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Article

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Waterbed leakage drives EU ETS emissions: COVID-19, the Green Deal & the recovery plan

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Because of the EU ETS' cancellation policy, its fixed cap or waterbed is punctured, meaning that shocks and overlapping policies can change cumulative carbon emissions, i.e., waterbed leakage. This paper explains the mechanisms behind waterbed leakage and quantifies the effect of COVID-19, the European Green Deal and the recovery stimulus package on cumulative EU ETS emissions and allowance prices. We find that the negative demand shock of the pandemic has limited effect on the EU ETS price and is almost completely translated into lower carbon emissions, because of high waterbed leakage. Increasing the 2030 reduction target to -55% increases the price of allowances to 67 €/ton CO₂ today and decreases carbon emissions in the period 2020-2050 by around 16.3 GtCO₂ or 42% of the cumulative cap under current policies. These results are robust to significant changes in allowance demand triggered by overlapping policies in the period 2021-2031.

Keywords: European Emission Trading System, Waterbed leakage, Carbon Emissions, COVID-19, European Green Deal, European recovery plan

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1 Introduction

The European Union Emissions Trading System (EU ETS), a cornerstone of EU climate policy, is being put to the test by three large shocks affecting carbon emissions: a temporary negative allowance demand shock because of COVID-19, a positive or negative allowance demand shock because of overlapping policies from the NextGenerationEU recovery stimulus package, and a permanent negative allowance supply shock because of the increased emission reduction target as part of the European Green Deal.

Under an emissions trading system with a fixed cap, these shocks would only affect the price of carbon emissions, like in the EU ETS during the 2009 recession (Koch et al., 2014), but cumulative emissions would equal the cumulative emissions cap – the so-called waterbed effect.¹ However, because the EU ETS’ cancellation policy is conditional on the total number of allowances in circulation (TNAC) (European Union, 2018), exogenous shocks impacting the TNAC – such as COVID-19, the recovery package or the Green Deal – will affect both carbon prices and cumulative carbon emissions, hence, causing waterbed leakage. Waterbed leakage is defined as the net effect of a shock or policy on cumulative emissions in EU ETS. It is positive when a policy that increases (decreases) emissions in a particular year leads to increased (decreased) cumulative emissions, and negative when a policy backfires. For example, waterbed leakage is 0.5 if a shock decreases emissions by 4 MtCO₂ and cumulative emissions by 2 MtCO₂.

First, we discuss the three factors that affect waterbed leakage and provide a graphical summary of its magnitude, depending on the year of the shock and the year in which the waterbed is sealed again. Second, we quantify the individual and joint effect of the COVID-19, European Green deal and stimulus package shocks on allowance prices and total cumulative emissions. Because of the large uncertainty in this forward simulation, we present a range of results that crucially depend on when the waterbed will be sealed again.

2 The punctured waterbed of the EU ETS

The European Union Emissions Trading Scheme (EU ETS) limits emissions from the electric power sector, the energy-intensive industry and intra-European aviation. This cap-and-trade system covers around 45% of the EU’s greenhouse gas emissions, equaling 1562 MtCO₂ in 2019 (European Commission, 2020a, 2019).

To address the large surplus of allowances in the system and to structurally signal future scarcity of emission allowances, the EU strengthened the EU ETS by adding a cancellation policy to its market stability reserve (MSR) (European Union, 2018). If the number of allowances in circulation (TNAC) surpasses 833 MtCO₂, the MSR absorbs a share of the allowances to be auctioned, so that they can be released again from the reserve in the future when allowances are scarce. Starting in 2023, however, a cancellation policy will be in effect, such that allowances held in the MSR exceeding the amount auctioned during the previous year will be canceled (European Union, 2018).

Without the cancellation policy, individual actions to reduce emissions only affect who emits and at what price, but not what ultimately matters, which is how much is emitted in total under the fixed cap – the waterbed effect (Perino, 2018). However, with a cancellation policy

¹This effect is described using the analogy of a waterbed because you can push down on a waterbed in any location, but the total volume of water in the bed remains the same (Perino, 2018).

in effect, changes to allowance demand, such as overlapping policies (Bertram et al., 2015; Perino, 2018; Perino et al., 2020; Rosendahl, 2019b; Bruninx et al., 2019), strategies to buy, bank, and burn allowances (Gerlagh and Heijmans, 2019), or exogenous shocks may result in changes to cumulative emissions – waterbed leakage. Waterbed leakage depends on three factors: the direct effect of cancellation (Appendix A.1), the indirect effect of expectations through adjustments of the price profile (Appendix A.2), and the (change in) duration of the waterbed puncture (Appendix A.3).

3 Waterbed leakage: impact on cumulative emissions

Because of the punctured waterbed, the effect of overlapping policies on cumulative emissions – waterbed leakage – is not obvious and depends on the year the policies are announced, the time profile of their effect on emissions, and the year in which the waterbed is sealed (Beck and Kruse, 2020; Bruninx et al., 2019; Gerlagh and Heijmans, 2019; Gerlagh et al., 2020b; Perino et al., 2020; Rosendahl, 2019a). Figure 1 presents a graphical summary of waterbed leakage depending on two of the above three dimensions: the year in which the overlapping policy reduces emissions on the horizontal axis and the year in which the waterbed is sealed on the vertical axis – assuming that the policy is announced in 2020. For details on the mathematical model used to derive these results, we refer the reader to Appendix B. Importantly, we ignore the possibility that overlapping policies affect the duration of the punctured waterbed, see Section A.3, which could lead to waterbed leakage that can have any positive or negative value. Hence, in this section, waterbed leakage is always between -1 and 1.

We can identify four different regions in Figure 1, based on the relative importance of the direct effect of the policy on emissions (Perino, 2018) and the indirect price effect caused by the adjustment of the equilibrium price (Rosendahl, 2019b; Bruninx et al., 2019).² First, in the upper-left part of the figure, the direct effect dominates, because the overlapping policy is executed well before the waterbed is sealed. In that case, changes to the TNAC affect cancellation over an extended period, as explained by Perino (2018). In the most extreme case, i.e., executing an overlapping policy in 2020 and the waterbed sealing in 2050, direct waterbed leakage nearly equals one. In other words, abatement now decreases cumulative emissions by the same amount. On the other hand, the closer the effect of the overlapping policy is to the year in which the waterbed is sealed, the lower the direct effect.

Second, below the diagonal line, the direct effect is zero as the overlapping policy only reduces emissions after the waterbed is sealed again. However, waterbed leakage is not zero, because of the indirect effect of announced future overlapping policies on the equilibrium price path, which affects emissions before the waterbed is sealed. This indirect price effect is negative, meaning that overlapping policies backfire: abatement efforts lead to an increase in cumulative emissions, announced increases in emissions lead to a decrease in cumulative emissions. This ‘new green paradox’ was first described by Rosendahl (2019a). Importantly, for a given duration of the waterbed puncture, the indirect effect increases with the time between the announcement of a policy and when it takes place (Gerlagh et al., 2020b). But as soon as the waterbed is sealed, the indirect effect becomes independent of the year in which the policy is executed (Gerlagh et al., 2020b).

²Figure 3 in Appendix C presents the direct and indirect separately.

(a) -40% by 2030

(b) -55% by 2030

Figure 1. Waterbed leakage (the net effect of a shock or overlapping policy on cumulative emissions in EU ETS) as a function of the year the overlapping policy or shock takes place (horizontal axis) and the year the waterbed is sealed (vertical axis). The solid black line indicates where the direct effect ends. Waterbed leakage is positive when a policy that increases (decreases) emissions leads to increased (decreased) cumulative emissions. It is negative when a policy backfires. Note that we ignore the possibility that overlapping policies affect the duration of the punctured waterbed. The numerical values behind these graphs are reported in Appendix C, alongside with a separate graphical representation of the direct and indirect effect.

Third, the indirect price effect is larger when the waterbed is sealed later and the policy is announced today, but executed later. As a result, waterbed leakage tends to -1 in the upper-right corner of Figure 1. Note furthermore that the indirect effect may dominate the direct effect in the years preceding the year in which the waterbed is sealed, yielding negative waterbed leakage in regions where one intuitively expects positive values.

Fourth, as soon as there are no more banked allowances and the total number of allowances in circulation is zero, there is no more inter-temporal arbitrage and waterbed leakage is zero. Both the direct effect and the indirect price effect will be zero and the EU ETS once again puts a strict cap on emissions. Overlapping policies will not have any effect on cumulative emissions, but will affect the EU ETS price.

4 The impact of COVID-19, the Green Deal and the recovery plan

Figure 2 summarizes the simulated (a) cumulative emissions and (b) allowances prices for each of six scenarios, which are constructed as follows.³ Scenario (1) and (2) consider the current -40% carbon reduction target by 2030, whereas scenarios (3)–(5) and (6) consider a reduction target of -55% and -60%, reflecting the implementation of the Green Deal.⁴ Scenario (1) does not consider the impact of COVID-19 (-0.72 GtCO₂ in the period 2020-2025), whereas all other scenarios do. Scenario (3) and (5) mimic the effect of an overlapping policy – induced by the recovery stimulus package – affecting emission allowance demand by 100 MtCO₂/year in the period 2021-2031, considering the -55% emission reduction target.

The vertical red lines represent the cumulative cap (2020-end ETS), including the surplus at the end of 2019 European Commission (2020b), in the absence of any cancellation. This means a cumulative cap of 38.8 GtCO₂ under the current policy scenario of a 40% carbon reduction target in 2030 ('-40% in 2030'). Because the pandemic does not affect the cumulative cap, it is equal under the second scenario ('-40% in 2030'). When the carbon reduction target in 2030 is increased to -55% ('-55% in 2030 pandemic') and -60% ('-60% in 2030 pandemic'), the cumulative cap lowers to 24.6 GtCO₂ and 22.0 GtCO₂.

The black and gray bars represent simulated cumulative emissions in each of the six scenarios. Because of cancellation, cumulative emissions are always lower than the cumulative emissions cap. In the pre-pandemic scenario (1), median expected cumulative emissions are 33.2 GtCO₂, which is 5.6 GtCO₂ lower than the fixed cap. However, there is a large range of uncertainty around these results, depending on when the waterbed is sealed again (indicated by the dates in the bars), which depends on a number of factors (see Appendix A.3). For example, total cancellations are only 2.7 GtCO₂ when the waterbed is already sealed in 2022. On the other hand, when the waterbed only seals in 2050, more allowances are cancelled and cumulative emissions in the pre-pandemic scenario are only 26.7 GtCO₂.

³Detailed descriptions of the scenarios can be found in Appendix B.

⁴For ease of referencing, we characterize our scenarios based on the overall European emission reduction target (-40%, -55% or -60%) relative to 1990 emission levels. Recall, however, that the emission reduction targets for the sectors covered by EU ETS are more stringent: -43%, -57.75% (estimated) and -63% (estimated), relative to 2005 emission levels.

(a) Cumulative emissions under the EU ETS as of 2020

(b) Simulated emission allowance prices in 2020.

Figure 2. Cumulative emissions (a) and allowances prices (b) in each of our six scenarios. The black and grey bars represent the range of outcomes, the white markers represent the median value and the vertical red lines represent the cumulative cap without cancellation (2020-end ETS). The indicated years are the years in which the waterbed is sealed in the edge cases (lowest-highest emissions). The cumulative impact of COVID-19 pandemic is assumed to be 0.72 GtCO₂ in the period 2020-2025 and is enforced in all scenarios except the "No pandemic" scenario. Scenario (3) and (5) mimic the effect of an overlapping policy reducing (3) or increasing (5) emissions by 100 MtCO₂/year in the period 2021-2031, considering the -55% emission reduction target.

Adding the COVID-induced negative demand shock of 0.72 GtCO₂ in the period 2020-2025 (scenario (2)), we find that it is largely translated into lower cumulative emissions. As discussed in Section A.1, the longer the duration of the waterbed puncture, the larger the share of the additional 0.72 GtCO₂ allowances that is cancelled. Importantly, because the negative demand shock induced by COVID measures increases the number of allowances in circulation, it will prolong the waterbed puncture. For example, in cases where the total number of allowances in circulation is low and the waterbed was expected to be closed in 2022, the negative demand shock of COVID extends the puncture to 2023.

Raising the ambition for 2030 to -55% or -60% (scenarios (4) and (6)), Figure 2 shows that the duration of the waterbed puncture increases to 2024 in the cases with the highest cumulative emissions. In line with our discussion in Section A.3, we find that median expected cumulative cancellations increase with approximately 2 GtCO₂ – from 5.6 GtCO₂ to 7.6 GtCO₂. Note that this counter-intuitive self-reinforcing effect, first discussed in (Bruninx et al., 2020, 2019), is less pronounced for the cases with lowest cumulative emissions, as these cases are characterized by shorter waterbed punctures.⁵

Finally, in scenarios (3) and (5) we add a shock to scenario (4) of -100 or +100 MtCO₂/year over the 2021-2031 period. This is an illustration of the effect of an overlapping policy, like renewable support (scenario (3)) or electric vehicles (scenario (5)). In line with the values in Figure 1, we find that the effect of these policies is almost completely translated into lower (3) or higher (5) cumulative emissions if the waterbed is punctured for a long time – indicating waterbed leakage close to one – as the direct effect dominates (scenario (3) and (5)) and the waterbed is sealed sooner (scenario (5)). When the waterbed is sealed soon, the effect on cumulative emissions is, as expected, lower. In these cases, the overlapping policy extends beyond the year in which the waterbed is sealed, such that the indirect effect dominates the direct effect in later years.

Zooming in on Figure 2(b), we find that the negative demand shock of the pandemic (scenario (2)) has a limited effect on the price of allowances in 2020. The raised ambitions, however, increase the price to a median value of 67 €/ton CO₂ (-55%) to 79 €/ton CO₂ (-60%) in 2020. Although EU ETS prices are currently at all-time highs, just below 40 €/tCO₂, which is within the estimated range in Figure 2(b), they are still at levels well below our median values, indicating that, for various reasons, the stringency of the new 2030 targets may have not yet been fully internalized by the market. The estimated EUA price is lower when the waterbed is sealed sooner and cancellation is lower. The price changes because of the overlapping policies in scenario (3) and (5) are higher when the waterbed is sealed sooner, because a smaller fraction of the shock is absorbed through cancellation.

⁵This counter-intuitive, self-reinforcing effect may be explained via the relation between the future cost of abatement and the cancellation volume. Cancellation volumes increase when the expected future cost of abatement is higher, as it makes banking allowances today more profitable, which increases the TNAC. This implies that the cancellation policy is more stringent when the cost of compliance is higher. Future abatement costs increase when, e.g., the linear reduction factor increases or when overlapping policies increase emissions in the future. For details, see Bruninx et al. (2020, 2019).

5 Conclusions

We quantify the effect of COVID-19, the European Green Deal and the recovery stimulus package on emission allowance prices and cumulative emissions in the EU ETS. Under a fixed cap, the negative allowance demand shock induced by the pandemic would only reduce prices and keep emissions fixed. Because of the punctured waterbed, we find that the temporary decrease in emissions almost one-to-one translates into a decrease of cumulative emissions, with limited effect on the EU ETS price, in line with the observed price recovery in 2020. This makes clear that the increased price stability due to the introduction of the market stability reserve and the cancellation policy has come at the expense of increased uncertainty in cumulative emissions.

Raising the ambition for 2030 to -55% or -60% will decrease cumulative EU ETS emission by another 18 or 21 GtCO₂. There is, however, a large range of uncertainty around these results, depending on when allowance cancellation stops and the waterbed is sealed again. This crucially depends on external shocks (e.g., COVID-19), overlapping policies (e.g., recovery stimulus package), European climate policy, and the shape of the abatement cost curve. The magnitude of waterbed leakage depends on the relative importance of the direct effect of the policy on emissions and the indirect price effect. We find, among other things, that all overlapping policies announced now and affecting emissions after the waterbed is expected to be sealed will backfire. For example, announcing today to close a coal-fired power plant in the future, might actually increase cumulative emissions over the lifetime of EU ETS, in absence of proper companion policies (e.g., voluntary cancellation of emission allowances (European Union, 2018)).

Most of the surprising and counter-intuitive aspects of the current EU ETS design that we identified in this paper arise because the supply of allowances depends on the scarcity of allowances in circulation, which makes cumulative emissions endogenous and exacerbates quantity uncertainty. In light of the upcoming 2021 review of the EU ETS, Perino et al. (2021) propose that allowance supply could be conditioned on the price of allowances instead of the total number of allowances in circulation, similar to the California cap-and-trade system. This has the potential to stabilize prices, but might not sufficiently decrease the uncertainty on cumulative emissions and might lead to oscillatory price behavior between the price cap and floor, as analyzed by Borenstein et al. (2019). This may be an interesting question for future research.

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A Direct effect, indirect effect and duration of the waterbed puncture

A.1 The direct effect

When actions change the TNAC, this will directly translate into changing levels of cancellation. This is not a one-to-one relationship, as the market stability reserve only absorbs a share of the TNAC in a given year – 24% from 2019 till 2023 and 12% from 2024 onward (European Union, 2018). As a result, changes in allowance supply or demand are gradually transferred to the market stability reserve and cancelled. For every ton of CO₂ affected by the overlapping policy, direct cancellation of allowances equals (Perino, 2018):

$$1 - (1 - 0.24)^n \cdot (1 - 0.12)^m \quad (1)$$

where n and m are the number of years between the time of increasing the TNAC and the year the waterbed is sealed again (i.e., when the TNAC is below the 833 MtCO₂ threshold), with intake rates of 24% and 12% (Bruninx et al., 2020). This means that the direct effect is higher when the action is earlier and the waterbed is sealed later. Actions taking place after the waterbed has been sealed again will not have a direct effect.

A.2 The indirect price effect or new green paradox

All actions that are announced before they take place will have an effect on the TNAC, irrespective of when the waterbed is sealed again, because of an indirect effect of expectations through adjustments of the price profile (Bruninx et al., 2019; Gerlagh et al., 2020b; Perino et al., 2020; Rosendahl, 2019a). For example, when a future action announced today, like a coal plant closure, is expected to increase the total number of allowances in circulation at some point in the future, market participants expect the future price of allowances to drop. Because EU ETS allowances have an infinite lifetime, the future drop in allowance prices will lead to lower prices today, assuming market participants are intertemporally optimizing. As a result, the incentive to abate today will decrease because of expected carbon abatement in the future. Similarly, announced future decreases of the TNAC will lead to higher abatement and a higher TNAC today.

Closed-form expressions for the indirect price effect do not exist – it may only be estimated numerically (Section 3). However, in general, one may state that the indirect price effect (i) works in the opposite direction as the direct effect; (ii) persists as long as the policy affects emissions in a period that the TNAC is not zero, hence, firms are still intertemporally optimizing or banking; (iii) is strongest when the policy affects emissions after the waterbed is sealed again and (iv) is stronger when the waterbed seals later.

A.3 The duration of the waterbed puncture

From the discussion above, it is evident that the duration of the waterbed puncture crucially affects the relative importance of the direct and indirect effect. The duration of the waterbed puncture is determined by the moment when the total number of allowances in circulation falls

below 833 MtCO₂, i.e., when the market stability reserve stops absorbing allowances. As a result, all changes to the TNAC can potentially affect the duration of the waterbed puncture, if it pushes the TNAC to be above or below the threshold. We discuss three distinct ways the TNAC, hence, the duration of the waterbed puncture, may change: expectations about marginal abatement costs, overlapping policies and exogenous shocks, and the design of EU ETS itself.

First, expectations about future abatement costs will affect the TNAC today. If firms expect higher abatement costs in the future, i.e., a more convex marginal abatement cost curve, they would likely choose to abate more today and bank the surplus allowances for future use. But because of the cancellation policy, if more allowances are banked today, the duration of the waterbed puncture may increase, more allowances will be cancelled, and the cumulative emissions reductions would be greater. In contrast, if firms expect future abatement costs to be low, e.g., because of technological learning (Creutzig et al., 2017), they would likely choose to postpone abatement and bank fewer allowances. With fewer banked allowances, the waterbed could be sealed sooner, fewer allowances would be cancelled, and cumulative emissions reductions would be lower (Rosendahl, 2019b). The design of the cancellation policy thus implies a counter-intuitive, self-reinforcing relation between the future cost of abatement and the cancellation volume, making the cancellation policy more stringent when the cost of compliance is higher – an effect first discussed by Bruninx et al. (2020, 2019).⁶ Although future marginal abatement costs are intrinsically uncertain (Borenstein et al., 2019), there is evidence that the marginal abatement cost curve is (highly) convex (Hintermayer et al., 2020; Landis, 2015).

Second, any European, national or local policy that affects the demand for allowances may change the TNAC and the duration of the waterbed puncture. For example, support for electric vehicles increases the demand, because gasoline (not covered by EU ETS) is substituted by electricity (covered by EU ETS), while support for renewable generation or the forced closure of a coal plant decreases it. As a result, the first measure may decrease the duration of the waterbed puncture, while the second may increase it: depending on the amount of emissions affected and timing of the policy, the year in which the waterbed is sealed may change.

Third, expected changes to the design of EU ETS, i.e., the supply of allowances, will affect the TNAC today and hence potentially change the duration of the waterbed puncture. For example, increasing the future linear reduction factor may prolong the puncture of the waterbed, because more costly future abatement leads to more abatement now. As a result, the linear reduction factor and cumulative emissions are positively correlated, meaning that decreasing the long-run supply of allowances increases cancellation volumes (Bruninx et al., 2020). Again, this underlines the counter-intuitive, self-reinforcing relation between the linear reduction factor – driving the cost of abatement – and the cancellation volume, making the cancellation policy more stringent when the cost of compliance is higher.

Note that the effect of any overlapping policy, shock or EU ETS design change on the duration of the waterbed puncture may be interpreted via its impact on firms' expectation on the cost of complying with the emissions cap.

⁶This surprising result crucially depends on the assumption that market participants are inter-temporally-optimizing over the full horizon of the EU ETS. Indeed, in models with a limited horizon, like in Queminn and Trotignon (2019), market participants do not consider the challenges further in the future and will abate less, which decreases cumulative cancellation. As a result, the positive correlation between the convexity of the marginal abatement cost curve and cancellation increases the more market participants look further into the future, assuming they face the same marginal abatement cost curve.

B Methods

B.1 Simulation model

We analyze the impact of these three shock on the emission allowance price and allowed emissions under EU ETS, leveraging our stylized EU-ETS-MSR model (Bruninx et al., 2019). This model is based on the detailed long-term investment model of Bruninx et al. (2020) and assumes rational, price-taking and risk-neutral firms that optimize their abatement and banking actions over the complete EU ETS horizon.

Since the marginal abatement cost curve of the EU ETS is fundamentally uncertain, we run each demand shock scenario for a comprehensive set of marginal abatement cost curves, which all adhere to the following functional form:

$$\forall t \in \mathcal{T} : \quad p_t = \beta \cdot (\bar{E} - q_t)^\gamma \quad (2)$$

In each year t , the marginal abatement cost p_t is defined by baseline emissions $\bar{E}$, a slope β and a curvature γ , following Bruninx et al. (2019).

Baseline emissions are set to 1900 MTCO₂, as in Perino and Willner (2017). The real discount rate is set to 8%. The curvature γ is varied between 0.5 and 3.5, with increments of 0.05. For each curvature value, the slope of each abatement cost curve is calibrated to reproduce the average 2019 emission allowance prices (24.7 €/tCO₂, based on EEX (Last accessed: April 1, 2020)) without the negative demand shocks and assuming a -40% emission reduction target by 2030, in line with 2019 policy, while imposing observed emissions in 2019 and the state of the EU ETS at the start of 2019 (European Commission, 2020a). Note that the Green Deal was first announced in December 2019, and hence, is assumed not to be internalized by market parties in the average 2019 prices. γ -values below 0.5 yield emissions in 2020 that would exceed 2017 levels, which is, at current emission allowance prices, deemed unrealistic. γ -values above 3.5 lead to waterbed closures after 2050.

This approach allows simulating the impact of waterbed closures in any year between 2022 and 2050 (Fig. 2) in absence of a demand shock: as the curvature increases, the waterbed is sealed later - as will be discussed in Section A.3. Note that we do not aim to quantify which abatement cost curve is more realistic and that all simulated abatement cost curves are consistent with 2019 emission allowance prices.

For more information on the numerical model and the solution strategy, see Bruninx et al. (2019) and Bruninx et al. (2020).

B.2 Estimating waterbed leakage

To estimate the direct and indirect effect of an overlapping policy (Figure 1), we take the following approach. From the set of calibrated marginal abatement cost curves (see above), we select a subset that ensures that each year in which the waterbed may be sealed (2023-2050) occurs in the output once. For each of these marginal abatement cost curves, we compute a reference equilibrium emission and EUA price path assuming a -40% or -50% emission reduction target for 2030, considering the impact of COVID-19. In a second set of simulations, considering the same marginal abatement cost curves and policy boundary conditions, we add

an overlapping policy reducing emissions by 1 MtCO₂ in a year between 2020 and 2050. Comparing cumulative emissions in the second set of simulations to the corresponding reference result yields an estimate of the waterbed effect.

Note that the estimates in Figure 1 pertain to policies affecting emissions in a single year. The total waterbed leakage of a policy or a combination of policies spanning over different years can be calculated as the weighted sum of its effect over time, assuming they do not affect the year in which the waterbed is sealed:

$$\frac{\sum_t \sum_i W L_t(t_{sealed}) \cdot q_{it}}{\sum_t \sum_i |q_{it}|} \quad (3)$$

where q_{it} is the effect (in tons of CO₂) of policy i in year t on the total number of allowances in circulation, while $W L_t(t_{sealed})$ is the magnitude waterbed leakage in year t , which is a function of the year the waterbed is sealed t_{sealed} . To make this more useful for researchers and policy makers, Tables C1 and C2 in Appendix C present the values of the waterbed leakage $W L_t(t_{sealed})$ for $t \in [2020, 2050]$ and $t_{sealed} \in [2023, 2050]$.

B.3 The three exogenous shocks affecting the EU ETS

To estimate the impact of the three exogenous shocks, we compute an equilibrium emission and price path for each of the calibrated marginal abatement cost curves in six policy scenarios. The sections below discuss in more detail the assumptions behind the six scenarios considered in Section 4.

B.3.1 COVID-19: a temporary negative allowance demand shock

The coronavirus pandemic and lockdown measures that combat it have drastically reduced energy demand throughout the world (Gillingham et al., 2020; Le Quéré et al., 2020; Liu et al., 2020). The final effect on 2020 carbon emissions of EU ETS firms is still unclear until the next publication of the total number of allowances in circulation by May 2021 (European Commission, 2020a). Other papers on EU ETS focusing entirely on COVID-19 (Azarova and Mier, 2020; Bruninx and Ovaere, 2020; Gerlagh et al., 2020a) all study three alternative scenarios regarding the severity and duration of the negative demand shock, similar to a U-shaped fast recovery, a V-shaped gradual recovery, and a profound recession or permanent demand shock. To limit the number of scenarios, in this paper we only simulate a U-shaped demand shock, which gradually vanishes between 2020 and 2025. We assume the demand shock linearly decreases from its initial value in 2020, 240 MtCO₂ (the worst-case estimate in (Bruninx and Ovaere, 2020)), to zero at the end of 2025. The total negative demand shock is, hence, 720 MtCO₂.

B.3.2 Increased carbon abatement targets under the European Green Deal: permanent negative allowance supply shock

As part of the European Green Deal aiming to make the EU’s economy sustainable and reach climate neutrality by 2050, the European Commission plans to reduce EU greenhouse gas emissions by at least 55% by 2030, compared to 1990 levels, up from the earlier target of 40%

(European Commission, 2020b). As of today, it is unclear how this target, covering all sectors, will translate into more ambitious targets for sectors covered under the EU ETS and higher linear reduction factors in the 2021 EU ETS review. In line with the previous 2030 EU ETS target of -43% relative to 2005 emission levels, we will assume that the future linear reduction factor will increase to reach a 57.75% carbon reduction target in the EU ETS by 2030, relative to emission levels in 2005 - which is achieved by increasing the linear reduction factor to 3.77 %. Because the European Parliament voted to update this target to a 60% reduction target relative to 1990, we will also run a scenario with a -63% target relative to 2005 emission levels for sectors covered by EU ETS, with a linear reduction factor of 4.33 %. Such increased linear reduction factors are considered to be a permanent negative allowance supply shock. We assume that all considered linear reduction factors are kept constant after 2030 until the supply is zero.

B.3.3 NextGenerationEU recovery stimulus package: a short- to long-term negative or positive allowance demand shock

To help repair the economic and social damage caused by the coronavirus pandemic, the EU agreed on the €750 billion NextGenerationEU recovery stimulus package, of which 37% will be spent directly on European Green Deal objectives, like hydrogen, building renovations and one million electric charging points. In addition, the entire €1.1 trillion EU budget for 2021-2027 will also have to follow the ‘Do No Significant Harm’ principle, which prohibits investments in fossil fuels and other technologies deemed contrary to the EU’s environmental objectives. As the additional overlapping policies funded by this budget can affect the demand for EU ETS allowances at different times and in many different ways, we will only simulate two generic scenarios. One that increases demand for allowances by 100 MtCO₂ per year from 2021 to 2031 (e.g., electric vehicles), and one that decreases demand for allowances by 100 MtCO₂ per year from 2021 to 2031 (e.g., renewables support).

C Detailed results

(a) Direct effect

(b) Indirect effect

Figure 3. Direct (top) and indirect (bottom) waterbed leakage as a function of the year the overlapping policy or shock takes place (x-axis) and the year the waterbed is sealed (y-axis). The solid black line indicates where the direct effect ends. Total waterbed leakage can be calculated as the sum of both effects.

(a) Direct effect

(b) Indirect effect

Figure 4. Direct (top) and indirect (bottom) waterbed leakage as a function of the year the overlapping policy or shock takes place (x-axis) and the year the waterbed is sealed (y-axis). The solid black line indicates where the direct effect ends. Total waterbed leakage can be calculated as the sum of both effects.

Table C1. Waterbed leakage of an overlapping policy, depending on the year in which waterbed is sealed (columns) and the year in which the overlapping policy affects the demand for allowances (rows). This table assumes a CO₂ emission reduction target of 40% by 2030.

		Year in which waterbed is sealed																											
		2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036	2037	2038	2039	2040	2041	2042	2043	2044	2045	2046	2047	2048	2049	2050
Year in which the policy reduces demand for allowances	2020	0.56	0.61	0.66	0.71	0.74	0.77	0.80	0.82	0.85	0.86	0.88	0.89	0.91	0.92	0.93	0.94	0.94	0.95	0.96	0.96	0.96	0.97	0.97	0.97	0.98	0.98	0.98	0.98
	2021	0.37	0.44	0.51	0.58	0.63	0.67	0.72	0.75	0.78	0.81	0.83	0.85	0.87	0.88	0.90	0.91	0.92	0.93	0.94	0.94	0.95	0.95	0.96	0.96	0.97	0.97	0.97	0.97
	2022	0.13	0.23	0.33	0.42	0.49	0.55	0.61	0.65	0.70	0.73	0.76	0.79	0.82	0.84	0.86	0.87	0.89	0.90	0.91	0.91	0.93	0.94	0.94	0.95	0.95	0.96	0.96	0.97
	2023	-0.03	0.08	0.19	0.30	0.39	0.46	0.53	0.58	0.63	0.68	0.71	0.75	0.78	0.81	0.83	0.85	0.87	0.88	0.89	0.90	0.91	0.92	0.93	0.94	0.94	0.95	0.95	0.96
	2024	-0.03	-0.05	0.07	0.20	0.29	0.38	0.46	0.52	0.58	0.63	0.67	0.71	0.74	0.78	0.80	0.83	0.85	0.86	0.88	0.88	0.90	0.91	0.92	0.93	0.94	0.94	0.95	0.95
	2025	-0.03	-0.05	-0.06	0.07	0.18	0.28	0.37	0.44	0.51	0.57	0.62	0.67	0.70	0.74	0.77	0.80	0.82	0.84	0.86	0.87	0.89	0.90	0.91	0.92	0.93	0.93	0.94	0.94
	2026	-0.03	-0.05	-0.06	-0.05	0.06	0.17	0.28	0.36	0.44	0.50	0.56	0.61	0.66	0.70	0.73	0.77	0.80	0.82	0.84	0.85	0.87	0.88	0.90	0.91	0.91	0.92	0.93	0.94
	2027	-0.03	-0.05	-0.06	-0.05	-0.07	0.05	0.17	0.26	0.35	0.43	0.50	0.56	0.61	0.66	0.69	0.73	0.76	0.79	0.81	0.83	0.85	0.86	0.88	0.89	0.90	0.91	0.92	0.93
	2028	-0.03	-0.05	-0.06	-0.05	-0.07	-0.08	0.04	0.15	0.26	0.34	0.42	0.49	0.55	0.60	0.65	0.69	0.73	0.76	0.79	0.80	0.83	0.84	0.86	0.87	0.89	0.90	0.91	0.91
	2029	-0.03	-0.05	-0.06	-0.05	-0.07	-0.08	-0.09	0.02	0.14	0.24	0.33	0.41	0.48	0.54	0.59	0.65	0.69	0.72	0.75	0.77	0.80	0.82	0.84	0.86	0.87	0.88	0.89	0.90
	2030	-0.03	-0.05	-0.06	-0.05	-0.07	-0.08	-0.09	-0.11	0.01	0.13	0.23	0.32	0.40	0.48	0.53	0.59	0.64	0.68	0.72	0.74	0.77	0.79	0.82	0.83	0.85	0.86	0.88	0.89
	2031	-0.03	-0.05	-0.06	-0.05	-0.07	-0.08	-0.09	-0.11	-0.12	0.00	0.11	0.22	0.31	0.40	0.46	0.53	0.58	0.63	0.67	0.70	0.73	0.76	0.79	0.81	0.83	0.84	0.86	0.87
	2032	-0.03	-0.05	-0.06	-0.05	-0.07	-0.08	-0.09	-0.11	-0.12	-0.14	-0.02	0.10	0.20	0.30	0.38	0.46	0.52	0.57	0.62	0.66	0.69	0.72	0.76	0.78	0.80	0.82	0.84	0.85
	2033	0.00	-0.05	-0.06	-0.05	-0.07	-0.08	-0.09	-0.11	-0.12	-0.14	-0.16	-0.04	0.08	0.20	0.28	0.38	0.45	0.51	0.56	0.61	0.65	0.68	0.72	0.75	0.77	0.79	0.81	0.83
	2034	0.00	0.00	-0.06	-0.05	-0.07	-0.08	-0.09	-0.11	-0.12	-0.14	-0.16	-0.18	-0.06	0.08	0.18	0.28	0.36	0.43	0.50	0.55	0.59	0.63	0.68	0.71	0.73	0.76	0.78	0.80
	2035	0.00	0.00	-0.06	-0.05	-0.07	-0.08	-0.09	-0.11	-0.12	-0.14	-0.16	-0.18	-0.20	-0.06	0.05	0.17	0.27	0.35	0.42	0.49	0.53	0.58	0.63	0.66	0.69	0.72	0.75	0.77
	2036	0.00	0.00	0.00	-0.05	-0.07	-0.08	-0.09	-0.11	-0.12	-0.14	-0.16	-0.18	-0.20	-0.21	-0.09	0.04	0.16	0.25	0.33	0.41	0.46	0.51	0.57	0.61	0.65	0.68	0.71	0.73
	2037	0.00	0.00	0.00	-0.05	-0.07	-0.08	-0.09	-0.11	-0.12	-0.14	-0.16	-0.18	-0.20	-0.21	-0.24	-0.10	0.03	0.13	0.23	0.32	0.38	0.44	0.50	0.55	0.59	0.63	0.67	0.69
	2038	0.00	0.00	0.00	-0.05	-0.07	-0.08	-0.09	-0.11	-0.12	-0.14	-0.16	-0.18	-0.20	-0.21	-0.24	-0.25	-0.12	0.00	0.12	0.22	0.28	0.35	0.43	0.48	0.53	0.57	0.62	0.65
	2039	0.00	0.00	0.00	-0.05	-0.07	-0.08	-0.09	-0.11	-0.12	-0.14	-0.16	-0.18	-0.20	-0.21	-0.24	-0.25	-0.27	-0.15	-0.02	0.10	0.18	0.26	0.34	0.40	0.46	0.51	0.56	0.59
	2040	0.00	0.00	0.00	-0.05	-0.07	-0.08	-0.09	-0.11	-0.12	-0.14	-0.16	-0.18	-0.20	-0.21	-0.24	-0.25	-0.27	-0.31	-0.17	-0.03	0.05	0.14	0.24	0.31	0.38	0.43	0.49	0.53
	2041	0.00	0.00	0.00	-0.05	-0.07	-0.08	-0.09	-0.11	-0.12	-0.14	-0.16	-0.18	-0.20	-0.21	-0.24	-0.25	-0.27	-0.31	-0.33	-0.19	-0.09	0.01	0.13	0.21	0.28	0.34	0.41	0.46
	2042	0.00	0.00	0.00	0.00	-0.07	-0.08	-0.09	-0.11	-0.12	-0.14	-0.16	-0.18	-0.20	-0.21	-0.24	-0.25	-0.27	-0.31	-0.33	-0.35	-0.26	-0.14	-0.01	0.09	0.17	0.24	0.33	0.38
	2043	0.00	0.00	0.00	0.00	0.00	-0.08	-0.09	-0.11	-0.12	-0.14	-0.16	-0.18	-0.20	-0.21	-0.24	-0.25	-0.27	-0.31	-0.33	-0.35	-0.43	-0.31	-0.16	-0.05	0.05	0.13	0.22	0.28
	2044	0.00	0.00	0.00	0.00	0.00	0.00	-0.09	-0.11	-0.12	-0.14	-0.16	-0.18	-0.20	-0.21	-0.24	-0.25	-0.27	-0.31	-0.33	-0.35	-0.43	-0.49	-0.34	-0.21	-0.10	0.00	0.10	0.17
	2045	0.00	0.00	0.00	0.00	0.00	0.00	-0.09	-0.11	-0.12	-0.14	-0.16	-0.18	-0.20	-0.21	-0.24	-0.25	-0.27	-0.31	-0.33	-0.35	-0.43	-0.49	-0.52	-0.39	-0.27	-0.16	-0.03	0.05
	2046	0.00	0.00	0.00	0.00	0.00	0.00	-0.09	-0.11	-0.12	-0.14	-0.16	-0.18	-0.20	-0.21	-0.24	-0.25	-0.27	-0.31	-0.33	-0.35	-0.43	-0.49	-0.52	-0.58	-0.46	-0.33	-0.19	-0.10
	2047	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-0.12	-0.14	-0.16	-0.18	-0.20	-0.21	-0.24	-0.25	-0.27	-0.31	-0.33	-0.35	-0.43	-0.49	-0.52	-0.58	-0.66	-0.53	-0.37	-0.26
	2048	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-0.12	-0.14	-0.16	-0.18	-0.20	-0.21	-0.24	-0.25	-0.27	-0.31	-0.33	-0.35	-0.43	-0.49	-0.52	-0.58	-0.66	-0.74	-0.58	-0.46
	2049	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-0.14	-0.16	-0.18	-0.20	-0.21	-0.24	-0.25	-0.27	-0.31	-0.33	-0.35	-0.43	-0.49	-0.52	-0.58	-0.66	-0.74	-0.79	-0.68
	2050	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-0.16	-0.18	-0.20	-0.21	-0.24	-0.25	-0.27	-0.31	-0.33	-0.35	-0.43	-0.49	-0.52	-0.58	-0.66	-0.74	-0.79	-0.90

Table C2. Waterbed leakage of an overlapping policy, depending on the year in which waterbed is sealed (columns) and the year in which the overlapping policy affects the demand for allowances (rows). This table assumes a CO₂ emission reduction target of 55% by 2030. As we did not encounter any situation in which the waterbed would seal in 2023 or after 2042, no values are reported for these years.

		Year in which waterbed is sealed																											
		2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036	2037	2038	2039	2040	2041	2042	2043	2044	2045	2046	2047	2048	2049	2050
Year in which the policy reduces demand for allowances	2020		0.61	0.65	0.69	0.73	0.77	0.79	0.82	0.84	0.85	0.87	0.88	0.89	0.90	0.91	0.91	0.92	0.92	0.92	0.92								
	2021		0.44	0.50	0.56	0.62	0.66	0.70	0.74	0.77	0.79	0.81	0.83	0.85	0.86	0.87	0.88	0.89	0.89	0.89	0.88								
	2022		0.23	0.32	0.40	0.48	0.54	0.59	0.64	0.68	0.71	0.74	0.76	0.79	0.81	0.82	0.83	0.84	0.84	0.85	0.84								
	2023		0.07	0.17	0.27	0.37	0.44	0.51	0.57	0.61	0.65	0.69	0.72	0.75	0.77	0.78	0.80	0.81	0.81	0.82	0.81								
	2024		-0.06	0.05	0.16	0.27	0.36	0.43	0.50	0.55	0.60	0.64	0.67	0.71	0.73	0.75	0.77	0.78	0.78	0.79	0.78								
	2025		-0.06	-0.08	0.03	0.16	0.26	0.34	0.42	0.48	0.54	0.59	0.62	0.66	0.69	0.71	0.73	0.75	0.75	0.76	0.74								
	2026		-0.06	-0.08	-0.10	0.04	0.15	0.24	0.34	0.41	0.47	0.52	0.56	0.61	0.64	0.67	0.69	0.71	0.71	0.72	0.70								
	2027		-0.06	-0.08	-0.10	-0.10	0.02	0.13	0.24	0.31	0.39	0.45	0.50	0.55	0.59	0.62	0.64	0.66	0.66	0.68	0.66								
	2028		-0.06	-0.08	-0.10	-0.10	-0.11	0.00	0.12	0.21	0.30	0.37	0.42	0.48	0.53	0.56	0.59	0.61	0.61	0.63	0.61								
	2029		-0.06	-0.08	-0.10	-0.10	-0.11	-0.14	-0.01	0.09	0.19	0.27	0.33	0.41	0.45	0.49	0.53	0.55	0.55	0.57	0.55								
	2030		-0.06	-0.08	-0.10	-0.10	-0.11	-0.14	-0.15	-0.05	0.07	0.16	0.23	0.31	0.37	0.42	0.45	0.49	0.49	0.51	0.48								
	2031		-0.06	-0.08	-0.10	-0.10	-0.11	-0.14	-0.15	-0.19	-0.07	0.03	0.11	0.21	0.27	0.33	0.37	0.41	0.41	0.43	0.40								
	2032		0.00	-0.08	-0.10	-0.10	-0.11	-0.14	-0.15	-0.19	-0.22	-0.12	-0.02	0.09	0.16	0.22	0.28	0.32	0.32	0.35	0.31								
	2033		0.00	0.00	-0.10	-0.10	-0.11	-0.14	-0.15	-0.19	-0.22	-0.27	-0.17	-0.05	0.04	0.11	0.17	0.21	0.21	0.25	0.20								
	2034		0.00	0.00	-0.10	-0.10	-0.11	-0.14	-0.15	-0.19	-0.22	-0.27	-0.33	-0.21	-0.11	-0.03	0.04	0.09	0.09	0.13	0.08								
	2035		0.00	0.00	0.00	-0.10	-0.11	-0.14	-0.15	-0.19	-0.22	-0.27	-0.33	-0.37	-0.28	-0.19	-0.11	-0.04	-0.04	0.00	-0.06								
	2036		0.00	0.00	0.00	-0.10	-0.11	-0.14	-0.15	-0.19	-0.22	-0.27	-0.33	-0.37	-0.45	-0.37	-0.28	-0.20	-0.20	-0.15	-0.22								
	2037		0.00	0.00	0.00	-0.10	-0.11	-0.14	-0.15	-0.19	-0.22	-0.27	-0.33	-0.37	-0.45	-0.55	-0.47	-0.38	-0.39	-0.33	-0.39								
	2038		0.00	0.00	0.00	0.00	-0.11	-0.14	-0.15	-0.19	-0.22	-0.27	-0.33	-0.37	-0.45	-0.55	-0.67	-0.59	-0.60	-0.52	-0.45								
	2039		0.00	0.00	0.00	0.00	0.00	-0.14	-0.15	-0.19	-0.22	-0.27	-0.33	-0.37	-0.45	-0.55	-0.67	-0.81	-0.82	-0.58	-0.51								
	2040		0.00	0.00	0.00	0.00	0.00	0.00	-0.15	-0.19	-0.22	-0.27	-0.33	-0.37	-0.45	-0.55	-0.67	-0.81	-0.90	-0.64	-0.51								
	2041		0.00	0.00	0.00	0.00	0.00	0.00	-0.15	-0.19	-0.22	-0.27	-0.33	-0.37	-0.45	-0.55	-0.67	-0.81	-0.90	-0.64	-0.51								
	2042		0.00	0.00	0.00	0.00	0.00	0.00	0.00	-0.22	-0.27	-0.33	-0.37	-0.45	-0.55	-0.67	-0.81	-0.90	-0.64	-0.51									
	2043		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-0.37	-0.45	-0.55	-0.67	-0.81	-0.90	-0.64	-0.51								
	2044		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-0.64	-0.51								
	2045		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-0.64	-0.51								
	2046		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-0.64	-0.51								
	2047		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-0.51								
	2048		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-0.51								
	2049		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00								
	2050		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00								

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Figures

(a) -40% by 2030

(b) -55% by 2030

Figure 1

Waterbed leakage (the net effect of a shock or overlapping policy on cumulative emissions in EU ETS) as a function of the year the overlapping policy or shock takes place (horizontal axis) and the year the waterbed is sealed (vertical axis). The solid black line indicates where the direct effect ends. Waterbed

leakage is positive when a policy that increases (decreases) emissions leads to increased (decreased) cumulative emissions. It is negative when a policy backfires. Note that we ignore the possibility that overlapping policies affect the duration of the punctured waterbed. The numerical values behind these graphs are reported in Appendix C, alongside with a separate graphical representation of the direct and indirect effect.

Figure 2

Cumulative emissions (a) and allowances prices (b) in each of our six scenarios. The black and grey bars represent the range of outcomes, the white markers represent the median value and the vertical red lines represent the cumulative cap without cancellation (2020-end ETS). The indicated years are the years in which the waterbed is sealed in the edge cases (lowest-highest emissions). The cumulative impact of COVID-19 pandemic is assumed to be 0.72 GtCO₂ in the period 2020-2025 and is enforced in all scenarios except the "No pandemic" scenario. Scenario (3) and (5) mimic the effect of an overlapping policy reducing (3) or increasing (5) emissions by 100 MtCO₂/year in the period 2021-2031, considering the -55% emission reduction target.

(a) Direct effect

(b) Indirect effect

Figure 3

Direct (top) and indirect (bottom) waterbed leakage as a function of the year the overlapping policy or shock takes place (x-axis) and the year the waterbed is sealed (y-axis). The solid black line indicates where the direct effect ends. Total waterbed leakage can be calculated as the sum of both effects.

(a) Direct effect

(b) Indirect effect

Figure 4

Direct (top) and indirect (bottom) waterbed leakage as a function of the year the overlapping policy or shock takes place (x-axis) and the year the waterbed is sealed (y-axis). The solid black line indicates where the direct effect ends. Total waterbed leakage can be calculated as the sum of both effects.