that we do not assume shadow costs of public funds. We discuss this assumption in section 5.

damage, i.e., the Pigouvian tax level (Pigou, 1920), as the marginal unit of the good is produced with the conventional technology, associated with an environmental damage of d. With this carbon price, the social planner inhibits all consumption with a lower benefit than damage to society.

We provide the optimal solutions under the different carbon pricing regimes in Appendix A. We find that

Proposition 1. *In the absence of risk, all carbon pricing regimes reach the social optimum. In all regimes, the carbon price is equal to the marginal environmental damage of production, i.e., $p = d$. The marginal firm using the emission-free technology balances the marginal investment costs and the respective marginal benefit of abatement, i.e., $\overline{\chi} = {}^{(d-c_v)}/_{c_i}$.*

In the absence of risk, i.e., under perfect foresight, the optimisation rationales in t_1 (before investing) and t_3 (after investing) regarding balancing the damage from carbon emission and the costs of abatement are identical. Therefore, it does not make a difference if the regulator commits to a carbon price before the firms invest or sets the carbon price flexibly afterward. Under all regimes, Pigouvian taxation is optimal. Hence, offering a CCfD in t_1 does not improve social welfare.

This result regarding the welfare ranking of carbon pricing regimes and, notably, CCfDs differs from Chiappinelli and Neuhoff (2020). In their model, firms also face an irreversible investment decision but behave strategically and influence the regulator's decision on the carbon price. Thereby, firms under-invest to induce higher carbon prices, leading to a hold-up problem. In this setting, CCfDs can alleviate the investment-hampering effect of flexible carbon prices and increase welfare. In contrast, firms do not have market power in our model and cannot affect the regulator's carbon pricing decision. Hence, it does not make a difference if the firms invest before or after the regulator sets the carbon price under perfect foresight.

Proof. We provide the proof of Proposition 1 in Appendix A. ■

3. Carbon pricing regimes in the presence of risk

In this section, we analyse the impact of damage and variable cost risk on the welfare ranking of the carbon pricing regimes in the presence of risk aversion.

3.1. Model framework in the presence of risk and socially optimal production

We integrate risk into the model by redefining the marginal environmental damage and the variable production costs of the emission-free technology from the model introduced in section 2.1 as random variables D and C_v. Both random variables realise after the firms invest in abatement (t_2), but before the late policy stage (t_3) and the market clearing (t_4). We denote the realisation of D and C_v by $\hat{d}$ and $\hat{c_v}$. In this section, we assume the production with the emission-free technology to be socially optimal under all circumstances, i.e., the environmental damage is always larger than the variable costs of abatement $P(D > C_v) = 1$. For this assumption to hold, we define the random variables to follow a truncated normal distribution, i.e., $D \sim TN(\mu_D, \sigma_D^2, \underline{\theta_D}, \overline{\theta_D})$ and $C_v \sim TN(\mu_{C_v}, \sigma_{C_v}^2, \underline{\theta_{C_v}}, \overline{\theta_{C_v}})$ with $\underline{\theta_D} > \overline{\theta_{C_v}}$, where μ denotes the mean value, σ^2 the variance and $\underline{\theta}$ and $\overline{\theta}$ the lower and upper limit of the distribution, respectively. Hence, the lowest possible damage is larger than the highest possible realisation of variable costs.[14] As in section 2, we assume

[14] We assess a setting in which the social costs of damage are potentially smaller than the variable costs of abatement, i.e., $P(D > C_v) < 1$, in section 4 by assuming an non-truncated normal distribution.

$\chi < Q(p(d))$, such that for all $\hat{d} \in D$ the total demand in the market exceeds the emission-free production capacity.

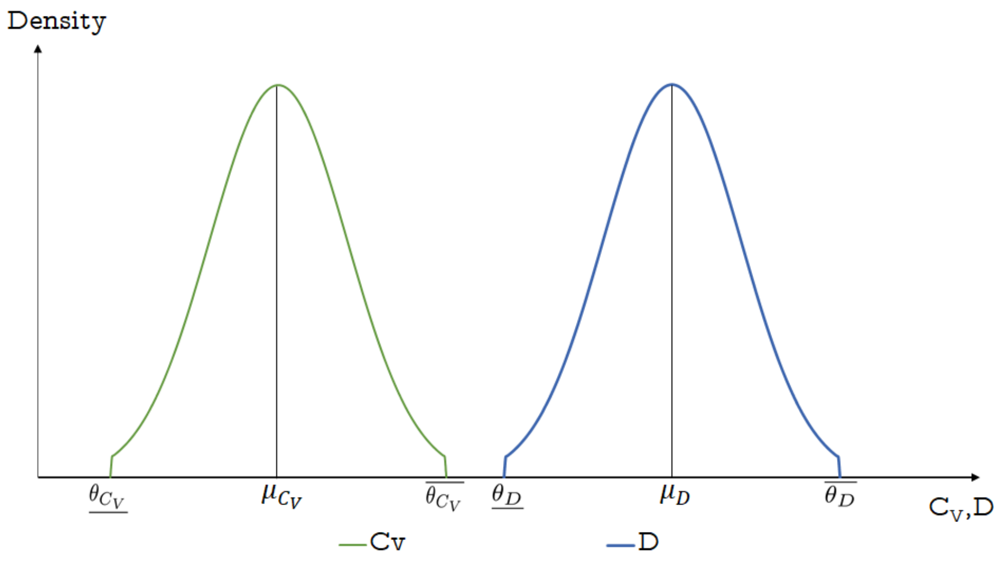


Figure 3: Density of D and C_v following a truncated normal distribution with $P(C_v > D) = 0$.

We assume that firms are risk averse, facing a utility that is exponential in profits. Whether or not risk aversion is a real-world phenomenon for firms and how it manifests in actions is debated within the broad literature of economics and the context of energy and environmental economics (Meunier, 2013). Diamond (1978) argues that even if markets were incomplete, firms should act as if they were risk neutral, and shareholders could hedge their risks at the capital markets. However, there are several reasons why firms may act aversely to risk (see e.g. Banal-Estañol and Ottaviani (2006) for a review). These reasons include non-diversified owners, liquidity constraints, costly financial distress, and nonlinear tax systems. Additionally, and independently of the owners' risk aversion, the delegation of control to a risk-averse manager paid based on the firm's performance may cause the firm to behave in a risk-averse manner.

How the firms' risk aversion can be modelled depends on the distributional assumptions of the underlying risks. Markowitz (1952) show that for non-truncated normally distributed profits, the mean-variance utility could express firms' optimisation rationale. However, this simplification is not appropriate for our model in which the distribution of firms' profits is truncated due to distributional assumptions on damage and variable cost risk. Norgaard and Killeen (1980) show that the optimisation rationale of an agent facing an exponential utility and truncated normally distributed profits can be approximated by a mean-standard deviation decision rule containing a risk aversion parameter λ.[15] We apply this approximation by using a mean-standard deviation utility in our model. Firms invest in the emission-free technology if their expected utility is positive. The expected utility of the marginal firm investing in the emission-free technology is equal

[15] In the context of energy and environmental economics, Alexander and Moran (2013) apply this approach to assess the impact of perennial energy crops income variability on the crop selection of risk-averse farmers.

to zero:

$$
\begin{aligned}
EU(\pi(\overline{\chi})) &= \mu_\pi(\overline{\chi}) - \lambda\sigma_\pi(\overline{\chi}) \\
&= (\mu_p - \mu_{C_v} - c_i\overline{\chi}) - \lambda\sigma_{p,C_v} \\
&= 0
\end{aligned} \tag{4}
$$

In contrast to the firms' risk aversion, we assume the regulator to be risk neutral. There are several reasons why environmental regulation is determined on a risk-neutral basis (see e.g. Kaufman (2014) for an extensive review). In the context of public economics, Arrow and Lind (1970) argue that with a sufficiently large population, the risk premiums converge to zero because they can be spread out among constituents. Fisher (1973) discusses the principles of Arrow and Lind in the context of risks stemming from environmental externalities. [16] Hence, we assume the regulator to maximise the expected welfare:

$$
E[\mathcal{W}] = E\left[\int_p^\infty Q(z)dz + (p-d)Q(p) + \int_0^{\overline{\chi}}(d - c_v - c_i z)dz\right] \tag{5}
$$

3.2. Policy ranking with damage risk

In the following, we focus on damage risk and neglect the risk of the variable production costs. Therefore, we set $\mu_{C_v} = c_v$ with $\sigma^2_{C_v} = 0$. We derive and compare the outcomes of the three carbon pricing regimes in terms of the emission-free production capacity $\overline{\chi}$ and carbon price p in the presence of damage risk. We contrast the three regimes to the social optimum and conclude that

Proposition 2. *In the presence of damage risk and firms' risk aversion, only the hybrid policy of offering a CCfD and setting the carbon price flexibly yields an socially optimal level of* p *and* $\overline{\chi}$*. A pure carbon pricing regime reaches either a socially optimal carbon price through allowing for flexibility or optimal investment through early commitment.*

As the valuation of environmental damage is not known before investing (t_1), while it is known after investing (t_3), the timing of the carbon pricing regimes changes the carbon prices and the resulting market outcomes. When setting the carbon price flexibly in t_3, all relevant information is available for the regulator. Hence, the *Regulatory Flexibility* regime results in the socially optimal carbon price for the market clearing. However, in this regime, firms face a risk regarding their revenues. Due to their risk aversion, firms consequently invest less than socially optimal. When committing to a carbon price in t_1, the regulator cannot take into account the information becoming available in t_3. Hence, the carbon price under *Commitment* is ex-post either too high or too low. However, the carbon price commitment incentivises socially optimal investments. It accounts for the risk in the valuation of environmental damage; that is, the firms and the regulator face the same problem. Offering a CCfD removes the impact of damage risk for the firms and enables socially optimal investments. Furthermore, socially optimal consumption is reached as the regulator sets the carbon price in t_3, having complete information on the damage valuation.

[16] Besides the risk neutrality of the regulator, we assume that her welfare maximisation is also not affected by the firms' risk aversion. This corresponds to the concept of the literature on non-welfarist taxation, which is common practice in public economics (e.g. Heutel (2019); Kanbur et al. (2006)). In essence, the regulator's *ignorance* of the risk-averse utility of the firms can stem from either paternalistic behaviour or an insufficiently large proportion of the firms on the market.

Proof. For the proof of proposition 2, we compare the socially optimal carbon price and emission-free production capacity to the three carbon pricing regimes. Appendix B presents a complete derivation of the respective optimal solutions. In the following, we provide the main results and the intuition behind the finding in proposition 2.

Social optimum

In the social optimum, the social planner sets the carbon price p after the actual environmental damage revealed. Following the rationale of the risk-free setting, the socially optimal carbon price equals the realised marginal damage, i.e., $p^{Opt} = \hat{d}$. As the social planner knows the actual damage level when setting the carbon price, the damage risk does not impact her decision.

In contrast, investments are due before the actual damage reveals. Hence, the social planner must set the emission-free production capacity $\overline{\chi}$ in the presence of damage risk. The social planner sets $\overline{\chi}^{Opt}$ such that it maximises the expected welfare gain from abatement investments.

$$\overline{\chi}^{Opt} = \frac{\mu_D - c_v}{c_i} \tag{6}$$

The emission-free production capacity balances the expected benefit of abatement, i.e., the expectation of the avoided environmental damage and the abatement costs, consisting of variable production costs and investment costs.

Regulatory flexibility

Similar to the social planner case, the regulator sets the carbon price after the actual damage revealed when she chooses *Regulatory Flexibility.* As the regulator and the social planner have the same objective function, both settings result in a carbon price at $p^{Flex} = p^{Opt} = \hat{d}$, i.e. the Pigouvian tax level.

In t_2, the firms choose to invest if their expected utility is positive, anticipating the carbon price set by the regulator in the following stage. However, the price is stochastic to firms, as it depends on the realised damage.

$$\overline{\chi}^{Flex} = \frac{\mu_{p^{Flex}} - c_v - \lambda\sigma_{p^{Flex}}}{c_i} = \frac{\mu_D - c_v - \lambda\sigma_D}{c_i} \tag{7}$$

Unlike in the case of a (risk-neutral) social planner, firms not only account for the expected revenues and costs of abatement but also consider a risk term stemming from the abatement revenue risk. This risk term reduces the firms' expected utility and consequently the emission-free production capacity, as firms aim to avoid situations where their investments are unprofitable. The dampening effect of risk on investments increases with the volatility of expected carbon prices and the firms' risk aversion.

Commitment

Under *Commitment*, the firms' investment rationale is based on the carbon price known at the time of taking their decision:

$$\overline{\chi}^{Com} = \frac{p^{Com} - c_v}{c_i} \tag{8}$$

Following the intuition of the setting without risk, those firms invest which increase their profit by adopting the emission-free technology. As revenues are not subject to risk, the firms' risk aversion does not impact their investment decisions in t_2 and the resulting emission-free technology balances the marginal revenue and the marginal costs of abatement.

In t_1, the regulator sets the carbon price maximising expected welfare and taking into account that firms solely invest if the investment is profitable. As a result, the regulator sets the carbon price to $p^{Com} = \mu_D$, i.e., the expected Piguvian tax level. Substituting the optimal carbon price p^{Com} into (8) yields $\overline{\chi}^{Com} = \frac{\mu_D - c_v}{c_i}$, which is equal to the solution of the social planner. However, the carbon price to which the regulator commits herself in t_1 is ex-post not optimal. If the revealed damage is greater than expected, the carbon price is too low, and vice versa.

CCfD

When the regulator can offer the firms a CCfD, the regulator faces the same objective function for setting the carbon price in t_3 as under *Regulatory Flexibility.* Hence, she chooses the Pigouvian tax level $p^{CCfD} = p^{Flex} = p^{Opt} = \hat{d}$.

In t_2, the firms' problem is identical to the one under *Commitment.* Here, the firms receive the strike price:

$$\overline{\chi}^{CCfD} = \frac{p_s - c_v}{c_i} \tag{9}$$

The rationale for investments is the same as without risk: Firms invest in the emission-free technology if it increases their profits. In t_1, the regulator chooses the strike price that maximises expected social welfare. She accounts for the firms' reaction function to the announced strike price and faces damage risk. The resulting strike price equals the expected marginal damage, i.e., $p_s = \mu_D$. By substituting p_s in (9), we see that under a *CCfD* regime, the emission-free production capacity equals the one under *Com* (and the social planner), i.e., $\overline{\chi}^{CCfD} = \overline{\chi}^{Com} = \overline{\chi}^{Opt}$). ■

Welfare Comparison

We calculate and compare the ex-ante social welfare in the different carbon pricing regimes in terms of welfare.[17] We find that:

$$E[\mathcal{W}^{Opt}_{\sigma_D}] = E[\mathcal{W}^{CCfD}_{\sigma_D}] \geq E[\mathcal{W}^{Com}_{\sigma_D}] \lesseqgtr E[\mathcal{W}^{Flex}_{\sigma_D}] \tag{10}$$

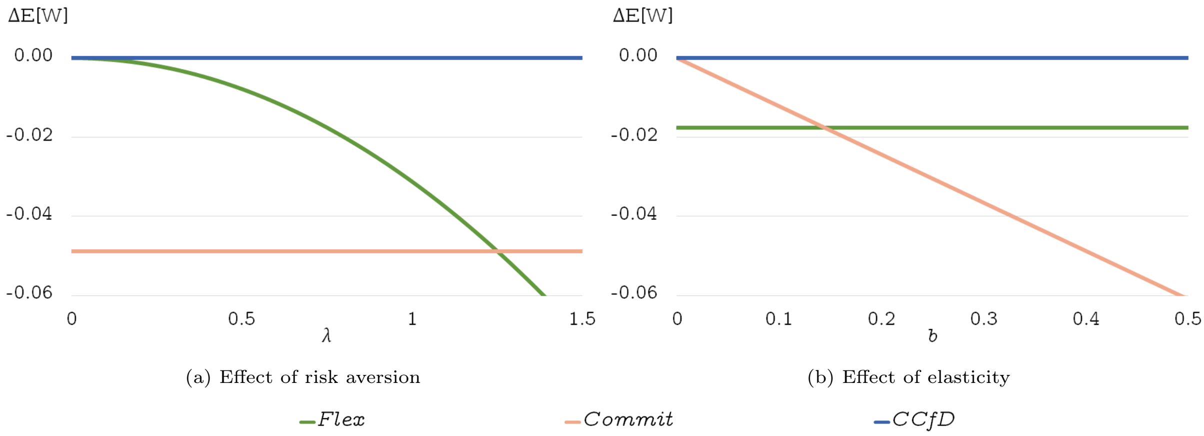
First, the carbon price and the emission-free production capacity are identical in the social optimum and the *CCfD* regime. Consequently, the *CCfD* regime results in the social optimum.

Second, we compare offering a CCfD against *Regulatory Flexibility* and *Commitment.* While the *CCfD* regime achieves the socially optimal emission-free production capacity, investments in *Flex* are lower. As the expected welfare increases in χ as long as $\chi \leq \overline{\chi}^{CCfD} = \frac{\mu_D - c_v}{c_i}$, the welfare under the *Flex* regime is lower than the social optimum or offering a CCfD. The welfare loss increases in the firms' risk aversion and

[17]The subscript σ_D represents the welfare in the presence of damage risk.

the standard deviation of environmental damage. However, if firms are risk neutral, the *Flex* regime reaches the socially optimal emission-free production capacity. Figure 4a shows these results numerically. Note that these parameter values are illustrative and do not correspond to empirical estimates.[18] In contrast to the case of *Regulatory Flexibility*, the policy regimes *Commitment* and *CCfD* both result in the socially optimal emission-free production capacity. However, these regimes differ concerning the carbon price level and the resulting utility from consumer surplus. Under the *Com* and *CCfD* regimes, consumers bear the same carbon prices in expectation. However, the consumer surplus is a convex function of the respective carbon price. I.e., a higher carbon price decreases the consumer surplus less than an equivalently lower carbon price would lead to an increase of the consumer surplus.[19] Hence, the difference in expected consumer surplus is positive, i.e., $E[\int_{p^{CCfD}}^{\infty} Q(z)dz] > \int_{p^{Com}}^{\infty} Q(z)dz$. With an increase in demand elasticity, the difference in consumer surplus of the *Com* and *CCfD* regimes increases. Therefore, the greater the demand elasticity, the higher the loss in ex-ante welfare arising from not setting the carbon price according to the actual marginal damage under *Com*. We illustrate this finding numerically in Figure 4b.

Third, it is unclear whether *Com* or *Flex* is welfare superior. *Flex* results in socially optimal carbon pricing, while *Com* allows for socially optimal emission-free production capacity. Which regime is welfare superior depends on the relevance of the two variables. In case of damage risk, setting a flexible carbon price is welfare superior to *Com* if demand elasticity is sufficiently high and the share of emission-free production is sufficiently low. The same holds vice versa for *Com*.



(a) Effect of risk aversion

(b) Effect of elasticity

Figure specific parameters in (a): $\lambda \in [0, 1.5]$, $Q(p) = 5 - 0.4p$ and (b): $\lambda = 0.75$, $Q(p) = 5 - bp$ with $b \in (0, 0.5]$.

Figure 4: Difference in welfare compared to social optimum in the presence of damage risk.

3.3. Policy ranking with variable cost risk

In this section, we focus on variable cost risk and set $\mu_D = d$ with $\sigma_D^2 = 0$. We derive the outcomes of the three carbon pricing regimes in terms of emission-free production capacity $\overline{\chi}$ and carbon price p when the firms do not know the variable costs of the emission-free technology when investing. We contrast the three regimes with the social optimum and conclude that

[18]Both Figure 4a and Figure 4b share the parameters regarding the distribution of the environmental damage $D \sim TN(\mu_D = 4, \sigma_D^2 = 0.25, \underline{\theta_D} = 2.5, \overline{\theta_D} = 5.5)$ and the cost parameters of the emission-free technology $c_v = 2$ and $c_i = 4$.

[19]This relation is also known as the Jensen gap stemming from Jensen's inequality.

Proposition 3. *In the presence of variable cost risk, only the hybrid policy of offering a CCfD and setting the carbon price flexibly yields a socially optimal level of* p *and* $\overline{\chi}$*. A pure carbon price in a regime with Regulatory Flexibility reaches a socially optimal carbon price* p *but falls short of the socially optimal emission-free production capacity* $\overline{\chi}$*. Commitment reaches neither the socially optimal level of* p *nor* $\overline{\chi}$*.*

When firms face a variable abatement costs risk, risk aversion reduces the utility from investing in the emission-free production technology. Depending on the carbon pricing regime, the regulator can mitigate this effect. The regulator can encourage firms to increase investments by setting the carbon price above the Pigouvian tax level when committing to a carbon price. However, the price increase results in inefficient consumption levels. Hence, the regulator faces a trade-off between high consumer surplus and low environmental damage, resulting in a deviation from the social optimum. When the regulator can offer a CCfD in addition to a carbon price, she does not face this trade-off. Instead, the regulator can offer a CCfD, which sufficiently compensates firms for facing risk regarding their revenue and enable socially optimal investments. Furthermore, the regulator achieves the socially optimal consumption level. She can set the carbon price to the Pigouvian tax level, indicating the benefit of having two instruments for different objectives. If the regulator cannot offer a CCfD and sets the carbon price flexibly, the regulator achieves the socially optimal consumption level but cannot alter the firms' investment decisions. Consequently, fewer firms invest than socially optimal.

Proof. For the proof of proposition 3, we compare the socially optimal carbon price and emission-free production capacity to the three carbon pricing regimes. Appendix C presents a complete derivation of the respective optimal solutions. In the following, we provide the main results and the intuition behind the finding in proposition 3.

Social optimum

In the social optimum, the social planner maximises welfare by setting the carbon price p^{Opt} after the level of variable costs revealed. She chooses the Pigouvian tax level $p^{Opt} = d$, which equals the social marginal costs of production.

The social planner sets the emission-free production capacity $\overline{\chi}^{Opt}$ under risk such that it maximises the expected welfare. The emission-free production capacity balances the marginal benefit and marginal costs from abatement. The optimisation rationale resembles the one under damage risk. However, in this case, not the benefit of emission-free production but its costs are subject to risk:

$$\overline{\chi}^{Opt} = \frac{d - \mu_{C_v}}{c_i} \tag{11}$$

Regulatory flexibility

Under *Regulatory Flexibility*, the regulator faces the same optimisation problem as the social planner. Hence, she sets the carbon price to the Pigouvian tax level $p^{Flex} = p^{Opt} = d$.

In t_2, firms invest in the emission-free technology if the investment increases the expected utility of the firm. For this, the firms anticipate the Pigouvian tax. As firms are risk averse, the firms' utility decreases in the level of risk and risk aversion. The resulting emission-free production capacity equals:

$$\overline{\chi}^{Flex} = \frac{p^{Flex} - \mu_{C_v} - \lambda\sigma_{C_v}}{c_i} = \frac{d - \mu_{C_v} - \lambda\sigma_{C_v}}{c_i} \tag{12}$$

The emission-free production capacity falls short of the social optimum in case of risk aversion ($\lambda > 0$). The shortfall increases with an increasing level of risk and risk aversion.

Commitment

Under *Commitment*, in t_2, firms choose to invest given the announced carbon price level. As in the case of *Regulatory Flexibility*, firms invest if they generate a positive expected utility, such that the emission-free production capacity equals:

$$\overline{\chi}^{Com} = \frac{p - \mu_{C_v} - \lambda\sigma_{C_v}}{c_i} \tag{13}$$

In t_1, the regulator sets the carbon price anticipating that her choice impacts firms' investment decisions and the consumer surplus. These two effects result in a trade-off which we can express as:

$$\frac{p-d}{p} = \frac{1}{\epsilon(p)} \frac{\partial \overline{\chi}^{Com}(p)}{\partial p} \frac{1}{Q(p)} (d - c_i \overline{\chi}^{Com}(p) - \mu_{C_v}), \tag{14}$$

where $\epsilon(p) = -\frac{\partial Q(p)}{\partial p} \frac{p}{Q(p)}$ is the elasticity of demand.

The resulting carbon price is higher than d, which we show in Appendix C. In fact, the optimal carbon price under commitment p^{Com} ranges from $[d, d + \lambda\sigma_{C_v}]$, depending on the configuration of parameters. Hence, the regulator sets a carbon price above the social marginal costs of the conventional technology, i.e. d, and the carbon price is higher than in the social optimum. The solution is a modified version of the Ramsey formula for monopolistic price setting under elastic demand (Laffont and Tirole, 1996; Höffler, 2006). The regulator increases the carbon price above the socially optimal level to encourage investments. This price mark-up is proportionate to the inverse price elasticity of demand and the marginal benefit from increased investments. The marginal benefit arises from the marginal increase in the share of emission-free production, i.e., $\frac{\partial \overline{\chi}^{Com}(p)}{\partial p} \frac{1}{Q(p)}$, and the benefit of the marginal emission-free production, i.e., $d - c_i\overline{\chi}^{Com}(p) - \mu_{C_v}$. In other words, the regulator balances the loss in consumer surplus and the abatement benefits.

The trade-off under *Com* with variable cost risk is different from the case with damage risk: With damage risk, the regulator commits to a carbon price that will be sub-optimal ex-post. By committing to a carbon price, the regulator takes up the firms' risk, mitigating the negative effect of the firms' risk aversion on social welfare. With cost risk, the regulator cannot take away the firms' risk, but she can compensate the firms for taking the risk. By committing to a carbon price that includes a premium, she incentivises more investments. However, this price increase has the downside of a loss in consumer surplus and, in consequence, neither consumption nor investments are socially optimal. If demand was fully inelastic, i.e., $Q'(p) = 0$, the trade-off would diminish. The regulator would set the carbon price such that she fully compensates the firms for their profit risk, i.e. $d + \lambda\sigma_{C_v}$.

CCfD

When the regulator can offer firms a CCfD in t_1, she sets the carbon price in t_3 after the actual variable costs revealed and firms invested in the emission-free technology. Her optimisation problem is the same as under *Regulatory Flexibility* and the social optimum. Hence, $p^{CCfD} = d$.

In t_2, the firms' optimisation rationale is the same as under the *Commitment*, only that they face a strike price instead of the carbon price.

$$\overline{\chi}^{CCfD} = \frac{p_s - \mu_{C_v} - \lambda\sigma_{C_v}}{c_i} \tag{15}$$

In t_1, the regulator chooses a strike price that maximises expected social welfare and accounts for the firms' reaction to the strike price.

$$p_s = d + \lambda\sigma_{C_v} \tag{16}$$

In contrast to the previous cases, the regulator sets the strike price above the expected benefit of abatement. By substituting p_s^{CCfD} in (15), we see that under a *CCfD* regime, the emission-free production capacity equals the choice of the social planner, i.e., $\overline{\chi}^{CCfD} = \overline{\chi}^{Opt}$. The mark-up $\lambda\sigma_{C_v}$ of the strike price compensates firms for taking the risk. The strike price equals the upper limit of the carbon price under *Commitment*, i.e., the level of p^{Com} with fully inelastic demand. As the strike price does not affect the consumer surplus, the regulator can fully assume the firms' risk. In the absence of risk aversion, the regulator sets the strike price at the level of marginal damage. ■

Welfare Comparison

This subsection compares the ex-ante social welfare of the different carbon pricing regimes to determine which regime is socially optimal in an environment with risk regarding variable costs. We see that offering a CCfD yield the social optimum, while the other regimes fall short of it. Under *Commitment*, the carbon price is too high and the emission-free production capacity too low. With *Regulatory Flexibility*, the carbon price is socially optimal, but the emission-free production capacity is too low. We find that:

$$E[\mathcal{W}_{\sigma_{C_v}}^{Opt}] = E[\mathcal{W}_{\sigma_{C_v}}^{CCfD}] \geq E[\mathcal{W}_{\sigma_{C_v}}^{Com}] \geq E[\mathcal{W}_{\sigma_{C_v}}^{Flex}] \tag{17}$$

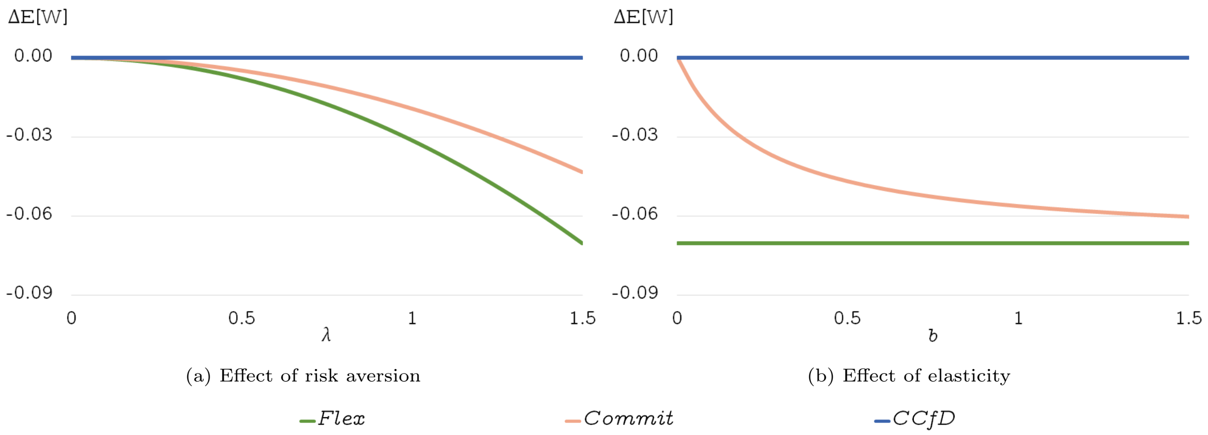
First, we compare the expected welfare in *CCfD* with the one the social planner obtains. As both the carbon price and the emission-free production capacity are identical, the *CCfD* regime results in the social optimum.

Second, we find that welfare in *Flex* falls short of the benchmark if firms are risk averse. Like in the case of damage risk, this arises due to too low investments. With increasing risk aversion, the shortfall of investments and welfare increases - a finding that can also be observed numerically in Figure 5a.[20]

Third, we find that welfare under *Commitment* falls short of the social optimum but is superior to *Regulatory Flexibility.* The shortfall in welfare arises as the *Com* regime reaches neither the socially optimal carbon price nor the socially optimal emission-free production capacity. The welfare superiority of *Com* compared to *Flex* emerges as the regulator can influence not only the market size but also the investments by setting the carbon price early. In contrast to the damage risk case, there is no disadvantage from setting the carbon price early as the realisation of the damage is known in t_1. When deciding on a carbon price

[20] Both, Figure 5a and Figure 5b, share the parameters regrading the distribution of the environmental damage and the costs related to the emission-free technology of Figure 4. The chosen parameter values are illustrative and do not correspond to empirical estimates.

under *Com*, the regulator balances the welfare gain from increased abatement arising from a higher carbon price against the welfare loss from decreased consumption. With an increasing elasticity of demand, e.g., due to an increasing slope of a linear demand function, the welfare loss from setting a higher carbon price increases. Hence, the higher the elasticity, the less the carbon price is increased compared to p^{Flex} by the regulator. In consequence, the relative advantage of *Com* compared to *Flex* decreases with increasing demand elasticity. Figure 5b displays the finding numerically. The analytical proof showing the welfare of *Com* is superior to *Flex* can be found in Appendix C.



(a) Effect of risk aversion

(b) Effect of elasticity

Figure specific parameters in (a): $\lambda \in [0, 1.5]$, $Q(p) = 5 - 0.4p$ and (b): $\lambda = 1.5$, $Q(p) = 5 - bp$ with $b \in (0, 1.5]$.

Figure 5: Difference in welfare compared to social optimum in the presence of cost risk.

4. Carbon pricing regimes with potentially socially not optimal production

In the previous section, we focused on the effects of different carbon pricing regimes in settings in which the production of the emission-free technology is always socially optimal in t_4, i.e., the variable costs of abatement are ex-post lower than the marginal environmental damage. In this section, we alleviate this assumption and allow for situations in which emission-free production may not be socially optimal.

4.1. Model framework in the presence of risk and socially not optimal production

To allow for situations in which the production of the emission-free technology is welfare reducing, we assume the environmental damage to be normally distributed instead of truncated normally distributed. That means there is a positive probability that variable costs exceed the realised damage, i.e. $P(C_V > D) > 0$ (see Figure 6).[21] We denote the cumulative distribution and probability density functions of D as $F_D(.)$ and $f_D(.)$. To keep investment in abatement ex-ante socially optimal in all cases, we maintain the assumption that $\mu_D > \mu_{C_V}$.

To emphasise the impact of potentially welfare-reducing production on the different carbon pricing regimes, we assume firms to be risk neutral when analysing the problem analytically (section 4.2). As

[21] The assumption of an untruncated normal distribution implies that $\chi < Q(p(d)$ cannot hold for all $\hat{d} \in D$. Instead, we can almost ensure that the emission-free capacity cannot cover the total demand by assuming $P(Q(p(d)) < \chi) \to 0$, such that the probability of this case is infinitesimally small and can be neglected.

the three carbon pricing regimes yield the same outcome in the variable cost risk case if firms are risk neutral (see section 3.3), we focus on the damage risk case.[22] Hence, we set $\mu_{C_V} = c_v$ with $\sigma^2_{C_V} = 0$ in the following. Being risk neutral, firms invest if their expected profits are positive, i.e., $E[\pi(\chi)] > 0$. To assess the combined effect of potentially welfare-reducing production and risk aversion, we analyse the model numerically in section 4.3.

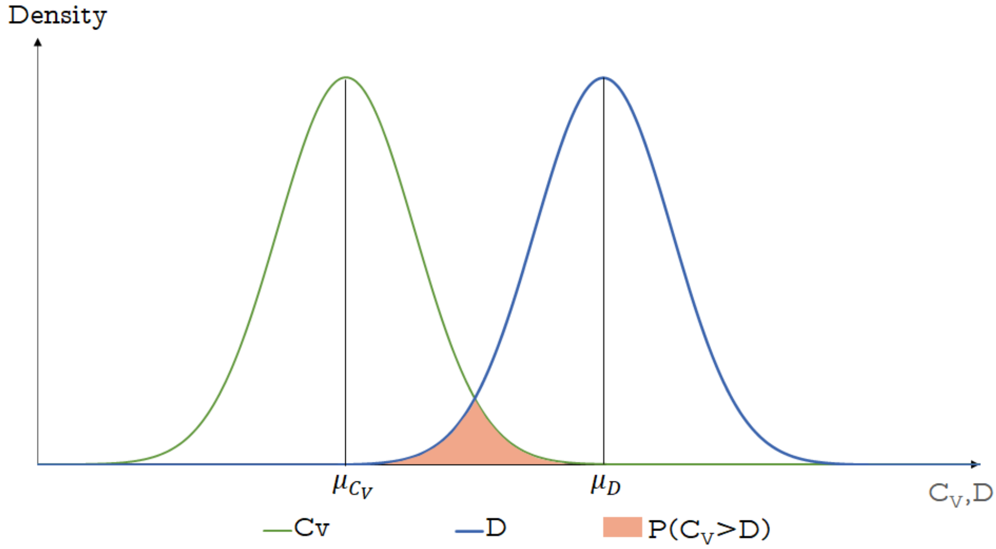


Figure 6: Density of normally distributed D and C_V with $P(C_V > D) > 0$.

Due to the adjusted assumptions on the distribution of damage and costs, the carbon price applied in t_4 may be smaller than the variable costs, such that firms may not produce.[23] Firms may decide not to produce even if they invested in the emission-free technology as investment costs are sunk. The profit function can be defined as:

$$\pi(\chi) = \begin{cases} p - c_v - c_i\overline{\chi} & \text{if } c_v \leq p \\ -c_i\overline{\chi} & \text{else} \end{cases} \tag{18}$$

Like in section 3, we assume the regulator to be risk neutral. Hence, she maximises the expected social welfare. As firms only produce if the carbon price exceeds the variable costs, welfare in t_4 is given by:

$$\mathcal{W} = \begin{cases} \int_p^\infty Q(z)dz + (p - \hat{d})Q(p) + \int_0^{\overline{\chi}}(d - c_v - c_i z)dz, & \text{if } c_v \leq p \\ \int_p^\infty Q(z)dz + (p - \hat{d})Q(p) - \int_0^{\overline{\chi}}(c_i z)dz, & \text{else} \end{cases} \tag{19}$$

4.2. Policy ranking with damage risk

This section analytically assess the different carbon pricing regimes when the emission-free production is potentially welfare reducing in a setting with damage risk and risk-neutral firms. We derive the outcomes

[22] Appendix E shows that all carbon pricing regimes yield the social optimum if risk stems from variable costs and production is potentially welfare reducing.
[23] In section 3.2, the realised carbon price by assumption is higher than the marginal costs of production, such that firms produce for any realisation of damage and costs.

of the three carbon pricing regimes regarding emission-free production capacity $\overline{\chi}$ and carbon price p. We contrast the three regimes to the social optimum and conclude that

Proposition 4. *In the presence of damage risk, potentially welfare-reducing production and risk-neutral firms, only setting a carbon price flexibly yield a socially optimal level of p and $\overline{\chi}$. Offering a CCfD or committing to a carbon price falls short of the social optimum, as these regimes safeguard emission-free production even if it is ex-post socially not optimal.*

Under *Regulatory Flexibility*, the regulator can react flexibly to the actual environmental damage and sets the socially optimal Pigouvian tax level. Concurrently, as firms are risk neutral, investments are not hampered by the risk in profits. Hence, in *Flex*, the emission-free production capacity is socially optimal. In contrast, if the regulator offers a CCfD or commits to a carbon price, the firms' production decision is independent of the actual environmental damage. Hence, these regimes safeguard emission-free production even if it is ex-post socially not optimal. Although the regulator anticipates this effect and, in the *CCfD* regime, lowers the strike price, she cannot reach the social optimum. In addition to the welfare-reducing production level, committing to a carbon price early on also sets the carbon price for consumers, which is ex-post socially not optimal. As in the previous section, this socially not optimal carbon price level additionally lowers welfare.

Proof. For the proof of proposition 4, we compare the socially optimal carbon price and the emission-free production capacity to the three carbon pricing regimes. Appendix D presents a complete derivation of the respective optimal solutions. In the following, we provide the main results and the intuition behind the finding in proposition 4. ■

Social optimum

In t_3, the social planner sets the carbon price p^{Opt} when the level of damage revealed. She optimises (19), anticipating that her choice of the carbon price impacts the production of the emission-free technology. Irrespective of the production decision, the social planner sets the carbon price equal to the actual environmental damage, i.e., the Pigouvian tax level $p^{Opt} = \hat{d}$. Hence, whether firms that invested in the emission-free technology in t_2 produce in t_4 or not depends on the realisation of marginal environmental damage.

In t_2, the social planner sets the emission-free production capacity $\overline{\chi}^{Opt}$ to maximise expected welfare. She considers the cases in which production of the emission-free technology may not be socially optimal, i.e., $c_v > \hat{d}$. Thereby, she knows that irrespective of the investment decision, firms will only produce if the realised damage is greater than the marginal variable costs of abatement. In the social optimum, she sets the emission-free production capacity to:

$$\overline{\chi}^{Opt} = \frac{\int_{c_v}^{\infty} (z - c_v) f_D(z) dz}{c_i} \tag{20}$$

The solution balances the expected benefit of abatement with its investment costs. The expected benefit of abatement is equal to the benefit from reduced environmental damage minus variable costs weighted by its probability of realisation represented by the integral over the distribution function. The integral is limited to c_v as there is no emission-free production for $c_v > \hat{d}$.

Regulatory flexibility

Under *Regulatory Flexibility*, the regulator sets the carbon price after the actual damage revealed. Hence, in t_3, the regulator faces the same optimisation problem as the social planner, such that $p^{Flex} = p^{Opt} = \hat{d}$.

Sunk investment costs from t_2 or whether the emission-free technology produces or not in t_4 are irrelevant for the regulator's decision.

In t_2, firms choose to invest if their expected utility is positive, anticipating that the Pigouvian carbon tax depends on the damage level that is not yet revealed. The firms anticipate that they will only produce if the damage (and the respective carbon price) is large enough, i.e., $c_v \leq \hat{d}$. Thereby, the marginal firm investing in the emission-free technology is defined by

$$\overline{\chi}^{Flex} = \frac{\int_{c_v}^{\infty}(z - c_v) f_D(z) dz}{c_i} \tag{21}$$

In the absence of risk aversion, the investment rationales of firms and the social planner are aligned, such that *Flex* reaches the social optimum. This result extends the findings from sections 3.2 and 3.3 with $\lambda = 0$ to the case in which emission-free production can be ex-post welfare reducing.

Commitment

Under *Commitment*, firms choose to invest in the emission-free technology in t_2 given the announced carbon price level. The investment decisions are identical to those under *Regulatory Flexibility*, only that the firms know the carbon price when making their decision. Hence, the marginal firm investing in the emission-free technology is characterised by

$$\overline{\chi}^{Com} = \begin{cases} \frac{p^{Com} - c_v}{c_i} & \text{for } c_v \leq p \\ 0 & \text{else} \end{cases} \tag{22}$$

In t_1, the regulator sets the carbon price anticipating that her choice impacts the firms' investment decision. She chooses a carbon price equal to the expected environmental damage, i.e., $p^{Com} = \mu_D$. As in section 3.2 the carbon price is either too high or too low. By assumption, the expected damage is greater than the variable costs, i.e., $\mu_D > c_v$, which implies that investments and production occur. In cases where $\hat{d} < c_v$, the emission-free technology should not produce but does so in response to a too high carbon price. Furthermore, plugging in p^{Com} in (22) and subtracting the socially optimal investment level shows that the investment level under *Com* falls short of the social optimum:

$$\begin{aligned} \overline{\chi}^{Com} - \overline{\chi}^{Opt} &= \frac{\int_{-\infty}^{\infty}(z - c_v) f_D(z) dz}{c_i} - \frac{\int_{c_v}^{\infty}(z - c_v) f_D(z) dz}{c_i} \\ &= \frac{\int_{-\infty}^{c_v}(z - c_v) f_D(z) dz}{c_i} \\ &\leq 0 \end{aligned} \tag{23}$$

This result shows that the regulator incentives less investments than socially optimal in order to limit the welfare loss arising from potentially welfare-reducing production.

CCfD

When the regulator offers a CCfD in t_1, the optimisation rationale in t_3 is the same as in the social optimum and under *Regulatory Flexibility* (19). The solution yields the socially optimal Pigouvian tax level

$$p^{CCfD} = p^{Opt} = p^{Flex} = \hat{d} \tag{24}$$

In t_2, the investment decision of firms is identical to the rationale under the other regimes and hence:

$$\overline{\chi}^{CCfD} = \begin{cases} \frac{p_s - c_v}{c_i}, & \text{for } c_v \leq p_s \\ 0, & \text{else} \end{cases} \tag{25}$$

If the strike price, i.e., the firms' marginal revenue, is larger than their variable costs, they invest in the emission-free technology. Otherwise, it is not worthwhile for firms to enter a CCfD and invest.

In t_1, the regulator chooses a strike price that maximises social welfare. She accounts for the firms' reaction to the strike price.

$$p_s = \begin{cases} \mu_D, & \text{for } c_v \leq \mu_D \\ 0 \leq p_s < c_v, & \text{else} \end{cases} \tag{26}$$

By assumption $\mu_D > c_v$ holds. Hence, only the first case materialises, and the regulator offers a CCfD that incentivises investments and production. The resulting emission-free production capacity and production coincide with the one under *Commitment*. Hence, socially not optimal production occurs in those cases were $\hat{d} < c_v$. Furthermore, less investments than socially optimal are incentivised ($\overline{\chi}^{CCfD} = \overline{\chi}^{Com} = \frac{\mu_D - c_v}{c_i} < \overline{\chi}^{Opt}$) in order to limit the negative welfare effects of socially not optimal production.

Welfare comparison

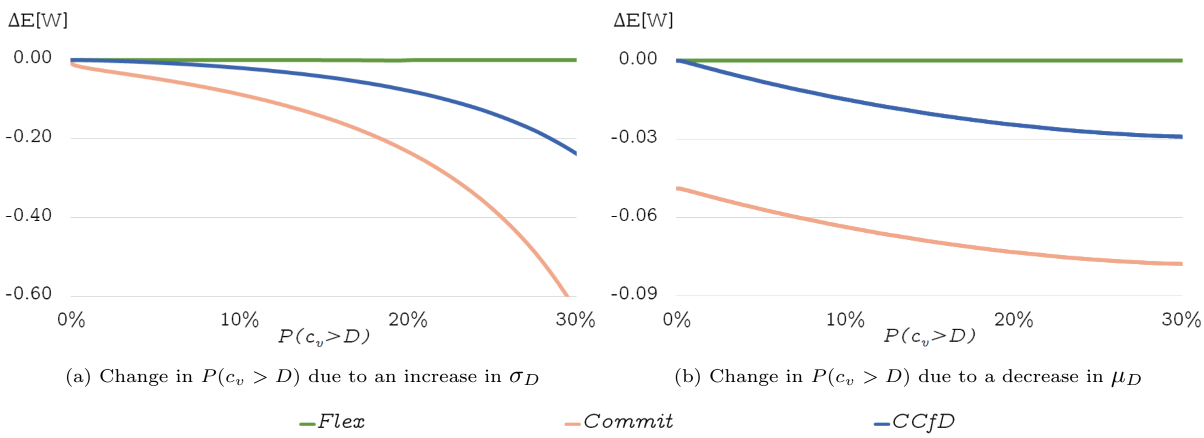
We now compare the welfare of the three carbon pricing regimes in a setting of damage risk, risk-neutral firms, and potentially welfare-reducing emission-free production. *Regulatory Flexibility* yields both the socially optimal emission-free production capacity and carbon price. Under the *CCfD* regime, the carbon price is socially optimal, but too few firms invest in the emission-free technology. *Commitment* falls equally short of the socially optimal investment level. In addition, it achieves a lower consumer surplus due to a sub-optimal carbon price. Hence we derive the ranking:

$$E[\mathcal{W}^{Opt}_{\sigma_D}] = E[\mathcal{W}^{Flex}_{\sigma_D}] \geq E[\mathcal{W}^{CCfD}_{\sigma_D}] \geq E[\mathcal{W}^{Com}_{\sigma_D}] \tag{27}$$

First, we find that *Regulatory Flexibility* reaches the social optimum. The firms face a carbon price equal to the marginal environmental damage and, thus, their production decision is socially optimal. Concurrently, as the firms are risk neutral, volatile profits do not impede investments.

Second, welfare falls short of the social optimum if the regulator offers a CCfD. Firms' production decision is independent of the actual carbon damage, such that emission-free production is safeguarded even if it is ex-post socially not optimal. We find that with an increasing probability of ex-post welfare-reducing production, welfare increasingly falls short of the social optimum. The probability of situations in which emission-free production is socially not optimal depends both on the variance (σ_D) and the expected value (μ_D) of the environmental damage. However, the impact of these two factors differs. As the expected value of environmental damage decreases, the welfare-deterring effect of the *CCfD* regime is partially mitigated as the socially optimal emission-free production capacity decreases, too. Figure 7 illustrates these findings for a numerical example.[24] We provide an analytical proof showing the welfare superiority of *Regulatory Flexibility* compared to the *CCfD* regime in Appendix D. Figure 7a presents welfare changes induced by an increase of the variance of the damage, σ_D, and Figure 7b welfare changes induced by an increase of the mean of the environmental damage, μ_D.

Third, confirming the results of Habermacher and Lehmann (2020), we find that *Com* likewise falls short of the social optimum. Moreover, *Com* performs worse than offering a CCfD. In addition to the welfare-reducing production, committing to a carbon price early on does not only affect producers but also consumers. Suppose the probability of socially not optimal production increases due to an increase of the damage variance, both the production and the consumption decisions are increasingly distorted. As a result, the welfare deterring effect in comparison to the *CCfD* regime increases. In turn, if the probability of socially not optimal production increases due to a reduced difference between μ_D and c_v, the shortfall in welfare is unaffected. We depict these results in Figure 7.



(a) Change in $P(c_v > D)$ due to an increase in σ_D

(b) Change in $P(c_v > D)$ due to a decrease in μ_D

Figure specific parameters in (a): $D \sim N(\mu_D = 2.75, \sigma_D^2 \in [0, 1.5]$ and (b): $D \sim N(\mu_D \in [2.25, 3.5]), \sigma_D^2 \in (0, 1.5])$.

Figure 7: Difference in welfare compared to social optimum in the presence of damage risk and potentially welfare-reducing production.

4.3. Numerical application with risk aversion

We complement our analytical results with a numerical application. The primary intention of this numerical exercise is to show how firms' risk aversion alters the effect of potentially welfare-reducing production in case of damage risk. Like in section 3, we assume the firms to have a utility which is exponential in profits (i.e., $EU[\pi(\chi)] = E[1 - e^{\pi(\chi)}]$. We find that the introduction of risk aversion reduces the superiority of *Regulatory Flexibility* and generates a trade-off for the regulator between incentivising investments and

[24] These parameter values are illustrative and do not correspond to empirical estimates. Both, Figure 7a and Figure 7b, share the parameters regrading the demand $Q(p) = 5 - 0.4p$ and the costs related to the emission-free technology $c_v = 2$ and $c_i = 1$.

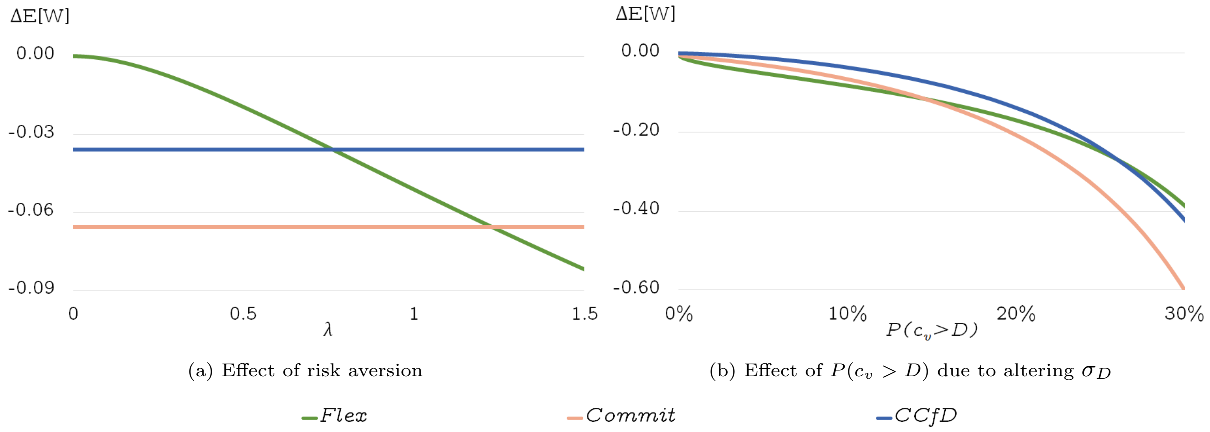
triggering socially optimal production. Note that these parameter values are illustrative and do not correspond to empirical estimates.[25] For the analysis, we vary two parameters in our model: firms' risk aversion and the distribution of the environmental damage. The latter results in different probabilities of socially not optimal production, i.e., how likely it is that variable costs of abatement are ex-post higher than the marginal environmental damage.

To illustrate the effects of these two variations, we calculate the expected welfare levels of the carbon pricing regimes and compare them to the social optimum. Figure 8 depicts the results. In Figure 8a, we analyse the impact of firms' risk aversion. Extending our analytical results for the case without risk aversion, *Commitment* and *CCfD* do not result in the social optimum, whereby the *CCfD* regime is superior to *Com*, as it sets the socially optimal carbon price. Firms' risk aversion does not impact the welfare levels as both regimes remove risk for the firms. Also reflecting the results of section 4.2, the *Flex* regime results in the social optimum if firms are risk neutral. However, as the risk aversion increases, fewer firms invest in the emission-free technology, whereby the expected welfare of this policy regime decreases. If this investment hampering effect of risk aversion becomes sufficiently large, the *Flex* regime becomes welfare inferior to *Com* and *CCfD*. Hence, there is a trade-off between the effects identified in section 3.2 and 4.2.

Figure 8b shows a similar effect when varying the probability of socially not optimal production, $P(C_v > D)$, by altering the variance of the marginal damage σ_D. In the absence of volatility and, hence, damage risk all regimes result in the social optimum, confirming the results from section 2.2. With increasing volatility, *Flex* becomes less efficient as firms' risk aversion increasingly impedes investments. Offering a CCfD and committing to a carbon price, in contrast, become less efficient due to the increasing probability of welfare-reducing production arising from increased volatility. The level of risk aversion does not impact this effect. Under *Com*, the ex-post socially not optimal carbon price also applies for consumers, such that welfare is lower than in the *CCfD* regime. With an increasing probability of socially not optimal production, the welfare-deterring effect of *CCfD* and *Com* becomes more pronounced compared to the *Flex* regime. Hence, with an increasing probability of welfare-reducing production, the *Flex* regime becomes welfare superior to *Com* and *CCfD*.[26]

[25]Figure 8a and Figure 8b share the parameters regarding the demand $Q(p) = 5-0.1$ and the costs related to the emission-free technology $c_v = 4$ and $c_i = 1$.

[26]When changes in the probability of socially not optimal production stem from decreasing the difference between μ_D and c_v, similar effects occur (see Appendix F).



(a) Effect of risk aversion

(b) Effect of $P(c_v > D)$ due to altering σ_D

Figure specific parameters in (a): $\lambda \in [0, 1.5]$, $D \sim N(\mu_D = 2.75, \sigma_D^2 = 0.7803)$ such that $P(c_v > D) = 10\%$ and (b): $\lambda = 1.5$, $D \sim N(\mu_D = 5, \sigma_D^2 \in (0, 2])$.

Figure 8: Difference in welfare compared to social optimum in the presence of damage risk, potentially welfare-reducing production and risk aversion.

Both numerical simulations show that the superiority of the respective carbon price regime is ambiguous and depends on specific parameters. However, if the regulator had to choose between offering a CCfD and committing to a carbon price early on, i.e., before the risk resolves, it is always beneficial to provide a CCfD.

5. Discussion

In the previous sections, we showed under which circumstances offering a CCfD can be a valuable policy measure. CCfDs could increase welfare compared to a flexible carbon price if the regulator expects that, first, firms will significantly under-invest in an abatement technology in the presence of risk and, second, the probability of welfare-reducing emission-free production is low. In other words, a CCfD is only beneficial if the benefit from the additional abatement that it incentivises outweighs the risk that it supports a technology that is socially not optimal.

There are several considerations beyond our model setup that determine whether a CCfD is an efficient policy instrument. First, it matters who can enter a CCfD. While policy constraints may imply that a regulator should offer CCfDs only to limited sectors, for instance, heavy industry, our research indicates that they may be helpful in a broader range of settings in which agents make insufficient investments for decarbonisation because of the presence of risk. Second, the variance of the variable at risk may increase with a longer duration of the CCfD. Hence, the probability of supporting an ex-post welfare-reducing technology may increase with the duration. Third, the process of how the regulator grants a CCfD determines its impact on welfare. Suppose the CCfD only addresses the risk regarding the valuation of damage. In that case, the strike price should equal the regulator's damage expectation, and she can offer the CCfD to any interested party. If, however, the regulator aims to address private information, for instance, on the expected variable costs or firms' risk aversion, an auction process may be preferable to minimise costs for the regulator. Likewise, this holds if the CCfD involves an additional subsidy.

In addition to the carbon price risk, the regulator may introduce an instrument, similar to a CCfD, that assumes risks on the firms' variable costs. For instance, the proposal of the German funding guidelines for large-scale decarbonisation investments in the industrial sector includes such an extended risk assumption by the government (BMU, 2021). The extended risk-bearing could reduce complementary investment subsidies from the regulator to risk-averse firms, as shown by Richstein et al. (2021).[27] However, the regulator would safeguard firms in situations with ex-post socially not optimal production, i.e., unexpectedly high variable costs which exceed marginal damage. Thereby, the probability of financing an ex-post socially not optimal technology would increase, decreasing welfare. This measure would need a reasonable justification, for instance, a significant level of firms' risk aversion or a sufficiently low probability that the low-carbon technology is socially not optimal.

Our research relies on several assumptions that, if relaxed, might dampen the identified effects and potentially change the policy rankings. Noteworthy, we assume the absence of shadow cost of public funding. Because taxation has distortionary effects, public expenses might come at a cost (e.g. Ballard and Fullerton, 1992, for a review). Including shadow costs of public funds into our model might yield two effects. First, the carbon price would optimally be higher than the marginal environmental damage. The regulator would value one unit of revenue from the carbon price at more than one unit of consumer surplus because it allows other distortionary taxes to be reduced (see, e.g., Helm et al., 2003, for a discussion of this *weak form* of a double-dividend). Second, offering a CCfD would be more costly, and the regulator might require a premium for providing the contract and safeguarding the investments. If this is the case, the benefits of offering a CCfD would partially diminish. We expect a trade-off between the benefit of increased investments and the costs of additional public funds when comparing a *CCfD* regime with *Regulatory Flexibility* and *Commitment*.

Similarly, the regulator may also be risk averse. In this case, we can see the three carbon pricing regimes from the angle of who bears the risk (see Hepburn, 2006, for a discussion of risk-sharing between the government and the private sector). While the risk remains with the firms under *Regulatory Flexibility*, the regulator assumes the risk under *Commitment* and *CCfD*. Suppose a risk-averse regulator bears the risk in the presence of an unknown valuation of environmental damage. To reduce the negative welfare effects in case of great environmental damage, she would set a higher strike price when offering a CCfD or increase the carbon price under *Commitment*. In contrast, with variable cost risk, she prefers incentivising a lower level of investment to reduce her risk. This aspect may change the policy ranking of the three carbon pricing regimes.

We analyse a setting where carbon prices determined by the marginal environmental damage result in a demand that exceeds the optimal emission-free production capacity. However, we could think of settings, in which demand can be covered entirely by the emission-free production. In these settings, the conventional technology would not produce. Hence, the marginal utility of consumption, given the production capacity of the emission-free technology, would determine the product price. In consequence, if firms would assume the product price to be set by the conventional technology, some of the firms using the emission-free technology would incur a loss. Instead, firms would anticipate a product price below the carbon price and reduce their investment. The marginal firm would avoid a loss by balancing its investment costs with the contribution margin, which is reduced to lower prices.

Our model results focus on the effects of each type of risk separately. In reality, stakeholders likely face

[27] In our model, e.g., in section 3.3, such a scheme would lower the average strike price to the expected damage and reduce the average spending of the regulator.

damage and cost risk simultaneously and both risks may be correlated. If risks are positively correlated, high environmental damage indicates high variable costs and vice versa. In this case, the emission-free production is likely to be ex-post socially optimal as $\mu_{C_V} > \mu_D$ holds. Results are then similar to the setting in section 3. If risks are negatively correlated, high environmental damage indicates low variable costs and vice versa. In the case of high damage and low variable costs, emission-free production is socially optimal. In the case of low damage and high variable costs, in turn, the emission-free production is likely to be welfare reducing. Hence, if risks are negatively correlated, the situation is similar to the setting in section 4.

The last simplification of our model we like to stress is the assumption of constant marginal environmental damage. We do not expect our main findings regarding the ranking of the carbon pricing regimes to change if we alleviate this assumption. If the marginal environmental damage was non-constant, the regulator would still choose the Pigouvian tax level after the firms have invested. In contrast to our assumption, the tax level would depend on the number of firms using the emission-free technology, i.e., total emissions. If markets are competitive, the impact of an individual firm on total emissions is negligible, and firms' investment decisions would not change compared to our model.

6. Conclusion

The decarbonisation of the industry sector requires large-scale irreversible investments. However, the profitability of such investments is subject to risk, as both, the underlying revenue and the associated costs of switching to an emission-free production process, are unknown and cannot be sufficiently hedged. The European Commission's Hydrogen Strategy and the *Fit for 55* package propose Carbon Contracts for Differences (CCfDs) to support firms facing large-scale investment decisions. Such contracts effectively form a hedging instrument to reduce the firms' risks.

With this research, we contribute to the understanding of how regulators should design this instrument and under which circumstances it is beneficial to offer a CCfD. We analyse the effects of a CCfD in the presence of risks stemming from environmental damage and variable costs on the decisions of a regulator and risk-averse firms facing an irreversible investment decision. Applying an analytical model, we compare three carbon price regimes against the social optimum: *Regulatory Flexibility*, *Commitment*, and offering a *CCfD*.

We conclude that a CCfD can be a welfare-enhancing policy instrument, as it encourages investments when firms' risk aversion would otherwise impede them. Additionally, offering a CCfD is always better than committing early to a carbon price as CCfDs incentivise investments in the same way while keeping the possibility to set the carbon price flexibly if new information,e.g., on the environmental damage, is available. However, if it is likely that the production of the emission-free technology turns out to be socially not optimal, CCfDs have the disadvantage that the regulator is locked in her decision, and she may distort the market clearing. In these situations, *Regulatory Flexibility* can be welfare superior to offering a CCfD. The comparison of *Regulatory Flexibility* and *Commitment* depends on the type of risk involved. With damage risk, *Regulatory Flexibility* is superior to *Commitment* if the level of risk aversion is low and the elasticity of demand is high. With variable cost risk, in contrast, *Regulatory Flexibility* performs worse than *Commitment.* While the regulator can only set the carbon price after the firm's investment under *Regulatory Flexibility*, she can balance additional investment incentives and the consumption level under *Commitment.*

This research focuses on the effects of CCfDs, aiming at mitigating the impact of risk regarding investments in emission-free technologies. Further research analysing CCfDs with more complex features and the interactions between CCfDs and other policy instruments may broaden our understanding of this instrument. To begin with, regulators may combine a CCfD with a subsidy payment to firms. This combination may be justified if the future carbon price is too low to incentivise sufficient emission-free investments, e.g., in the presence of learning effects or other positive externalities. Research could focus on whether combining a CCfD and a subsidy has advantages over offering both instruments separately. Additionally, proposals for the use of CCfDs focus on sectors competing in international markets. Our model assumes complete cost pass-through of the carbon price and, hence, increased revenues for firms investing in abatement. If not all firms on an international market face a (similar) carbon price, this may not hold. It remains open how the design of CCfDs would need to change in such settings to ensure investments' profitability. Future analyses could consider the possibility of introducing carbon border adjustment mechanisms, such that producers from countries without a carbon price at the domestic level cannot offer the goods at a lower price. The question how other hedging instruments offered by private actors compare to CCfDs is also worth analysing in more detail. Moreover, future research could assess the role of shadow costs of public funds by extending our model in this regard. As pointed out in section 5, we assume payments under a CCfD to be welfare-neutral. Considering shadow costs of public funds may worsen the welfare ranking of CCfDs compared to pure carbon pricing regimes.

References

Alexander, P. and D. Moran (2013). Impact of perennial energy crops income variability on the crop selection of risk averse farmers. *Energy Policy 52*, 587–596. Special Section: Transition Pathways to a Low Carbon Economy.

Arrow, K. and R. C. Lind (1970). Uncertainty and the evaluation of public investment decisions. *American Economic Review 60*(3), 364–78.

Arrow, K. J. and G. Debreu (1954). Existence of an equilibrium for a competitive economy. *Econometrica: Journal of the Econometric Society*, 265–290.

Baldursson, F. M. and N.-H. M. Von der Fehr (2004). Price volatility and risk exposure: on market-based environmental policy instruments. *Journal of Environmental Economics and Management 48*(1), 682–704.

Ballard, C. L. and D. Fullerton (1992). Distortionary taxes and the provision of public goods. *Journal of Economic Perspectives 6*(3), 117–131.

Banal-Estañol, A. and M. Ottaviani (2006). Mergers with product market risk. *Journal of Economics & Management Strategy 15*(3), 577–608.

Blundell, W., G. Gowrisankaran, and A. Langer (2020, August). Escalation of scrutiny: The gains from dynamic enforcement of environmental regulations. *American Economic Review 110*(8), 2558–85.

BMU (2021). Eckpunkte für eine Förderrichtlinie Klimaschutzverträge zur Umsetzung des Pilotprogramms „Carbon Contracts for Difference“. https://www.bmu.de/fileadmin/Daten_BMU/Download_PDF/Klimaschutz/eckpunktepapier_klimaschutzvertraege_ccfd_bf.pdf, accessed: 20.08.2021.

Borch, K. (1962). Equilibrium in a reinsurance market. *Econometrica 30*(3), 424–444.

Brändle, G., M. Schönfisch, and S. Schulte (2021). Estimating long-term global supply costs for low-carbon hydrogen. *Applied Energy 302*, 117481.

Bundesverfassungsgericht (2021). Constitutional complaints against the federal climate change act partially successful. https://www.bundesverfassungsgericht.de/SharedDocs/Pressemitteilungen/EN/2021/bvg21-031.html;jsessionid=C62AC122F5A4EAFDC942FEB0AB0F9B96.1_cid377, accessed: 20.08.2021.

Chao, H.-P. and R. Wilson (1993). Option value of emission allowances. *Journal of Regulatory Economics 5*(3), 233–249.

Chiappinelli, O., T. Gerres, K. Neuhoff, F. Lettow, H. de Coninck, B. Felsmann, E. Joltreau, G. Khandekar, P. Linares, J. Richstein, et al. (2021). A green covid-19 recovery of the eu basic materials sector: identifying potentials, barriers and policy solutions. *Climate Policy*, 1–19.

Chiappinelli, O. and K. Neuhoff (2020). Time-consistent carbon pricing: The role of carbon contracts for differences. *DIW Berlin Discussion Paper 1859*, 1–35.

Christiansen, V. and S. Smith (2015). Emissions taxes and abatement regulation under uncertainty. *Environmental and Resource Economics 60*(1), 17–35.

Datta, A. and E. Somanathan (2016). Climate policy and innovation in the absence of commitment. *Journal of the Association of Environmental and Resource Economists 3*(4), 917–955.

Diamond, P. A. (1978). The role of a stock market in a general equilibrium model with technological uncertainty. In *Uncertainty in Economics*, pp. 209–229. Elsevier.

Dixit, A. K., R. K. Dixit, and R. S. Pindyck (1994). *Investment under uncertainty.* Princeton university press.

Dorsey, J. (2019). Waiting for the courts: Effects of policy uncertainty on pollution and investment. *Environmental and Resource Economics 74*(4), 1453–1496.

Economist (2021). A court ruling triggers a big change in germany's climate policy. *The Economist*. https://www.economist.com/europe/2021/05/08/a-court-ruling-triggers-a-big-change-in-germanys-climate-policy, accessed: 20.08.2021.

European Commission (2021a). Proposal for a Directive of the European Parliament and of the Council - Amending Directive 2003/87/EC establishing a system for greenhouse gas emission allowance trading within the Union, Decision (EU) 2015/1814 concerning the establishment and operation of a market stability reserve for the Union greenhouse gas emission trading scheme and Regulation (EU) 2015/757. *Official Journal of the European Union*.

European Commission (2021b). Towards competitive and clean european steel. , Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions.

Fernandez, V. (2018). Price and income elasticity of demand for mineral commodities. *Resources Policy 59*, 160–183. Sustainable management and exploitation of extractive waste: towards a more efficient resource preservation and waste recycling.

Fisher, A. C. (1973). Environmental externalities and the arrow-lind public investment theorem. *The American Economic Review 63*(4), 722–725.

Habermacher, F. and P. Lehmann (2020). Commitment versus discretion in climate and energy policy. *Environmental and Resource Economics 76*(1), 39–67.

Harstad, B. (2012). Climate contracts: A game of emissions, investments, negotiations, and renegotiations. *The Review of Economic Studies 79*(4), 1527–1557.

Helm, D., C. Hepburn, and R. Mash (2003). Credible carbon policy. *Oxford Review of Economic Policy 19*(3), 438–450.

Hepburn, C. (2006). Regulation by prices, quantities, or both: a review of instrument choice. *Oxford review of economic policy 22*(2), 226–247.

Heutel, G. (2019). Prospect theory and energy efficiency. *Journal of Environmental Economics and Management 96*, 236–254.

Höffler, F. (2006). Monopoly prices versus ramsey-boiteux prices: Are they "similar", and: Does it matter? *Journal of Industry, Competition and Trade 6*(1), 27–43.

Höffler, F. (2014). *Ökonomische Analyse des Energieumweltrechts*, Volume 2.

IEA (2019). The future of hydrogen. `https://www.iea.org/reports/the-future-of-hydrogen`, accessed: 20.08.2021.

IEA (2021). *World Energy Outlook 2021*. IEA. `https://www.oecd-ilibrary.org/content/publication/14fcb638-en`.

IPCC (2021). Summary for policymakers. *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. [Masson-Delmotte, V., P. Zhai, A. Pirani, S. L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M. I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T. K. Maycock, T. Waterfield, O. Yelekçi, R. Yu and B. Zhou (eds.)]. Cambridge University Press. In Press.

Jakob, M. and S. Brunner (2014). Optimal commitment under uncertainty: adjustment rules for climate policy. *Strategic Behavior and the Environment 4*(3), 291–310.

Kanbur, R., J. Pirttilä, and M. Tuomala (2006). Non-welfarist optimal taxation and behavioural public economics. *Journal of Economic Surveys 20*(5), 849–868.

Kaufman, N. (2014). Why is risk aversion unaccounted for in environmental policy evaluations? *Climatic change 125*(2), 127–135.

Laffont, J.-J. and J. Tirole (1996). Pollution permits and environmental innovation. *Journal of Public Economics 62*(1-2), 127–140.

López Rodríguez, J. M., A. Sakhel, and T. Busch (2017). Corporate investments and environmental regulation: The role of regulatory uncertainty, regulation-induced uncertainty, and investment history. *European Management Journal 35*(1), 91–101.

Markowitz, H. (1952). Portfolio selection. *The Journal of Finance 7*(1), 77–91.

Meunier, G. (2013). Risk aversion and technology mix in an electricity market. *Energy Economics 40*, 866–874.

Newbery, D. M., D. M. Reiner, and R. A. Ritz (2019). The political economy of a carbon price floor for power generation. *The Energy Journal 40*(1).

Norgaard, R. and T. Killeen (1980). Expected utility and the truncated normal distribution. *Management Science 26*(9), 901–909.

OECD (2002, Jan). Glossary of statistical terms - homogenous products.

OECD (2021). *Managing Climate Risks, Facing up to Losses and Damages*.

OEIS (2021). The role of hydrogen in the energy transition. *Oxford Energy Forum*. `https://www.oxfordenergy.org/wpcms/wp-content/uploads/2021/05/OEF-127.pdf`, accessed: 20.08.2021.

Pigou, A. C. (1920). The economics of welfare.

Quiggin, J. C., G. Karagiannis, and J. Stanton (1993). Crop insurance and crop production: an empirical study of moral hazard and adverse selection. *Australian Journal of Agricultural Economics 37*(429-2016-29192), 95–113.

Requate, T. and W. Unold (2003). Environmental policy incentives to adopt advanced abatement technology: Will the true ranking please stand up? *European Economic Review 47*(1), 125–146.

Richstein, J. C. (2017). Project-based carbon contracts: A way to finance innovative low-carbon investments. *DIW Berlin Discussion Paper*.

Richstein, J. C., M. Kröger, K. Neuhoff, O. Chiappinelli, and F. Lettow (2021). Carbon contracts for difference. *DIW Berlin*.

Schlund, D., S. Schulte, T. Sprenger, et al. (2021). The who's who of a hydrogen market ramp-up: A stakeholder analysis for germany. Technical report, Energiewirtschaftliches Institut an der Universitaet zu Koeln (EWI).

Tietjen, O., K. Lessmann, and M. Pahle (2020). Hedging and temporal permit issuances in cap-and-trade programs: the market stability reserve under risk aversion. *Resource and Energy Economics*, 101214.

Unold, W. and T. Requate (2001). Pollution control by options trading. *Economics Letters 73*(3), 353–358.

Vogl, V., M. Åhman, and L. J. Nilsson (2018). Assessment of hydrogen direct reduction for fossil-free steelmaking. *Journal of Cleaner Production 203*, 736–745.

Willems, B. and J. Morbee (2010). Market completeness: How options affect hedging and investments in the electricity sector. *Energy Economics 32*(4), 786–795.

Appendix A. Proof of Proposition 1

For the proof of Proposition 1, we compare the socially optimal outcome to the three carbon pricing regimes. In the following, we derive the outcomes of these regimes.

Regulatory flexibility

In a setting with *Regulatory flexibility*, the regulator sets the carbon price after the firms have invested in the emission-free technology. The regulator faces the optimisation problem:

$$\max_p \mathcal{W} = \int_p^\infty Q(z)dz + (p-d)Q(p) + \int_0^{\overline{\chi}} (d - c_v - c_i z)dz \tag{A.1}$$

We derive the optimal solution by deriving the first-order conditions:

$$\frac{\partial \mathcal{W}}{\partial p} = -Q(p) + Q(p) + Q'(p)(p-d) = 0 \longrightarrow p^{Flex} = d \tag{A.2}$$

As in the social optimum, the carbon price equals the damage of one additional unit of the good. In t_3, the investments are already set, and, hence, the social planner and the regulator face identical problems. The carbon price does not influence the emission-free production capacity but only determines the optimal level of consumption and, in consequence, pollution.

In t_2, the firms choose to invest in the emission-free technology, as long as the associated profits are positive. Firms anticipate the carbon price that arises in the subsequent stage. The profit of the marginal firm investing in the emission-free technology is zero and, hence, the emission-free production capacity is defined by

$$\begin{aligned} \pi(\overline{\chi}) &= p^{Flex} - c_v - c_i\overline{\chi} = 0 \\ \longrightarrow \overline{\chi}^{Flex} &= \frac{p^{Flex} - c_v}{c_i} \end{aligned} \tag{A.3}$$

The optimal emission-free production capacity is at the socially optimal level, as the carbon price set in t_3 equals the marginal damage ($p^{Flex} = d$), i.e. $\overline{\chi}^{Flex} = {}^{d-c_v}/_{c_i}$.

Commitment

When the regulator commits to a carbon price, she faces no decision in t_3. In t_2, the firms choose to invest in the emission-free technology if the associated profits are positive, such that the marginal firm investing is defined by:

$$\begin{aligned} \pi(\overline{\chi}) &= p - c_v - c_i\overline{\chi} = 0 \\ \longrightarrow \overline{\chi}^{Com} &= \frac{p - c_v}{c_i} \end{aligned} \tag{A.4}$$

In t_1, the regulator chooses the carbon price that maximises the social welfare function while anticipating the reaction function of firms to the announced price.

$$\begin{aligned} \max_p \mathcal{W} &= \int_p^\infty Q(z)dz + (p-d)Q(p) + \int_0^{\overline{\chi}(p)} (d - c_v - c_i z)dz \\ \frac{\partial \mathcal{W}}{\partial p} &= -Q(p) + Q(p) + Q'(p)(p-d) + \overline{\chi}'(p)(d - c_v - c_i\overline{\chi}) = 0 \end{aligned} \tag{A.5}$$

Inserting the optimal investment level $\overline{\chi}^{Com}$ from (A.4), the expression yields:

$$Q'(p)(p-d) = \overline{\chi}'(p)(p-d) \longrightarrow \quad p^{Com} = d \tag{A.6}$$

As under *Regulatory flexibility*, the solution yields the social optimum. In the absence of risk, there is no difference for the regulator in setting the carbon price in t_1 or t_3.

CCfD

When the regulator offers a CCfD, she sets the carbon price in t_3 after the firms invested in the emission-free technology. The solution yields the same result as under *Regulatory flexibility*, as the regulator can only control the size of the market at this stage.

$$\begin{aligned} \max_p \mathcal{W} &= \int_p^\infty Q(z)dz + (p-d)Q(p) + \int_0^{\overline{\chi}} (d - c_v - c_i z)dz \\ \longrightarrow \ p^{CCfD} &= d \end{aligned} \tag{A.7}$$

In t_2, the firms choose to invest in the emission-free technology according to their profit function, which depends on the strike price of the CCfD. The carbon price is irrelevant to the firms.

$$\begin{aligned} \pi(\overline{\chi}) &= p_s - c_v - c_i\overline{\chi} = 0 \\ \longrightarrow \overline{\chi}^{CCfD} &= \frac{p_s - c_v}{c_i} \end{aligned} \tag{A.8}$$

The result is the socially optimal emission-free production capacity that balances the marginal costs and the benefit of abatement, i.e., savings from reduced payment of the strike price. In t_1, the regulator chooses the strike price that she offers to the firms. She faces the following optimisation problem:

$$\begin{aligned} \max_{p_s} \mathcal{W} &= \int_p^\infty Q(z)dz + (p-d)Q(p) + \int_0^{\overline{\chi}(p_s)} (d - c_v - c_i z)dz \\ \frac{\partial \mathcal{W}}{\partial p_s} &= [d - c_v - c_i\overline{\chi}(p_s)]\overline{\chi}'(p_s) = 0 \end{aligned} \tag{A.9}$$

Inserting the optimal investment level $\overline{\chi}^{CCfD}$ from (A.8), the expression yields $p_s^{CCfD} = d$. Hence, the strike price equals marginal damage, and the strike price and carbon price have the same level in the absence of risk. Firms and consumers receive the same signal regarding the benefit from investments or the damage from consumption, respectively. Both prices are at the socially optimal level.

Welfare ranking

As all three carbon pricing regimes result in the socially optimal carbon price and the socially optimal emission-free production capacity, it is straightforward that the respective welfare is equal to the social optimum.

Appendix B. Proof of Proposition 2

For the proof of Proposition 2, we derive the optimal solutions in the respective carbon pricing regimes and under the assumption of a social planner.

Social optimum

In the social optimum, the social planner sets the carbon price p in t_3 after the actual environmental damage revealed. She optimises:

$$\max_{p} \mathcal{W} = \int_{p}^{\infty} Q(z)dz + (p - \hat{d})Q(p) + \int_{0}^{\overline{\chi}} (\hat{d} - c_v - c_i z)dz \tag{B.1}$$

Given the first-order conditions, the optimal solution is equal to:

$$\frac{\partial \mathcal{W}}{\partial p} = -Q(p) + Q(p) + Q'(p)(p - \hat{d}) = 0 \longrightarrow p^{Opt} = \hat{d} \tag{B.2}$$

The investments are due before the actual damage reveals. Hence, the social planner must choose the emission-free production capacity in the presence of risk. The social planner optimises the expected welfare with respect to the emission-free production capacity $\overline{\chi}$.

$$\max_{\overline{\chi}} E[\mathcal{W}] = E\left[\int_{p}^{\infty} Q(z)dz + (p - d)Q(p) + \int_{0}^{\overline{\chi}} (d - c_v - c_i z)dz\right] \tag{B.3}$$

Given the expected damage, the optimal solution is equal to:

$$\frac{\partial E[\mathcal{W}]}{\partial \overline{\chi}} = E[d] - c_v - c_i\overline{\chi} = 0 \longrightarrow \overline{\chi}^{Opt} = \frac{E[d] - c_v}{c_i} = \frac{\mu_D - c_v}{c_i} \tag{B.4}$$

Regulatory flexibility

Under *Regulatory flexibility*, similar to the assumption of a social planner, the regulator sets the carbon price after the actual damage revealed. As shown in Appendix A, in this case, the regulator and the social planner have the same objective function. Hence, in *Flex*, the regulator optimises (B.1), which yields $p^{Flex} = \hat{d}$.

In t_2, the firms choose to invest in the emission-free technology, as long as the associated profits are positive. They anticipate the subsequent carbon price:

$$\begin{aligned} &EU(\pi(\overline{\chi})) = E[p^{Flex}] - c_v - c_i\overline{\chi} - \lambda\sigma_{p^{Flex}} = 0 \\ &\longrightarrow \overline{\chi}^{Flex} = \frac{p^{Flex} - c_v - \lambda\sigma_{p^{Flex}}}{c_i} = \frac{\mu_D - c_v - \lambda\sigma_D}{c_i} \end{aligned} \tag{B.5}$$

where the last step stems from replacing the statistical moments of the carbon price in *Flex* with the ones of the environmental damage, i.e., $E[p^{Flex}] = \mu_D$ and $\sigma_{p^{Flex}} = \sigma_D$. The emission-free production capacity decreases with the volatility of the environmental damage and firms' risk aversion, as $\frac{\partial \overline{\chi}^{Flex}}{\partial \lambda} = -\frac{\sigma_D}{c_i}$ and $\frac{\partial \overline{\chi}^{Flex}}{\partial \sigma_D} = -\frac{\lambda}{c_i}$ are both smaller than zero.

Commitment

When the regulator commits to a carbon price, she faces no decision in t_3. In t_2, the firms make their investment decision given the announced carbon price level. In this setting, all parameters are known, such that firms face no risk:

$$\begin{aligned} \pi(\overline{\chi}) &= p - c_v - c_i\overline{\chi} = 0 \\ \longrightarrow \overline{\chi}^{Com} &= \frac{p - c_v}{c_i} \end{aligned} \tag{B.6}$$

In t_1, the regulator sets the carbon price maximising expected welfare and accounting for the firms' reaction function to the announced price:

$$\begin{aligned} \max_p E[\mathcal{W}] &= E\left[\int_p^\infty Q(z)dz + (p - d)Q(p) + \int_0^{\overline{\chi}(p)} (d - c_v - c_i z)dz\right] \\ \frac{\partial E[\mathcal{W}]}{\partial p} &= -Q(p) + Q(p) + Q'(p)(p - \mu_D) + \overline{\chi}'(p)(\mu_D - c_v - c_i\overline{\chi}) = 0 \end{aligned} \tag{B.7}$$

Inserting the resulting emission-free production capacity $\overline{\chi}^{Com}$ from (B.6), the expression yields:

$$Q'(p)(p - \mu_D) = \overline{\chi}'(p)(p - \mu_D) \longrightarrow \quad p^{Com} = \mu_D \tag{B.8}$$

CCfD

When the regulator offers a CCfD, she sets the carbon price in t_3 after the firms made their investment decision. Hence, she optimises (B.1), and the solution is identical with the one of the social planner and under *Regulatory flexibility*, i.e., $p^{CCfD} = \hat{d}$.

In t_2, the firms choose to invest accounting for the strike price of the CCfD. The carbon price is irrelevant to firms. Hence, the maximisation problem is identical to (A.8), and the solution is equal to:

$$\overline{\chi}^{CCfD} = \frac{p_s - c_v}{c_i} \tag{B.9}$$

In t_1, the regulator chooses the strike price that maximises the expected social welfare:

$$\begin{aligned} \max_{p_s} E[\mathcal{W}] &= E\left[\int_p^\infty Q(z)dz + (p - d)Q(p) + \int_0^{\overline{\chi}(p_s)} (d - c_v - c_i z)dz\right] \\ \frac{\partial E[\mathcal{W}]}{\partial p_s} &= [\mu_D - c_v - c_i\overline{\chi}(p_s)] = 0 \end{aligned} \tag{B.10}$$

Inserting the optimal investment level $\overline{\chi}^{CCfD}$ from (B.9), the first-order condition yields $p_s^{CCfD} = \mu_D$. Hence, the strike price equals the expected marginal damage. Inserting p_s^{CCfD} into (B.9) shows that the investment level is socially optimal and equals the solution under *Commitment*.

Welfare ranking

As shown before, the carbon price and the emission-free production capacity are identical in the social optimum and in the *CCfD* regime. Thus, welfare in the *CCfD* regime and in the social optimum is identical, i.e., $E[\mathcal{W}_{\sigma_D}^{Opt}] = E[\mathcal{W}_{\sigma_D}^{CCfD}]$.

The emission-free production capacity under *Regulatory flexibility* is lower than the under the *CCfD* regime, as:

$$\overline{\chi}^{CCfD} - \overline{\chi}^{Flex} = \frac{\mu_D - c_v}{c_i} - \frac{\mu_D - c_v - \lambda\sigma_D}{c_i} = \frac{\lambda\sigma_D}{c_i} \geq 0 \tag{B.11}$$

Expected welfare increases with the number of firms investing in the emission-free technology, as long as $\overline{\chi} \leq \overline{\chi}^{CCfD} = \frac{\mu_D - c_v}{c_i}$, since $\frac{\partial E[\mathcal{W}]}{\partial \overline{\chi}} = \mu_D - c_v - c_i\overline{\chi}$ which is a positive number for all $\overline{\chi} < \frac{\mu_D - c_v}{c_i}$. Hence, welfare under regulatory flexibility is lower than socially optimal, i.e., $E[\mathcal{W}_{\sigma_D}^{CCfD}] \geq E[\mathcal{W}_{\sigma_D}^{Flex}]$.

The difference in welfare between the policy regimes of *Commitment* and *CCfD* stems from the difference in consumer surplus, as the respective emission-free production capacity are identical. Since the consumer surplus is a convex function, the welfare difference is positive:[28]

$$E[\mathcal{W}_{\sigma_D}^{CCfD}] - E[\mathcal{W}_{\sigma_D}^{Com}] = E[\int_D^\infty Q(z)dz] - \int_{\mu_D}^\infty Q(z)dz \geq 0 \tag{B.12}$$

Hence, it holds that $E[\mathcal{W}_{\sigma_D}^{CCfD}] \geq E[\mathcal{W}_{\sigma_D}^{Com}]$.

Whether the difference in expected welfare between *Flex* and *Com* is positive or not, is ambiguous. The difference is equal to

$$\begin{aligned} E[\mathcal{W}_{\sigma_D}^{Flex}] - E[\mathcal{W}_{\sigma_D}^{Com}] = & \underbrace{E[\int_D^\infty Q(z)dz] - \int_{\mu_D}^\infty Q(z)dz}_{\geq 0} \\ & \underbrace{+(\mu_D - c_v)(\overline{\chi}^{Flex} - \overline{\chi}^{Com}) - \int_{\overline{\chi}^{Com}}^{\overline{\chi}^{Flex}} (c_i z)dz}_{\leq 0}, \end{aligned} \tag{B.13}$$

where the first part, i.e., difference in consumer surplus, is positive and the second part, i.e., the difference in abatement benefit, is negative.

Appendix C. Proof of Proposition 3

For the proof of Proposition 3, we derive the optimal solutions in the respective carbon pricing regimes and under the assumption of a social planner.

[28]This relation is also known, as Jensen gap stemming from Jensen's inequality.

Social optimum

In the social optimum, the social planner sets in t_3 the carbon price p after the actual level of variable costs revealed. She optimises:

$$\begin{aligned} \max_p \mathcal{W} &= \int_p^\infty Q(z)dz + (p-d)Q(p) \int_0^{\overline{\chi}} (d - \hat{c_v} - c_i z)dz \\ \frac{\partial \mathcal{W}}{\partial p} &= -Q(p) + Q(p) + Q'(p)(p-d) = 0 \end{aligned} \tag{C.1}$$

Given the first-order condition, the optimal solution is equal to $p^{Opt} = d$.

The investments are due before the level of variable costs reveals. Hence, the social planner must set the emission-free production capacity in the presence of risk. The social planner optimises the expected welfare with respect to the emission-free production capacity $\overline{\chi}$, as depicted in (B.3). Given the expected variable costs, the optimal solution is equal to:

$$\frac{\partial E[\mathcal{W}]}{\partial \overline{\chi}} = d - E[c_v]c_i - \overline{\chi} = 0 \longrightarrow \overline{\chi}^{Opt} = \frac{d - \mu_{C_v}}{c_i} \tag{C.2}$$

Regulatory flexibility

As under the assumption of a social planner, the regulator sets the carbon price in t_3. Again, the regulator and the social planner have the same objective function. Hence, under *Regulatory flexibility*, the regulator optimises (C.1), which yields $p^{Flex} = d$.

In t_2, the firms take their investment decision, anticipating the risk in variable costs that arises in the subsequent stage:

$$\begin{aligned} &EU(\pi(\overline{\chi})) = p^{Flex} - E[c_v] - c_i\overline{\chi} - \lambda\sigma_{C_v} = 0 \\ &\longrightarrow \overline{\chi}^{Flex} = \frac{p^{Flex} - \mu_{C_v} - \lambda\sigma_{C_v}}{c_i} = \frac{d - \mu_{C_v} - \lambda\sigma_{C_v}}{c_i} \end{aligned} \tag{C.3}$$

where the last step stems from replacing the optimal carbon price in *Flex*. The emission-free production capacity decreases with the volatility of the variable costs and the firms' risk aversion, as $\frac{\partial \overline{\chi}^{Flex}}{\partial \lambda} = -\frac{\sigma_{C_v}}{c_i}$ and $\frac{\partial \overline{\chi}^{Flex}}{\partial \sigma_{C_v}} = -\frac{\lambda}{c_i}$, which both are smaller than zero.

Commitment

When the regulator commits to a carbon price, she faces no decision in t_3. In t_2, the firms choose to invest in the emission-free technology given the announced carbon price level. In this setting, the firms still face a risk, stemming from the variable costs. The firms invest if their expected utility is greater than zero. Hence, the marginal firm investing in the emission-free technology is characterised by:

$$\begin{aligned} &EU(\pi(\overline{\chi})) = p^{Com} - E[c_v] - c_i\overline{\chi} - \lambda\sigma_{C_v} = 0 \\ &\longrightarrow \overline{\chi}^{Com} = \frac{p^{Com} - \mu_{C_v} - \lambda\sigma_{C_v}}{c_i} \end{aligned} \tag{C.4}$$

In t_1, the regulator sets the carbon price maximising expected welfare and accounting for the reaction function of the firms to the announced price:

$$\begin{aligned} \max_{p} E[\mathcal{W}] &= E\Big[\int_{p}^{\infty} Q(z)dz + (p-d)Q(p) \int_{0}^{\overline{\chi}} (d - \hat{c_v} - c_i z)dz\Big] \\ \frac{\partial E[\mathcal{W}]}{\partial p} &= Q'(p)(p-d) + \overline{\chi}'(p)(d - \mu_{C_v} - c_i\overline{\chi}(p)) = 0 \\ \longrightarrow p - d &= \frac{\overline{\chi}'(p)}{-Q'(p)}(d - \mu_{C_v} - c_i\overline{\chi}(p)) \end{aligned} \tag{C.5}$$

Rearranging the first-order condition and substituting $\epsilon(p) = -\dfrac{\partial Q(p)}{\partial p}\dfrac{p}{Q(p)}$ yields the expression in (14). Additionally, we define $\eta = \frac{\overline{\chi}'(p)}{-Q'(p)}$. Substituting η in (C.5) and using $\overline{\chi}(p)^{Com}$ from (C.4), yields

$$p^{Com} = d + \frac{\eta}{1+\eta}\lambda\sigma_{C_v} \tag{C.6}$$

The resulting carbon price is greater than the environmental damage d, as η is a positive number.

CCfD

When the regulator offers a CCfD, she sets the carbon price in t_3 after the firms made their investment decision. Hence, she optimises (C.1), and the solution is identical with the one of the social planner and under *Regulatory flexibility*, i.e., $p^{CCfD} = d$.

In t_2, the firms invest in the emission-free technology accounting for the strike price of the CCfD. As in the other carbon pricing regimes, the firms face a risk in variable costs. The marginal firm investing in the emission-free technology is characterised by:

$$\begin{aligned} EU(\pi(\overline{\chi})) &= p_s - E[c_v] - c_i\overline{\chi} - \lambda\sigma_{C_v} = 0 \\ \longrightarrow \overline{\chi}^{CCfD} &= \frac{p_s - \mu_{C_v} - \lambda\sigma_{C_v}}{c_i} \end{aligned} \tag{C.7}$$

In t_1, the regulator chooses the strike price that maximises the expected social welfare:

$$\begin{aligned} \max_{p_s} E[\mathcal{W}] &= E\Big[\int_{p}^{\infty} Q(z)dz + (p-d)Q(p) + \int_{0}^{\overline{\chi}(p_s)} (d - c_v - c_i z)dz\Big] \\ \frac{\partial E[\mathcal{W}]}{\partial p_s} &= d - \mu_{C_v} - c_i\overline{\chi}(p_s) = 0 \end{aligned} \tag{C.8}$$

Inserting the optimal investment level $\overline{\chi}^{CCfD}$ from (C.7), the first-order condition is equal to

$$\Big(\frac{d - \mu_{C_v}}{c_i} - \frac{p_s - \mu_{C_v} - \lambda\sigma_{C_v}}{c_i}\Big) = 0 \tag{C.9}$$

, which yields $p_s^{CCfD} = d + \lambda\sigma_{C_v}$. Inserting p_s^{CCfD} into (C.7) shows that the emission-free production capacity is equal to tne one under a social planner, i.e., $\overline{\chi}^{CCfD} = \frac{d-\mu_{C_v}}{c_i}$

Welfare ranking

As shown before, the carbon price and the emission-free production capacity are identical in the social optimum and in the *CCfD* regime. Thus, welfare in the *CCfD* regime and in the social optimum is identical, i.e., $E[\mathcal{W}^{Opt}_{\sigma_{C_v}}] = E[\mathcal{W}^{CCfD}_{\sigma_{C_v}}]$.

Similar to the case of damage risk in Appendix B, the emission-free production capacity under *Regulatory flexibility* is lower than the under the *CCfD* regime, as:

$$\overline{\chi}^{CCfD} - \overline{\chi}^{Flex} = \frac{\lambda \sigma_{C_v}}{c_i} \geq 0 \tag{C.10}$$

Expected welfare increases in the emission-free production capacity $\overline{\chi}$, as long as $\overline{\chi} \leq \overline{\chi}^{CCfD} = \frac{d-\mu_{C_v}}{c_i}$, since $\frac{\partial E[\mathcal{W}]}{\partial \overline{\chi}} = d - \mu_{C_v} - c_i \overline{\chi}$. Hence, welfare in *Flex* is lower than socially optimal, i.e., $E[\mathcal{W}^{CCfD}_{\sigma_{C_v}}] \geq E[\mathcal{W}^{Flex}_{\sigma_{C_v}}]$.

To show that offering a CCfD is welfare superior to *Commitment*, we first compare the strike price with optimal carbon price in *Com*. Inserting $\overline{\chi}^{Com}$ and rearranging (C.6), yields:

$$p^{Com} - p_s = d + \frac{\eta}{1+\eta}\lambda\sigma_{C_v} - (d + \lambda\sigma_{C_v}) = (\frac{\eta}{1+\eta} - 1)\lambda\sigma_{C_v} \tag{C.11}$$

As η is a positive number, the first expression is negative and the difference is negative. Hence, we see that the optimal carbon price under commitment p^{Com} is smaller than the strike price of the CCfD. Consequently, the emission-free production capacity in *Com* is lower than when offering a CCfD, i.e., $\overline{\chi}^{CCfD} \geq \overline{\chi}^{Com}$. Similarly, it is straightforward to show that the carbon price under the *Com* regime is higher than under the *CCfD* regime. Both variables lead to lower welfare and, hence, we show that $E[\mathcal{W}^{CCfD}_{\sigma_{C_v}}] \geq E[\mathcal{W}^{Com}_{\sigma_{C_v}}]$.

To show that in this setting, *Commitment* to a carbon price is welfare superior to *Regulatory flexibility*, we can make use of the optimality of the carbon price in *Com*. The regulator sets a price above the marginal environmental damage to incentivise additional investments. She could, however, choose not to. We show the optimality by comparing:

$$E[\mathcal{W}^{Com}_{\sigma_{C_v}}] = E\Bigg[\int_{p^{Com}}^{\infty} Q(z)dz + (p^{Com} - d)Q(p) + d\overline{\chi}^{Com} - \frac{c_i}{2}(\overline{\chi}^{Com})^2 - c_v\overline{\chi}^{Com})\overline{Q}\Bigg] \tag{C.12}$$

$$\geq E\Bigg[\int_{p^{Flex}}^{\infty} Q(z)dz + (p^{Flex} - d)Q(p) + d\overline{\chi}^{Com} - \frac{c_i}{2}(\overline{\chi}^{Com})^2 - c_v\overline{\chi}^{Com})\overline{Q}\Bigg] \tag{C.13}$$

$$\geq E\Bigg[\int_{p^{Flex}}^{\infty} Q(z)dz + (p^{Flex} - d)Q(p) + d\overline{\chi}^{Flex} - \frac{c_i}{2}(\overline{\chi}^{Flex})^2 - c_v\overline{\chi}^{Flex})\overline{Q}\Bigg] = E[\mathcal{W}^{Flex}_{\sigma_{C_v}}], \tag{C.14}$$

where the first inequality is given by the optimality of p^{Com} and the second by the fact that $\overline{\chi}^{Flex} \leq \overline{\chi}^{Com}$ (c.f. Chiappinelli and Neuhoff, 2020).

Appendix D. Proof of Proposition 4

For the proof of Proposition 4, we derive the optimal solutions in the respective carbon pricing regimes and under the assumption of a social planner.

Social optimum

In t_3, the social planner sets the carbon price p after the actual environmental damage revealed, by optimising (B.1). Hence, the optimal carbon price is equal to $p^{Opt} = \hat{d}$.

In t_2, the social planner sets the emission-free production capacity under risk such that it maximises the expected welfare. She considers the cases in which production may not be optimal, i.e., $c_v > \hat{d}$.

$$\begin{aligned} \max_{\overline{\chi}} E[\mathcal{W}] =& P\Big(\int_p^\infty Q(z)dz + (p-\hat{d})Q(p) + \int_0^{\overline{\chi}} (\hat{d} - c_v - c_i z)dz \mid c_v \leq p \Big) \\ &+ P\Big(\int_p^\infty Q(z)dz + (p-\hat{d})Q(p) - \int_0^{\overline{\chi}} (c_i z)dz \mid c_v > p \Big) \\ =& \int_p^\infty Q(z)dz + (p-\mu_D)Q(p) - \int_0^{\overline{\chi}} (c_i z)dz + \int_{c_v}^\infty \overline{\chi}(z-c_v) f_D(z)dz \end{aligned} \tag{D.1}$$

, where $f_D(z)$ is the density function of the environmental damage. Given the first-order condition, the optimal solution is equal to:

$$\frac{\partial E[\mathcal{W}]}{\partial \overline{\chi}} = \int_{c_v}^\infty (z-c_v) f_D(z)dz - c_i \overline{\chi} = 0 \longrightarrow \overline{\chi}^{Opt} = \frac{\int_{c_v}^\infty (z-c_v) f_D(z)dz}{c_i} \tag{D.2}$$

Regulatory flexibility

As under the assumption of a social planner, the regulator sets the carbon price after the actual damage revealed with the same objective function. Hence, she sets $p^{Flex} = \hat{d}$.

In t_2, the firms invest in the emission-free technology if the associated expected utility is positive. They anticipate that the Pigouvian carbon tax depends on the damage level that is not yet revealed. The marginal firm investing in the emission-free technology is characterised by:

$$\begin{aligned} EU(\pi(\overline{\chi})) &= P\Big(p^{Flex} - c_v - c_i\overline{\chi} \mid c_v \leq p^{Flex} \Big) + P\Big(- c_i\overline{\chi} \mid c_v > p^{Flex} \Big) \\ &= \int_{c_v}^\infty (z-c_v) f_D(z)dz - c_i \overline{\chi} = 0 \\ &\longrightarrow \overline{\chi}^{Flex} = \frac{\int_{c_v}^\infty (z-c_v) f_D(z)dz}{c_i} \end{aligned} \tag{D.3}$$

The emission-free production capacity equals the socially optimal level, as the carbon price set in t_3 equals the marginal damage ($p^{Flex} = \hat{d}$), i.e. $\overline{\chi}^{Flex} = \overline{\chi}^{Opt}$.

Commitment

In t_2, the firms make their investment decision given the announced carbon price level. In this setting, the firms know all parameters affecting their profits, such that the firms face no risk. However, the profit functions of firms depend on the carbon price level, and they have to distinguish two cases.

$$\pi(\chi) = \begin{cases} p - c_v - c_i\chi, & \text{for } c_v \leq p \\ -c_i\chi, & \text{else} \end{cases} \tag{D.4}$$

Given the indifference condition of the marginal firm investing in the emission-free technology:

$$\overline{\chi}^{Com} = \begin{cases} \frac{p^{Com}-c_v}{c_i}, & \text{for } c_v \leq p \\ 0, & \text{else} \end{cases} \tag{D.5}$$

In t_1, the regulator sets the carbon price anticipating that her choice impacts the firms' investment decision:

$$\max_p E[\mathcal{W}] = \begin{cases} \int_p^\infty Q(z)dz + (p-\mu_D)Q(p) + \int_0^{\overline{\chi}(p)} \int_{-\infty}^\infty (t-c_v) f_D(t) - (c_i z) dt dz, & \text{if } c_v \leq p \\ \int_p^\infty Q(z)dz + (p-\mu_D)Q(p), & \text{else} \end{cases} \tag{D.6}$$

For the second case, is straightforward to show that the regulator sets carbon price equal to the expected damage. The solution for the first case is identical to the optimisation in (B.7). In both cases, the optimal carbon price equals the expected environmental damage and, thus,

$$p^{Com} = \begin{cases} \mu_D, & \text{if } c_v \leq p \\ \mu_D, & \text{else} \end{cases} \tag{D.7}$$

As by assumption the expected damage is higher than the variable costs, i.e., $\mu_D > c_v$, only the first case materialises. Thus, the optimal emission-free production capacity is equal to $\overline{\chi}^{Com} = \frac{\mu_D - c_v}{c_i}$.

CCfD

When the regulator offers a CCfD, she sets the carbon price in t_3 after the firms made their investment decision. Hence, she optimises (B.1), and the solution is identical with the one of the social planner and under *Regulatory flexibility*, i.e., $p^{CCfD} = \hat{d}$.

In t_2, the firms take their investment decision and account for the strike price of the CCfD. The carbon price is irrelevant to the firms. However, the firms only invest, if the strike price is above the variable costs.

$$\pi(\chi) = \begin{cases} p_s - c_v - c_i\chi, & \text{for } c_v \leq p_s \\ -c_i\chi, & \text{else} \end{cases} \longrightarrow \overline{\chi}^{CCfD} = \begin{cases} \frac{p_s - c_v}{c_i}, & \text{for } c_v \leq p_s \\ 0, & \text{else} \end{cases} \tag{D.8}$$

In t_1, the regulator chooses the strike price that maximises the expected social welfare:

$$\max_{p_s} E[\mathcal{W}] = \begin{cases} \int_p^\infty Q(z)dz + (p-\mu_D)Q(p) \int_0^{\overline{\chi}(p_s)} \int_{-\infty}^\infty (t-c_v) f_D(t) - (c_i z) dt dz, & \text{if } c_v \leq p_s \\ \int_p^\infty Q(z)dz + (p-\mu_D)Q(p), & \text{else} \end{cases} \tag{D.9}$$

For the second case, the strike price can take any realisation between zero and c_v, as firms would not invest. For the first case, the solution is identical to (C.8). Hence, the result is equal to

$$p_s = \begin{cases} \mu_D \\ 0 \leq p_s < c_v \end{cases} \tag{D.10}$$

Again, only the first case materialises, as by assumption $\mu_D > c_v$. Inserting p_s^{CCfD} into (D.8) shows that the investment level is equal to $\overline{\chi}^{CCfD} = \frac{\mu_D - c_v}{c_i}$.

Welfare ranking

As shown before, the carbon price and the emission-free production capacity are identical in the social optimum and under *Regulatory flexibility*. Thus, welfare in this carbon pricing regime is identical to the social optimum, i.e., $E[\mathcal{W}_{\sigma_D}^{Opt}] = E[\mathcal{W}_{\sigma_D}^{Flex}]$.

To compare *Flex* and *CCfD*, we evaluate the difference of expected welfare. Since $p^{Flex} = p^{CCfD}$, there is only a difference regarding welfare from production with the emission-free technology. Taking the derivatives of (19), we see that the expected social welfare is increasing in investments as long as $\overline{\chi} \leq \overline{\chi}^{Opt} = \overline{\chi}^{Flex}$:

$$\begin{aligned} \frac{\partial E[\mathcal{W}]}{\partial \overline{\chi}} &= \int_{c_v}^{\infty} (z - c_v) f_D(z) dz - c_i \overline{\chi} > 0 \,\forall\, \overline{\chi} < \frac{\int_{c_v}^{\infty} (z - c_v) f_D(z) dz}{c_i} \\ \frac{\partial^2 E[\mathcal{W}]}{\partial \overline{\chi}^2} &= -c_i < 0 \end{aligned} \tag{D.11}$$

As $\overline{\chi}^{CCfD} \leq \overline{\chi}^{Flex}$, we conclude that $E[\mathcal{W}_{\sigma_D}^{Flex}] \geq E[\mathcal{W}_{\sigma_D}^{CCfD}]$.

Lastly, it is straightforward to show that *Commitment* is welfare-inferior to the *CCfD* regime. As investments are identical in both regimes, the difference in welfare stems form the consumer surplus. Again, applying Jensen's inequality, it holds that

$$E[\mathcal{W}_{\sigma_D}^{CCfD}] - E[\mathcal{W}_{\sigma_D}^{Com}] = E[\int_{D}^{\infty} Q(z)dz] - \int_{\mu_D}^{\infty} Q(z)dz \geq 0. \tag{D.12}$$

Appendix E. Regulatory solutions with variable cost risk and potentially socially not optimal production

Under variable cost risk and potentially welfare-reducing production, the increase in marginal production costs might be so high that firms using the emission-free technology do not produce in t_4. As the investments in abatement are sunk, they do not impact the production decision. Overall welfare in t_4 is given by:

$$\mathcal{W} = \begin{cases} \int_p^{\infty} Q(z)dz + (p - d)Q(p) + \int_0^{\overline{\chi}} (d - \hat{c_v} - c_i z)dz, & \text{for } \hat{c_v} < d \\ \int_p^{\infty} Q(z)dz + (p - d)Q(p) - \int_0^{\overline{\chi}} (c_i z)dz, & \text{for } \hat{c_v} \geq d \end{cases} \tag{E.1}$$

Social optimum

In the social optimum, the social planner sets the carbon price p^{Opt} after the level of variable costs revealed. The optimisation is identical to maximising (B.1). Hence, it holds that $p^{Opt} = d$. The social planner sets the emission-free production capacity $\overline{\chi}^{Opt}$ such that it maximises expected welfare:

$$\begin{aligned}\max_{\overline{\chi}} E[\mathcal{W}] =& P\Big(\int_p^\infty Q(z)dz + (p-d)Q(p) + \int_0^{\overline{\chi}}(d - c_v - c_i z)dz \mid c_v \leq d\Big)\\ =& \int_p^\infty Q(z)dz + (p-d)Q(p) - \int_0^{\overline{\chi}}(c_i z)dz + P((d-c_v)\overline{\chi} \quad | \; c_v < d)\\ =& \int_p^\infty Q(z)dz + (p-d)Q(p) - \int_0^{\overline{\chi}}(c_i z)dz + \int_{-\infty}^{d}(d-z)\overline{\chi} f_{C_v}(z)dz\end{aligned} \tag{E.2}$$

We solve the problem using the first-order conditions:

$$\begin{aligned}\frac{\partial E[\mathcal{W}]}{\partial \overline{\chi}} =& - c_i\overline{\chi} + \int_{-\infty}^{d}(d-z)f_{C_v}(z)dt = 0\\ \longrightarrow \overline{\chi}^{Opt} =& \frac{\int_{-\infty}^{d}(d-z)f(z)dt}{c_i}\end{aligned} \tag{E.3}$$

The integral of the distribution function represents the marginal benefit from abatement (damage minus variable costs) weighted by its probability of realisation. The integral is limited to d as beyond this point production does not occur and the marginal benefit, hence, is zero.

Regulatory flexibility

As under the assumption of a social planner, the regulator sets the carbon price after the firms made their investment. Hence, she optimises (C.1) and sets $p^{Flex} = \hat{d}$, which is the Pigouvian tax.

In t_2, the firms choose to invest if their expected utility is greater than zero, given the risk regarding its future variable costs and anticipating the Pigouvian carbon tax rational of the regulator. The marginal firm investing in the emission-free technology is characterised by:

$$\begin{aligned}EU(\pi(\overline{\chi})) =& P\Big(p^{Flex} - c_v - c_i\overline{\chi} \mid c_v \leq p^{Flex}\Big) + P\Big(-C(\overline{\chi}) \mid c_v > p^{Flex}\Big) = 0\\ =& \int_{-\infty}^{d}(d-z)f_{C_v}(z)dz - c_i\overline{\chi} = 0\\ \longrightarrow \overline{\chi}^{Flex} =& \frac{\int_{-\infty}^{d}(d-z)f_{C_v}(z)dz}{c_i}\end{aligned} \tag{E.4}$$

, where we inserted the optimal carbon price ($p^{Flex} = d$). As in the case of damage risk without risk aversion, *Regulatory flexibility* reaches the social optimum.

Commitment

Under *Commitment*, the firms choose to invest after the regulator has announced the carbon price. The rationale for investments is identical to the one of *Regulatory flexibility*, as no damage risk exists. Hence, the structural solution is identical with one under the flexible carbon price regime.

$$\overline{\chi}^{Com} = \frac{\int_{-\infty}^{p}(p-z)f_{C_v}(z)dz}{c_i} \tag{E.5}$$

In t_1, the regulator sets the carbon price anticipating that her choice impacts the firms' investment decision:

$$\begin{aligned}\max_p E[\mathcal{W}] &= \int_p^\infty Q(z)dz + (p-d)Q(p) - \int_0^{\overline{\chi}(p)} (c_i z)dz + \int_{-\infty}^{p} \overline{\chi}(d-t) f_{C_v}(t)dt \\ &\longrightarrow p^{Com} = d\end{aligned} \tag{E.6}$$

The result is identical to the one of *Regulatory flexibility* and the social planner. As the firms are not risk averse, the regulator chooses the Piguvian tax level, that they can perfectly anticipate.

CCfD

When the regulator can offer firms a CCfD in t_1, she sets the carbon price in t_3 after the actual variable costs revealed and the firms made their investment decision. The firms using the emission-free production technology produce, if their variable costs are lower than the conventional technology, i.e., if $c_v < p_s$. The solution yields the socially optimal Pigouvian tax, i.e. $p^{CCfD} = d$. In t_2, the firms invest in the emission-free technology given the announced strike price. The costs remain risky, hence the marginal firm investing in the emission-free technology is characterised by:

$$\begin{aligned}EU(\pi(\overline{\chi})) &= P\Big(p_s - c_v - c_i\overline{\chi} \mid c_v \leq p_s\Big) + P\Big(- c_i\overline{\chi} \mid c_v > p_s\Big) = 0 \\ &= \int_{p_s}^{\infty} (p_s - z) f_{C_v}(z)dz - c_i\overline{\chi} = 0 \\ \longrightarrow \overline{\chi}^{CCfD} &= \frac{\int_{-\infty}^{p_s} (p_s - t) f_{C_v}(z)dz}{c_i}\end{aligned} \tag{E.7}$$

In t_1, the regulator chooses a strike price that maximises expected welfare. She accounts for the firms' reaction to the strike price:

$$\begin{aligned}\max_{p_s} E[\mathcal{W}] &= \int_p^\infty Q(z)dz + (p-d)Q(p) - \int_0^{\overline{\chi}(p)} (c_i z)dz + \int_{-\infty}^{p_s} \overline{\chi}(d-t) f_{C_v}(t) \\ &\longrightarrow p_s = d\end{aligned} \tag{E.8}$$

Welfare ranking

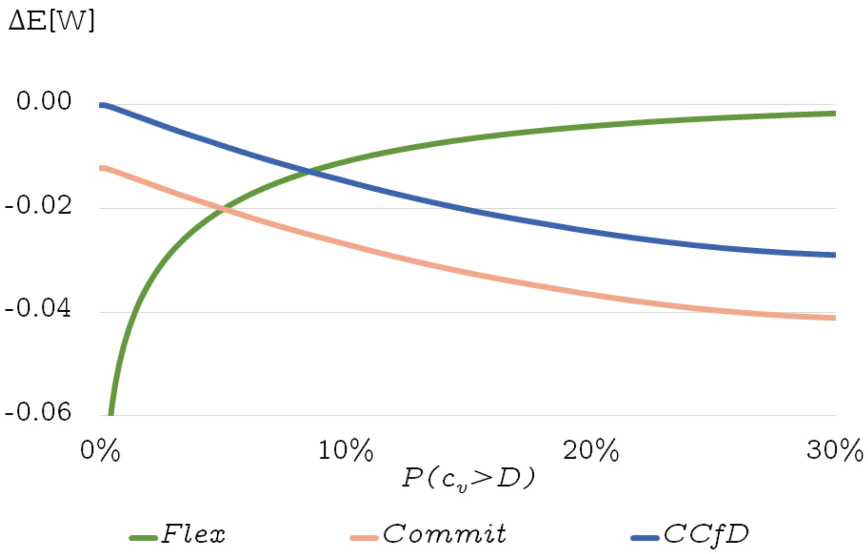
As all carbon pricing regimes result in the socially optimal carbon price and emission-free production capacity, there is no difference in welfare. The absence of risk aversion in this setting leads to equivalent welfare expectations.

Appendix F. Welfare difference compared to the social optimum in the presence of damage risk, and (ex post) potentially socially not optimal abatement due to an increase in $\boldsymbol{\sigma_D}$

Figure F.9 shows a similar effect, when varying the probability of socially not optimal production, $P(C_v > D)$, by altering the expected value of the marginal damage, μ_D.

The welfare of *CCfD* and *Commitment* is not affected by the presence of risk aversion (compare Figure F.9 (with risk aversion) with Figure 7b (no risk aversion)). Hence, as explained in section 4.2, the shortfall in welfare increases with an increased probability of socially not optimal production. Furthermore, the effect is concave in the probability of socially not optimal emission-free production as the welfare-deferring effect is mitigated by decreasing socially optimal investments.

The *Regulatory flexibility* regime does not result in the social optimum if the firms are risk averse. However, as the socially optimal emission-free production capacity decrease, the absolute gap in welfare compared to the social optimum decreases.



$D \sim N(\mu_D \in [4.25; 5.5], \sigma_D^2 = 0.25)$, $\lambda = 1.5$, $Q(p) = 5 - 0.1p$, $c_v = 4$, $c_i = 1$.

Figure F.9: Difference in welfare compared to social optimum due to change in $P(c_v > D)$ by altering μ_D in the presence of damage risk and potentially welfare-reducing production.