

# Adjusting the CO<sub>2</sub> cap to subsidised RES generation: Can CO<sub>2</sub> prices be decoupled from renewable policy?<sup>☆</sup>

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## Abstract

The low prices in the European Emission Trading System (EU ETS) have triggered discussions of various possible reforms. One option is to decouple the CO<sub>2</sub> prices from renewable energy policy by adjusting the emission cap to renewable energy investment overshoots. We introduce two ways of reducing the CO<sub>2</sub> cap in response to overshoots of renewable policy investment over previously announced targets. We investigate these options with the agent-based model EMLab-generation. We find that both policy implementations are successful in restoring prices. They also ensure that making public investments that exceed policy targets contribute to carbon emission reduction, and that renewable policy does not benefit the most emission-intensive power plants. However, neither policy is suitable for achieving specific levels of prices or price volatility.

*Keywords:* EU-ETS, Carbon Market, Renewable policy, Dynamic cap adjustment, Agent-based modelling, Electricity Market

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## 1. Introduction

When a stringent emission trading system (ETS) is in place, the establishment of a renewable energy policy does not lead to additional emission reductions<sup>1</sup> [1]. Indeed, within the electricity sector the emission reductions due to renewable electricity generation might be offset by a shift to more polluting power plants [1, 2]; or as Böhringer and Rosendahl [3] put it, “green promotes the dirtiest”. As the broad literature on CO<sub>2</sub> market and renewable policy interactions documents, renewable energy policy also lowers CO<sub>2</sub> prices in an ETS [1, 4, 2]. This effect may have contributed to the strong price drop in CO<sub>2</sub> prices in the EU ETS in recent years [5] (whereas Koch et al. [6] argue that this effect has been negligible).

While renewable and climate policies can, and have been, coordinated ex-ante [7, 8] to mitigate these effects, this paper investigates the implementation options of a dynamic rule-based cap adjustment mechanism that mitigates

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<sup>1</sup>Barring political-economical dynamics that might developed from low CO<sub>2</sub> prices.

11 CO<sub>2</sub> price drops and makes renewable policy climate effective under an ETS, even in cases when the development  
12 of renewable policy deviates from ex-ante targets. Such a mechanism could also be part of a broader cap adjustment  
13 mechanism that not only reacts to fluctuations in renewable energy production, but also to other indices such as  
14 economic growth, energy efficiency or estimated abatement costs [9, 10]; in this paper, however, we focus exclusively  
15 on adjustments with regard to renewable diffusion.

16 While such a mechanism has been proposed and qualitatively analysed by Diekmann [11], Del Río et al. [8]  
17 and Del Río [12], only one brief proposal for how to translate renewable policy fluctuations quantitatively into cap  
18 adjustments was found [12], and no quantitative evaluation of such a policy has, to the knowledge of the authors,  
19 been presented so far. The literature search was carried out with the search term ("*EU ETS*" OR "*emission trading*"  
20 OR "*emissions trading*" OR "*cap-and-trade*" OR "*CO2 market*" OR "*carbon market*") AND ("*cap adjustment*" OR  
21 "*adjusting the cap*" OR "*adjusting the emissions cap*" OR "*dynamic mechanism*") AND (*renewable* OR *RES*) on  
22 ScienceDirect, Google Scholar and Google. Additionally, we searched for the titles of the three mentioned references  
23 [11, 8, 12] to find citing literature. We propose two heuristics for calculating cap reductions dynamically. We evaluate  
24 the two policies by extending the agent-based model (ABM) EMLab-Generation with these dynamic cap reduction  
25 mechanisms. We use an ABM because we wish to model realistic limitations to investment decisions such as the  
26 financial constraints and myopia of market participants (they do not know the future), the discreteness of investment  
27 choices in power plants. Since rule-based mechanisms act with a delay they cause dynamic effects which may even  
28 exacerbate the CO<sub>2</sub> price shocks which the policy is supposed to mitigate. These can be captured best with a dynamic  
29 model.

### 30 1.1. Related literature

31 The policy investigated in this paper is related to two strands of literature: on the one hand to the very broad  
32 category of ETS and renewable policy interactions, and on the other hand to the discussion of ETS design options,  
33 and more specifically possible reforms of the EU ETS.

34 Given the current state of technology, both climate and renewable policies are considered as necessary for achiev-  
35 ing carbon and climate policy goals simultaneously and efficiently, while a single policy would achieve its respective  
36 single goal more efficiently [4, 13] (this does not necessarily hold theoretically [14]). While both RES quota and  
37 carbon prices are impacted by the other policy, it is usually found that the decreasing effect on prices in the ETS by  
38 a RES policy is stronger than the other way around [13, 5], until the ETS cap no longer is binding and the carbon  
39 price drops to zero. In terms of wealth redistribution, RES policy tends to relatively decrease consumer bills (this  
40 is known as the merit order effect, which may or may not<sup>2</sup> outweigh the increase in subsidy spending [15, 16]) and  
41 reduce producer rents, while the opposite is true for carbon policy [13, 17]. Del Río [12] and Del Río et al. [8] give  
42 a broader overview of the ETS and renewable policy interactions. Related to the discussion on cap reduction is the

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<sup>2</sup>Depending on the design of the subsidy scheme and the cost of the used technologies.

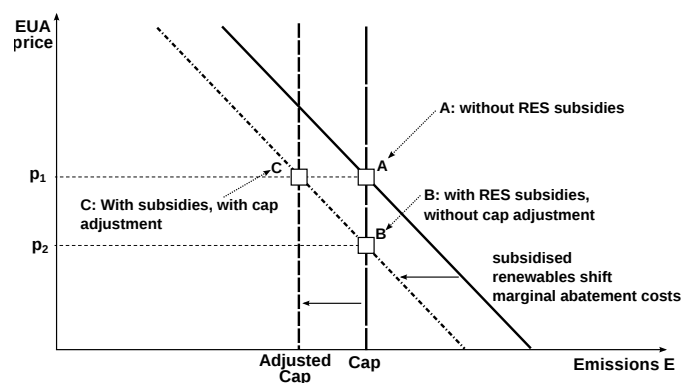


Figure 1: Example of a cap adjustment based on renewables. Adapted from Diekmann [11].

43 topic of fungibility [12], that is the convertibility of credits in RES quota systems to ETS permits. However, since this  
 44 leads to problems of double crediting [12] and RES policy is not uniformly organised in quota systems in Europe, we  
 45 do not analyse this option further.

46 Grosjean et al. [10] provide a comprehensive overview of possible EU ETS reforms and place them in a two-  
 47 dimensional reform space that is spanned by the degree of delegation and the balance between price and quantity  
 48 certainty in an ETS (with a pure ETS having total quantity certainty). As the authors point out, cap adjustment based  
 49 on indices, as suggested by the IETA [9], would be a “rule-based” approach which would increase price certainty in  
 50 the ETS. As we discuss later, price uncertainty is not likely to be minimised unless all relevant indices are included  
 51 in such a mechanism. Notable long-term reforms that are currently being discussed are the Market Stability Reserve  
 52 (MSR, evaluated for example in [18, 19, 10, 20]), price corridors (see [21, 22, 22, 10]) and a central carbon bank  
 53 [23, 10, 24]. These policies all adjust the emission cap, but in more general ways than the cap adjustment policy  
 54 discussed in this paper. The MSR adjusts the cap based on the volume of banked ETS permits, the price corridor  
 55 restricts price movements (and thereby automatically providing less or more EUAs to the market) and the central  
 56 bank works in a discretionary manner.

### 57 1.2. Rationale for and against cap adjustment based on subsidised renewable electricity production

58 Several arguments can be brought forward in support of a cap adjustment based on subsidised renewable electricity  
 59 sources (SRES). Renewable energy policies impact both electricity markets and, as discussed previously, carbon  
 60 markets. As can be seen in Figure 1, and discussed previously, renewable energy policy does not lead to emission  
 61 reductions when the ETS cap is binding [11, 3, 8, 12]. Instead, the marginal abatement cost curve is shifted to the  
 62 left and the EUA price drops (from point A with price  $p_1$  to point B with price  $p_2$ ). A cap adjustment policy that  
 63 effectively offsets the impact of SRES on carbon prices should reduce policy uncertainty for private investors in CO<sub>2</sub>  
 64 abatement. In Figure 1, the objective would be to adjust the cap so the intersection of the demand curve and the cap  
 65 would be in point C and the price would be  $p_1$  again. For example, it should be possible to offset the effect of a sudden

66 increase in investment in renewable energy, as can happen under a price-based policy. An example is the boom in  
67 photovoltaic installations in Germany, which occurred under a feed-in-tariff.

68 A second argument for adjusting the CO<sub>2</sub> cap to unexpected increases in SRES is that it reinstates one of the  
69 key benefits of, and arguments for, renewable energy policy, namely that it reduces carbon emissions. In the past,  
70 the Dutch government, for example, issued cost-benefit analyses of offshore wind projects in which the CO<sub>2</sub> benefits  
71 where judged to be zero [25, 26]. It could also be expected that a cap adjustment policy would reduce the required  
72 subsidy per unit of SRES, since the market revenues from renewables rise with a higher carbon price. Del Río et al.  
73 [8] further point out that cap adjustment might increase the long-term dynamic efficiency because it supports the CO<sub>2</sub>  
74 price; lower CO<sub>2</sub> prices and the shift to more polluting power plant might lead to less innovation in low-emission  
75 technologies in the ETS [27].

76 On the other hand there are potential disadvantages to a cap adjustment. An emission trading scheme theoretically  
77 delivers the most cost-efficient emission reductions, given a certain cap [2]. Such a cap should be set in a way as  
78 to avoid global warming<sup>3</sup>. A reduction of the cap would therefore impose additional costs. Such a political decision  
79 regarding greenhouse emission targets should in principle be made independent of renewable energy policy (following  
80 the one goal, one policy approach of Tinbergen [28]), which is currently usually made at a national level. The EUA  
81 price also signals to governments the degree of scarcity in the carbon market and renewable energy policy provides  
82 them a tool for mitigating scarcity without changing the carbon reduction goal.

### 83 *1.3. Design options for a cap adjustment based on subsidised renewable electricity production*

84 While the notion of offsetting the price effect of SRES and making public RES investments climate effective by  
85 reducing the emission cap appears simple, implementation of such a policy is not straightforward [8, 12]. In principle,  
86 the cap should be lowered by the volume of the “avoided emissions”. This should prevent the drop of prices that SRES  
87 may cause otherwise. For the cap adjustment we only take subsidised renewable investment into account, while other  
88 drivers of renewable deployment may exist [29], such as climate and other energy policies or institutional and private  
89 incentives.

90 The first challenge is which level of renewable investment to choose as a baseline for adjusting the cap. A level  
91 of zero public investment is one possible answer. However, in the design of the third period of the EU ETS, policy  
92 makers explicitly took renewable energy policy into account in an impact assessment when setting the cap [7]. Since  
93 the cap was designed with renewable energy policy in mind, it seems appropriate to act only when more SRES is  
94 developed than anticipated ex-ante, instead of basing the policy action on the absolute quantity of SRES. While the  
95 cap could theoretically also be raised when renewable energy policy targets are not achieved, this would lead to a  
96 failure to achieve the climate goal<sup>4</sup> and is therefore not desirable.

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<sup>3</sup>While the EU ETS is limited in its scope to influence the global climate, in the long run, global climate policy is intended lead to regional climate policies that together avoid global warming.

<sup>4</sup>We assume the climate policy goal to be a minimum goal in this paper.

97 The second challenge is to calculate the extent of the cap reduction, a task which is far from trivial for a regulator<sup>5</sup>  
 98 [8, 12]. In an ideal world, the regulator would have a perfect model of the carbon market. He would create counter-  
 99 factual scenarios of the carbon market with and without SRES, isolating the effect of renewable energy policy, and  
 100 use such an ideal model to calculate the cap reduction necessary to avoid an EUA price drop due to more ambitious  
 101 development than planned originally of renewable energy policy. The problem with creating such a model is the un-  
 102 certainty of the effects of the investment in SRES, since the counter-factual scenarios also need to take investments in  
 103 other generation capacity into account that would have taken place without the deviation in SRES from the announced  
 104 goals.

105 Another approach would be to base the *cap reduction on displaced emissions*, either using the marginal emission  
 106 rate of the power system, or the average emission rate. This however, presents the regulator with the same conundrum  
 107 as in the previous approach; the regulator would need to build counter-factual scenarios of which emissions would  
 108 have taken place in absence of subsidised RES-E. Simply using average observed emissions of previous years, as  
 109 briefly suggested by Del Río [12], can lead to a less effective policy, since these are downward affected by the cap  
 110 reduction policy (given that there is excess SRES), and in turn affect the policy itself. This would make the policy less  
 111 effective for high shares of renewables<sup>6</sup>.

112 A simpler, more pragmatic approach is to reduce the cap proportional with the volume of additional SRES in  
 113 the generation mix. This raises the question to which baseline the additional SRES is compared to. One could set  
 114 the excess SRES in relation to only thermal, or even only fossil generation and lower the cap. However, again the  
 115 regulator would be forced to build counter-factual scenarios of how private investment had evolved in absence of the  
 116 additional subsidised renewables.

117 The remaining approach is to set the volume of additional SRES in proportion to directly observable quantities of  
 118 production: the entire generation mix, or only the non-subsidised part of the generation mix. In case of the proportional  
 119 reduction with regard to the total electricity production, the CO<sub>2</sub> cap in  $t$  is reduced proportionally to the excess SRES  
 120 of the previous year ( $G_{SRES,t-1} - G_{SRES,Announced,t-1}$ ) over the total electricity production of the previous year ( $G_{t-1}$ ).  
 121 This is termed in this paper as total electricity production-based adjustment or short *TBA*.

$$C_{CO_2,t,TBA} = \left(1 - \frac{\max(G_{SRES,t-1} - G_{SRES,Announced,t-1}, 0)}{G_{t-1}}\right) \cdot C_{CO_2,t,original} \quad (1)$$

122 In case the reduction is only proportional to the non-subsidised electricity production, the CO<sub>2</sub> in  $t$  is reduced  
 123 in proportion to the excess SRES of the previous year ( $G_{SRES,t-1} - G_{SRES,Announced,t-1}$ ) over the originally planned  
 124 electricity production of all non-subsidised generators (termed from now on relative electricity production based  
 125 adjustment, *RBA*). This is equal to reducing the cap proportionally to the amount of non-subsidised electricity that has

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<sup>5</sup>Since the policy is currently not implemented, it is open who would have that regulatory power. The European Commission would be a logical option.

<sup>6</sup>We confirmed this effect in simulations, but decided to exclude it from the paper for conciseness.

126 been displaced by SRES. The cap reduction is thus stronger than in the RBA case.

$$C_{CO_2,t,RBA} = \left(1 - \frac{\max(G_{SRES,t-1} - G_{SRES,Announced,t-1}, 0)}{G_{t-1} - G_{SRES,Announced,t-1}}\right) \cdot C_{CO_2,t,original} \quad (2)$$

127 While we limit our analysis to the power sector, the two approaches can be extended to the entire ETS by consid-  
 128 ering all SRES generation (including non electric sources) in comparison to all energy consumption that is covered  
 129 by the EU ETS. As an overview the discussed design options, their characteristics and whether they are simulated in  
 130 this work are given in Table 1.

Method	Strength of cap reduction	Preciseness	Method	Complexity	Simulated
Perfect model	Medium	High	Counter-factual scenario	High	No
Displaced emissions	Medium	Medium-High	Counter-factual scenario	High	No
TBA	Weaker	Medium-Low	Heuristic	Low	Yes
RBA	Stronger	Medium-Low	Heuristic	Low	Yes

Table 1: Characteristics of design options.

#### 131 1.4. Choice of modelling methodology

132 The long-term development of electricity markets and carbon markets is characterised by several features which  
 133 make modelling them a challenge: the decisions of actors are non-linear, as is the formation of prices (due to the non-  
 134 continuous merit order). Power plants are discrete, very long-lived objects with different technological characteristics  
 135 and long building times. In competitive electricity markets, operation of and investment in electricity production are  
 136 in the hands of several private parties. As Olsina et al. [30] noted, the electricity market can therefore not be assumed  
 137 to be on a cost-optimal trajectory and is prone to business cycles. Thus path dependence is a challenge. Furthermore,  
 138 power companies do not have perfect foresight, they are limited in their forecasting capabilities by the long-term  
 139 complexities of fuel and technology markets and by their processing power, causing them to have bounded rationality  
 140 [31].

141 Agent-based models (ABM) are well suited to match these challenging characteristics. In an ABM, the behaviour  
 142 of a system is modelled by introducing autonomous decision making entities (the agents), who assess situations and  
 143 make decisions based on rules [32]. Their behaviour is encapsulated in algorithms and then executed by comput-  
 144 ers. ABM is especially suited when behaviour is non-linear, discrete, involves if-then rules and when behaviour is  
 145 boundedly rational and heterogeneous [33]. It is thus well equipped to model non-equilibrium economics and path de-  
 146 pendencies [34], as we find in long-term power markets. As a result, ABMs have become more popular in modelling  
 147 long-term dynamics in the power sector, such as interactions with CO<sub>2</sub> markets [35, 36], renewable policies [37, 13],  
 148 generation adequacy [38] and market concentration [39].

149 To analyse the question of CO<sub>2</sub> cap adjustment, we decided to extend the agent-based model EMLab-Generation,  
 150 which was previously used for analysing national and international price caps [22]. Besides the general advantages of  
 151 an ABM for modelling electricity markets, CO<sub>2</sub> cap adjustment policy is best modelled in a dynamic setting in order to

152 capture the delay caused by the rule-based mechanism. Additionally, myopia of market participants<sup>7</sup> may exacerbate  
153 the price effect of additional investment in SRES on the EU ETS. This myopia is captured in the agent-based model  
154 EMLab-Generation.

## 155 **2. Model description and assumptions**

156 In this section, we summarise the model description of the agent-based simulation model that we use and introduce  
157 in more detail the changes introduced to the model. The full model description was published by Richstein et al.  
158 [22] and de Vries et al. [40], who provided more extensive and formal specifications of the model. Except for the  
159 differences that we will mention here, the model and scenario inputs are identical. Sections 2.2 and 2.3 describe the  
160 extensions to the model that were made for this paper.

### 161 *2.1. General model structure & agents*

162 EMLab-Generation is an agent-based simulation of two interconnected electricity market and a common CO<sub>2</sub>  
163 market, which is published as open-source<sup>8</sup>. The modelled interconnected prize zones are Central Western Europe  
164 (CWE, consisting of Belgium, France, Germany, Luxembourg and The Netherlands) and Great Britain (GB). The EU  
165 ETS is scaled down to the electricity markets of CWE and GB. Market clearing is done via market coupling. The  
166 generation capacity evolves endogenously by investment of energy producers in discretely modelled power plants of  
167 different generation types<sup>9</sup>. The model has time steps of one year length, and the electricity load is approximated via  
168 a load duration curve with different segments (load levels), based on ENTSOE data from 2010.

169 The main agents of the model are energy producers. They submit bids to the electricity markets (based on the fuel  
170 mix, efficiency of the power plant and a 10% general mark-up for market power), pay for maintenance and their loans,  
171 determine the fuel mix of power plants and dispatch them. Most importantly they invest in new generation capacity,  
172 based on bottom up forecasts of the net present value (NPV) for a reference year (6-8 years ahead) and the different  
173 generation technologies. These forecasts are based on regression analysis of input variables to the merit order forecast,  
174 such as of fuel prices, electricity demand trends and the long-term CO<sub>2</sub> price. The agents are thus not omniscient,  
175 which is an important characteristic for modelling long-term dynamics (cf. Section 1.4). Investment occurs in several  
176 rounds, where investment actions of the agents are reflected in subsequent profitability calculations of other agents.  
177 When no energy producer is willing to invest any more the investment rounds are stopped.

178 The other important agent of the model is the ElectricitySpotMarket agent which clears the joint electricity and  
179 carbon market, including modelling the joint banking behaviour of the energy producers<sup>10</sup>. It does so by clearing

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<sup>7</sup>Caused by their limited foresight, but also by their limited ability to bank CO<sub>2</sub> permits above their hedging needs due to risk management procedures.

<sup>8</sup>The model and input data used for this paper can be found at: <https://github.com/EMLab/emlab-generation/tree/paper/resCapAdaption>

<sup>9</sup>Technologies are based on the World Energy Outlook 2011 New Policies Scenario [41] and additional assumptions [22].

<sup>10</sup>This is a departure from pure ABM modelling; however, the focus of this models lies in the long-run not the short-term

180 the two electricity spot markets via market coupling: first the market is cleared for all segments of the load duration  
 181 curve under no transmission constraints (operational are not considered). If the existing interconnected capacity is not  
 182 exceeded the market is considered as cleared (done individually for the different segments). Otherwise the markets  
 183 are cleared separately with the market loads adjusted by the interconnector capacity. This clearing of the electricity  
 184 markets is nested in an iterative price search for an EUA price which clears the CO<sub>2</sub> market. The clearing condition  
 185 for the CO<sub>2</sub> market is encapsulated in the following condition:

$$C_{CO_2,t} + C_{CO_2,t+3} + \Delta T_B/r = E_t(p_{t,CO_2}) + \hat{E}_{t+3}(p_{t,CO_2} * (1 + i_B)^3) \quad (3)$$

186 It states that emissions of the current year ( $E_t$ , dependent on the EUA price  $p_{t,CO_2}$ ) and the expected emissions in  
 187 three years time ( $\hat{E}_{t+3}(p_{t,CO_2} * (1 + i_B)^3)$ ) are equal to the current emission cap  $C_{CO_2,t}$ , the emission cap in three years  
 188 time  $C_{CO_2,t+3}$  and the delta from the banking target of energy producers divided by a target banking speed factor  $r$   
 189 of three years. The banking target of producers is set by 80% of expected emissions in the one year time, 50% of  
 190 expected emissions in two years time and 20% in three years time and based on empirical data of energy producers  
 191 hedging behaviour [42, 43]. The condition ensures that on the one hand producers bank according to their hedging  
 192 needs, yet some inter-temporal optimisation takes place.

193 The other agents in the model are mostly implementations of exogenous variables and policy actions (Commodi-  
 194 tySupplier, EnergyConsumer), or are agents which are used for the accounting of the energy producers' costs (Pow-  
 195 erPlantManufacturer, PowerPlantMaintainer, BigBank). Fuel prices are based on triangular distributions for lignite,  
 196 biomass and uranium [22]. Hard coal and gas prices are correlated stochastic Ornstein-Uhlenbeck processes [22],  
 197 based on data from UK Department of Energy and Climate Change [44].

## 198 2.2. Modelling the adjustment of the cap based on renewable policy

199 As discussed in Section 1.3, we implemented two different rule-based cap adjustment mechanisms based on the  
 200 volume of subsidised renewable energy production that exceeds the policy targets. In the first, the SRES excess is  
 201 set in proportion to the total electricity production (TBA). In the second, it is only set in proportion to unsubsidised  
 202 electricity production only (RBA). We assume that implementation is based on observed data, which is available with  
 203 a delay. Therefore, indicators of the previous year's data (electricity production, emissions and SRES) are used to  
 204 calculate the current year's cap reduction. If the regulator would wish to adjust the cap in real time, he would need to  
 205 rely on forecasts and estimations.

206 The adjustment of the cap needs to be implemented in two parts of the electricity & carbon market clearing. Firstly  
 207 in the current cap  $C_{CO_2,t,TBA}$  or  $C_{CO_2,t,RBA}$ , which replaces  $C_{CO_2,t}$  in Equation (3). This is a certain adjustment, because  
 208 it occurs in the current year. Secondly, in the future the expected cap  $\hat{C}_{CO_2,t+3,RBA}$  or  $\hat{C}_{CO_2,t+3,TBA}$ , depending on the,  
 209 replaces  $C_{CO_2,t+3}$  in Equation (3). The expected cap adjustments needs to be estimated from expected generation of  
 210 renewables. The formulas that are used to implement the TBA and RBA policy options in the current market are



211 introduced in Section 1.3, by Equations (1) and (2). The expected cap in  $t + 3$  is calculated with the same equations  
 212 but with forecasts<sup>11</sup>:

$$\hat{C}_{CO_2,t+3,TBA} = \left(1 - \frac{\max(\hat{G}_{SRES,t+2} - G_{SRES,Announced,t+2}, 0)}{\hat{G}_{t+2}}\right) \cdot C_{CO_2,t+3,original} \quad (4)$$

$$\hat{C}_{CO_2,t+3,RBA} = \left(1 - \frac{\max(\hat{G}_{SRES,t+2} - G_{SRES,Announced,t+2}, 0)}{\hat{G}_{t+2} - \hat{G}_{SRES,Announced,t+2}}\right) \cdot C_{CO_2,t+3,original} \quad (5)$$

213  
 214 Since the renewable and overall generation in  $t+2$  needs to be estimated, the values for  $\hat{G}_{t+2}$ ,  $\hat{G}_{t+2}$  and  $\hat{G}_{SRES,t+2}$  are  
 215 linearly interpolated between the generation results current market clearing (in time step  $t$ ) and the future generation  
 216 results of the market clearing in time step  $t+3$  (which is a direct result of the market clearing algorithm). Since the RES  
 217 investment targets are given in the model as absolute capacity, not as relative production targets,  $G_{SREG,Announced,t-1}$   
 218 and  $G_{SREG,Announced,t+2}$  need to be calculated as a counter-factual scenario. This is done by scaling the production  
 219 according to the ratio of the planned capacity to the actual installed capacity.

### 220 2.3. Investment in RES

221 In order to represent renewable policy in the model, an investor with exogenous renewable investment time series is  
 222 implemented in the model. In deviation from [22], renewable energy policy is also a stochastic parameter in this paper.  
 223 The national governments in the simulation have announced renewable policy targets in terms of absolute capacity  
 224 targets, however actual renewable investment by governments may deviate from it. This is done in order to depict the  
 225 uncertainty that private market parties face when it comes to renewable policy. The implementation takes the yearly  
 226 installation target and multiplies it with a stochastic realisation drawn from a normal distribution (separately for each  
 227 year, so over time governments achieve there targets on average). In the case of this paper the normal distribution has  
 228 a standard deviation of 0.5 and the expected mean corresponds to the renewable policy scenario<sup>12</sup>. Thus while large  
 229 stochastic deviations from government targets may occur in single years, over several years they average out. The  
 230 mean shares of the different renewable scenarios are given in Figure 2.

## 231 3. Model results and discussion

232 We combine the discussion and analysis of our results in one section. We begin with the description of the  
 233 scenarios used in our analysis. Next, we present our model results regarding the effects of the different CO<sub>2</sub> cap  
 234 adjustments on CO<sub>2</sub> prices and emissions in Section 3.2. All statistical evaluations and graphs were made in GNU R  
 235 [45].

<sup>11</sup>Denoted by a hat above the forecasted variables

<sup>12</sup>That is, for a case in which the government just reaches its policy targets, the mean of the distribution is 1. In a scenarios where the government over-achieves its targets by 50% the distribution mean is 1.5.

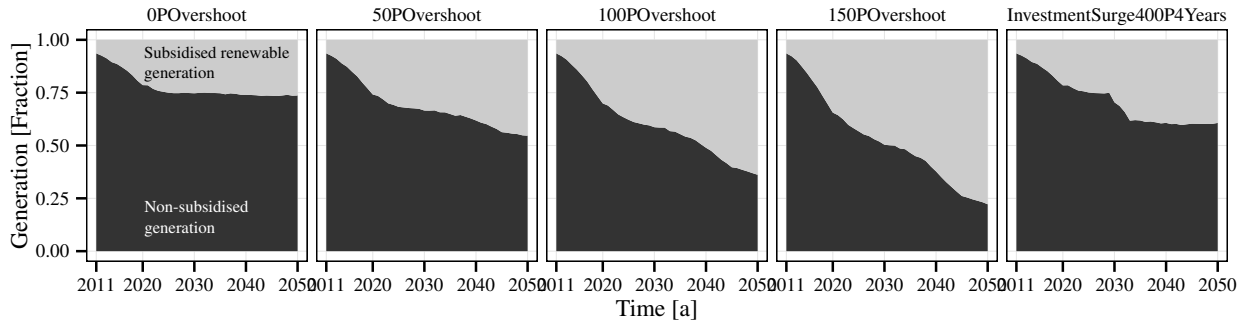


Figure 2: Mean share of subsidised renewable energy production in generation.

### 236 3.1. Scenarios

237 We investigate three CO<sub>2</sub> policy scenarios: the original EU ETS (“PureETS”, following the EU ETS cap reduction  
 238 scaled to CWE and the UK, but without the backloading measure), the adaption of the emission cap based on the total  
 239 electricity production as a baseline (“TBA”) and the emission cap adaption based only on the non-subsidised part of  
 240 the electricity generation as a baseline (“RBA”). We also vary the overshoot of renewable installations in excess of the  
 241 announced governmental targets. We include five different scenarios: a scenario without overshoot (0POvershoot),  
 242 with 50%, 100% and 150% of excess installed capacity as compared to the original target (50POvershoot, 100POver-  
 243 shoot and 150POvershoot), and finally a scenario in which an investment surge takes place over a period of 4 years, in  
 244 which 400% excess capacity of the yearly targets is installed in the years 2030 to 2033. The reason for investigating an  
 245 investment surge is to investigate the sensitivity of the carbon price to such an event. The years 2030-2033 have been  
 246 chosen because they represent a relatively stable price period in the PureETS case. The average share of subsidised  
 247 renewable generation is shown in Figure 2. Please note that we took a rather conservative relative share of renewable  
 248 energy policy as a base case. This was to better illustrate the effects of a cap reduction in response to an overshoot of  
 249 renewable energy targets.

250 Since we want our results to be robust against different fuels, demand and renewable capacity variations, we con-  
 251 duct a Monte-Carlo simulation of the policy scenarios. For each combination of the CO<sub>2</sub> and renewable deployment  
 252 scenarios, we run the simulation with 120 stochastically generated time series of fuel price development, electricity  
 253 demand growth and the exact capacity of yearly installed renewable generation capacity. The 120 time series are, as a  
 254 group, identical in the different policy scenarios. This assures that there are no random variations in the results due to  
 255 fuel and demand development and enables us to make pairwise comparisons of the policy scenarios with exactly the  
 256 same time series.

### 257 3.2. Results and analysis

258 The main focus of the results section is on the differences in EUA price development between the different sce-  
 259 narios (Section 3.3) and on the effect of the policy on CO<sub>2</sub> emissions (Section 3.4).

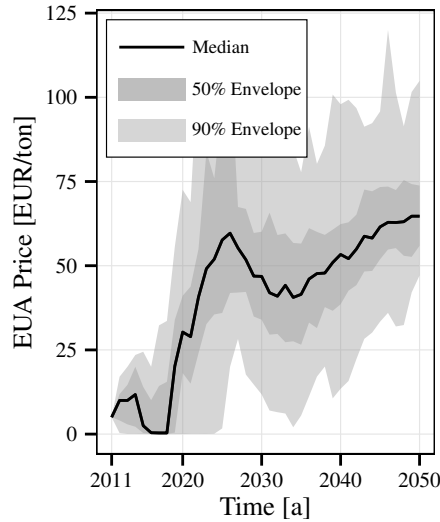


Figure 3: EUA prices in PureETS-0POvershoot scenario.

261 In order to show the price differences between the PureETS-0POvershoot scenario (i.e. no modification of the  
 262 ETS and the governments are on average meeting their announced renewable targets) and the other scenarios, we  
 263 make a pairwise comparison of EUA prices in the corresponding Monte-Carlo runs in each scenario<sup>13</sup>. The prices in  
 264 the PureETS-0POvershoot scenario are depicted in Figure 3. Figure 4 shows the price differences; the rows show the  
 265 different CO<sub>2</sub> policies, and the columns the subsidised renewable deployment scenarios. The black line is the median  
 266 of the price difference, the darker shaded area corresponds to a 50% envelope, and the lighter area to a 90% envelope.

267 As can be seen in the first row, which depicts the PureETS case under different renewable deployment scenar-  
 268 ios, the stronger the renewable deployment, the stronger the carbon price drop, as compared to the planned SRES  
 269 development. While the impact on the carbon price is nominally lower in the initial years (2011 to 2020) in the  
 270 100POvershoot and 150POvershoot scenarios, it should be noted that this still is caused by a complete collapse of  
 271 the EUA price during several years. The original prices in the 0POvershoot scenario (Figure 3) are very low, so a  
 272 price reduction of around 20 EUR/ton corresponds to a total price collapse in those years. In the rightmost subgraph,  
 273 the price drop during the investment surge can also clearly be seen. This lasts longer than the underlying investment  
 274 surge, which ends in 2033, because of course the additional SRES stays in the market for several more years and the  
 275 market only slowly adjusts to the sudden EUA price drop.

276 Comparing the cap adjustment scenarios in the lower two rows to the PureETS scenario, it can be seen that in  
 277 both cap adjustment scenarios the median line and the envelope of the price difference are significantly closer to the

<sup>13</sup>This means that for each pairwise comparison, the fossil fuel price development, the exact renewable deployment and the demand growth are identical.

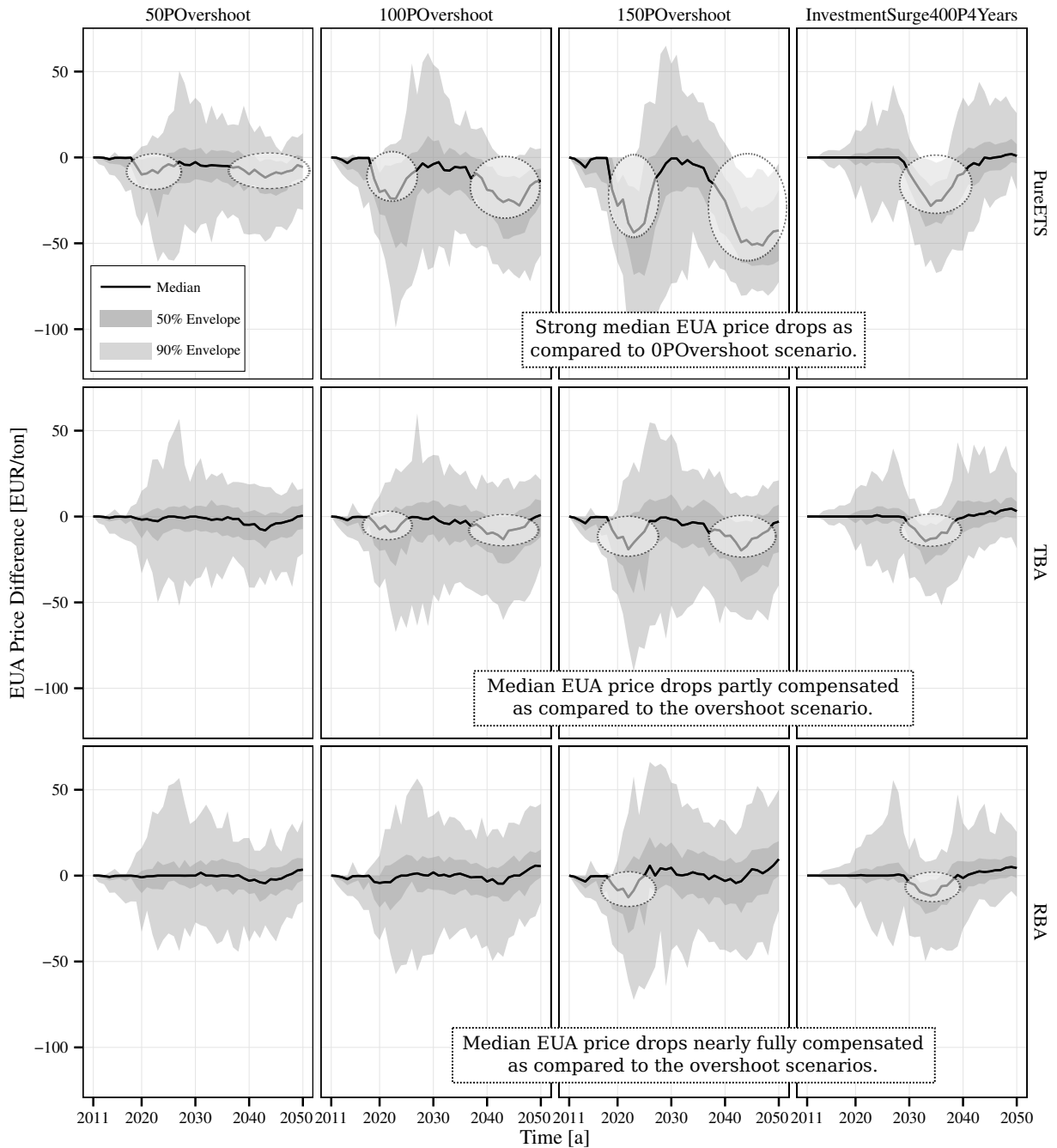


Figure 4: EUA price differences relative to the PureETS-0POvershoot scenario.

278 zero line. This means the price drop that is induced by excess SRES is mitigated in the mean case of all renewable  
 279 deployment scenarios. However, the range of uncertainty is relatively large, with both far higher and lower prices  
 280 occurring than in the corresponding PureETS-0POvershoot scenario. In most cases of the TBA scenario, the price  
 281 deviation is still negative, which means that despite the cap adjustment the prices are still lower than without the

282 SRES overshoot. Only in a few outlier cases, in a limited number of years, does the cap adjustment overcompensate  
 283 the effect of the excess renewable deployment. In the RBA scenario, the price adjustment is stronger. While in most  
 284 years the median line is slightly below zero, in the last years of the simulation the price is over compensated. The  
 285 stronger price compensation is no surprise. Per definition, the volume of non-subsidised generation is smaller than  
 286 total generation in a given year. Thus the denominator in the RBA equation (Equation (2)) is smaller than in the  
 287 RBA equation ((Equation (1))), resulting in a stronger cap adjustment. Table 2 shows the average price difference  
 288 between the PureETS-0POvershoot scenario over the entire simulation horizon. The price differences in the table  
 289 between three CO<sub>2</sub> policy scenarios are significant over all renewable scenarios with overshoots, except for the In-  
 290 vestmentSurge400P4Years renewable scenario, in which RBA and TBA are not significantly different from each other  
 291 (cf. Appendix A).

CO2Scenario	50POvershoot	100POvershoot	150POvershoot	InvestmentSurge400P4Years
PureETS	-7.37	-14.84	-22.81	-5.61
TBA	-3.21	-6.60	-9.75	-1.71
RBA	-1.05	-1.63	-1.66	-0.88

Table 2: EUA price difference as compared to the PureETS-0POvershoot scenario.

292 Regarding the level and volatility of EUA prices, no general conclusion can be drawn. Since the policy acts to  
 293 restore the CO<sub>2</sub> price levels without an overshoot of renewable energy targets, the outcome in terms of price level  
 294 and volatility depends on the counter-factual scenario that is being restored. In case of acceptable price levels and  
 295 volatility, or in the case of relatively low prices, the cap reduction would serve to stabilise prices by restoring an  
 296 acceptable price environment. On the other hand, if the original cap is set ambitiously, leading to potential price  
 297 shocks, exceeding the renewable policy target could dampen price extremes and the cap reduction could restore a  
 298 volatile environment.

299 In Section 1.2 we hypothesised that with a higher CO<sub>2</sub> price induced by a cap adjustment policy, the renewable  
 300 revenues from the spot market would increase, and thus the expenditure of governments and/or consumers to subsidise  
 301 them would decrease (via market premiums or quota systems). While this effect is visible in the model, it is relatively  
 302 small. The largest difference in the market value of renewables (the revenue that they earn per MWh) under the  
 303 TBA policy, as compared to the PureETS-0POvershoot scenario, occurs on average in the years 2024 to 2026, in  
 304 the 150POvershoot scenario, and ranges between 11.40 and 13.79 EUR/MWh at an average EUA price difference  
 305 of 26 to 28 EUR/ton. In the RBA-150POvershoot scenario, the market value difference with the PureETS scenario  
 306 ranges between 15.61 €/MWh and 20.20 €/MWh during the same years. In most other years and policy scenarios,  
 307 the difference is small (less than 6 EUR/MWh). While the CO<sub>2</sub> price difference is similarly high in the years 2045  
 308 between the PureETS and RBA case in the 150POvershoot scenario of the simulation, the mean difference in market  
 309 value is still only 4.41 EUR/MWh in the RBA-150POvershoot scenario. The relatively small difference in market  
 310 value can be explained from the way in which the merit order curve changes in comparison to earlier years. Since the

311 power sector is largely decarbonised by the end of the simulation, the marginal prices in the base load and shoulder  
312 load hours are usually not set by CO<sub>2</sub> intensive generation units. Thus the renewables receive relatively little revenue  
313 from high EUA prices as their share increases. It should be noted, though, that due to the simplified modelling of  
314 the short-term market and the absence of storage technologies, the model may represent the effects of high shares of  
315 renewables only in a limited fashion.

### 316 3.4. CO<sub>2</sub> emissions

317 Since the policy under investigation directly affects the emission cap, it is interesting to evaluate how the actual  
318 emissions change under different scenarios with increased production of renewables. Figure 5 shows the probability  
319 density distribution of CO<sub>2</sub> emissions over the entire simulation as compared to the CO<sub>2</sub> emissions allowed under  
320 the original cap<sup>14</sup>. A high density at 100% on the x axis means that emissions are close to the original cap in a  
321 large percentage of cases. This is for example true for nearly all of the simulations in the PureETS scenarios and the  
322 OPOvershoot scenarios (since in either scenario the cap is not adjusted).<sup>15</sup>. Our simulations correspond with earlier  
323 theoretical and equilibrium-model based results [1, 2] that renewable policy under an ETS does not lead to additional  
324 emission reductions, but to a shift in the market to more polluting power plants.

325 As can be seen, both the TBA and RBA reduce the emission cap, rendering additional renewable policy beyond  
326 the original targets climate-effective. In the case of the 150POvershoot scenarios, the cap is reduced by around 20%  
327 over the entire simulation for the TBA adjustment and around 25% for the RBA adjustment. It is clear that the RBA  
328 reduces the cap more because it sets it in relation to only the non-subsidised part of generation. The spread of the  
329 emission distributions increases with the higher overshoot scenarios. The reason for this lies with the stochastic nature  
330 of the SRES target investor agent, which causes small differences in actual installed renewable capacity in the different  
331 scenarios and the ensuing adjustment of the cap.

### 332 3.5. Green promotes the dirtiest - cap adaption impedes them

333 Our simulation confirms the analytic result of Böhringer and Rosendahl [3], that “green promotes the dirtiest” in  
334 a dynamic transition setting. Figure 6 shows the relative share in generation of lignite, the “dirtiest” technology in  
335 our simulation, over the three CO<sub>2</sub> and four renewable scenarios (we exclude the investment surge scenario for an  
336 easier to read figure). As can be seen, in the PureETS case, the larger the overshoot, the larger is the share of lignite  
337 in the overall generation mix; this is part of the reason why the emissions stay unchanged in the PureETS scenario,  
338 regardless of the renewable policy overshoot. This effect is stronger in the medium term, rather than at the end of the  
339 simulation. The two cap adaption policies undo this effect in the medium term and effectively reverse it towards the  
340 end of the simulation when there are high shares of renewable energy.

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<sup>14</sup>It is a Gaussian kernel density estimate, using the R inbuilt function density.

<sup>15</sup>On average emissions are slightly above 1, since agents start out with banked EUA permits. They reduce thus starting stock over the course of the simulation, which leads to emissions over the cap.

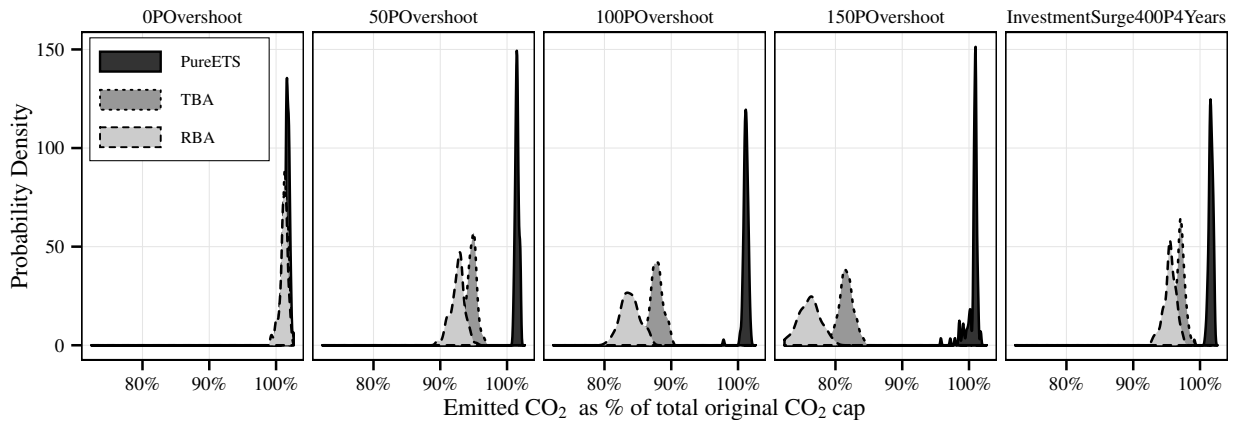


Figure 5: Total CO<sub>2</sub> emissions in different Monte-carlo scenarios (Probability density function).

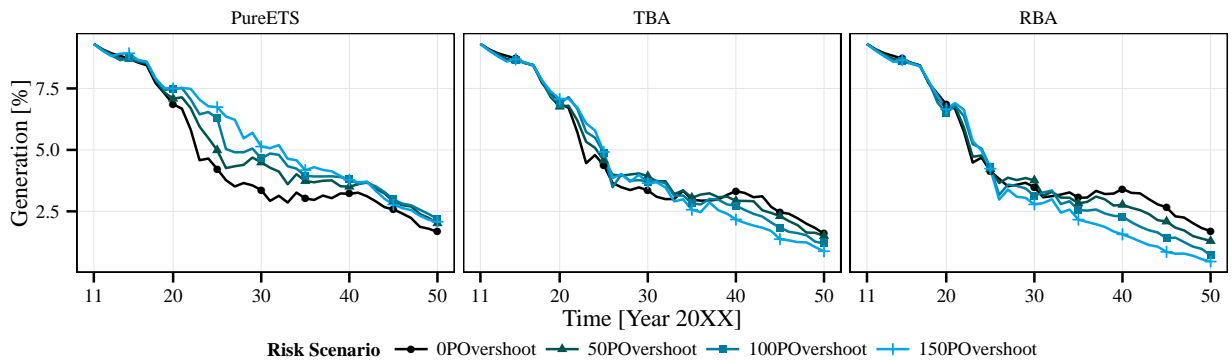


Figure 6: Relative generation of lignite in CO<sub>2</sub> and renewable policy scenarios.

#### 341 4. Conclusions and policy implications

342 We discuss possible options for dynamically adjusting the CO<sub>2</sub> emission cap in response to overshoots in sub-  
343 subsidised renewable electricity generation as compared to the policy targets for renewable energy. The goals of such a  
344 CO<sub>2</sub> cap adjustment policy would be to reduce the impact of the renewable energy policy on the CO<sub>2</sub> price and to  
345 make public subsidies in renewable energy climate-effective.

346 While the concept is fairly straightforward, devising a cap reduction policy that removes the impact of renewable  
347 policy on CO<sub>2</sub> prices is not a simple task for a regulator because he would need perfect knowledge to create counter-  
348 factual scenarios in order to correctly adjust the cap. We propose two ways to adjust the CO<sub>2</sub> cap to unexpectedly high  
349 investment in renewable energy generation. They reduce the cap in proportion to the volume of subsidised renewable  
350 electricity generation that exceeds ex-ante government targets, as compared to either total generation (termed TBA),  
351 or as compared to the originally planned electricity production of all non-subsidised generators (termed RBA). We  
352 use the agent-based model EMLab-Generation, which simulates the investment in two electricity markets (based on  
353 Central-Western Europe and Great Britain) to investigate the possible effects of such a policy implementation.

354 We find that both policy implementations perform reasonably well within the simulation with regard to the afore-  
355 mentioned goals: on average, they restore price levels to close to what they would have been without an overshoot of  
356 renewable policy versus originally planned targets; however, in individual cases the policies may over or under com-  
357 pensate significantly. TBA is the weaker instrument and tends to not fully restore prices. RBA leads to prices closer to  
358 the counter-factual scenario; however, it sometimes leads to higher CO<sub>2</sub> prices. Both policies reduce the cap and the  
359 emissions in the simulation, and thus render public investment above governments minimum targets climate-effective.  
360 The policies also undo the “green promotes the dirtiest” effect [3], so that an overshoot in renewable energy results in  
361 less electricity generation by the most emission-intensive power plants.

362 It should be noted that neither method of CO<sub>2</sub> cap adjustment is suitable for achieving specific CO<sub>2</sub> price goals or  
363 volatility goals because they merely restore a counterfactual CO<sub>2</sub> price that would have existed without the renewable  
364 energy policy overshoot, which may be relatively high or low, volatile or not. To achieve these aims, price floors and  
365 price caps [22, 21] or an independent authority adjusting the cap [23] would be better suited.

366 As the cap adjustment policies lead to higher CO<sub>2</sub> prices, they should lower the need for financial support for  
367 renewable generation. However, this effect appears to be small and declines over time as the power plant stock is  
368 decarbonised and carbon-intensive power plants set the marginal price less frequently.

369 Implementation of the proposed options is not straightforward: because the cap adjustment is a function of re-  
370 newable policy targets, subsequent adjustment of these targets would change the response strength of the policy. This  
371 raises the question of how long in advance formal policy targets should be formulated and how to treat changes to  
372 policy targets in the future.



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381 comments and suggestions.

382 **Appendix A. Test statistics**

383 We performed pairwise Wilcoxon tests for the mean difference of EUA prices between CO<sub>2</sub> policy scenarios for a  
 384 given renewable scenario. For a significance level of 5% all the policy scenarios are statistically different from each  
 385 other, except the RBA and TBA scenario in the InvestmentSurge400P4Years renewable scenario.

Renewable Scenario		PureETS	TBA
50POvershoot	TBA	3.26e-06	
	RBA	8.20e-12	1.40e-02
100POvershoot	TBA	2.80e-12	
	RBA	1.27e-23	9.61e-08
150POvershoot	TBA	4.81e-20	
	RBA	9.64e-32	2.44e-10
InvestmentSurge400P4Years	TBA	5.04e-08	
	RBA	1.81e-10	1.76e-01

Table A.3: EUA mean price Wilcoxon test

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