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EU carbon prices signal high policy credibility and farsighted actors

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Carbon prices in the EU emissions trading system are a key instrument driving Europe's decarbonization. Between 2017 and 2021, they surged tenfold, exceeding €80 tCO_2^{-1} and reshaping investment decisions across the electricity and industry sectors. What has driven this increase is an open question. While it coincided with two significant reforms tightening the cap ('MSR reform' and 'Fit for 55'), we argue that a reduced supply of allowances alone cannot fully explain the price rise. A further crucial aspect is that actors must have become more farsighted as the reform signalled policymakers' credible long-term commitment to climate targets. This is consistent with model results that show historic prices can be better explained with myopic actors, whereas explaining prices after the reforms requires actors to be farsighted. To underline the role of credibility, we test what would happen if a crisis undermines policy credibility such that actors become myopic again, demonstrating that carbon prices could plummet and endanger the energy transition.

The EU emissions trading system (EU ETS) is a central pillar of the European Union's decarbonization strategy. It covers the electricity sector, large-scale industrial installations, aviation and maritime transport and hence controls above 40% of the European Union's total greenhouse gas emissions[1]. Over a period with two major reforms of the ETS and notably a substantial tightening of the cap, the carbon market underwent a remarkable transition: carbon prices increased tenfold within four years, with a first rise in 2018 from below €10 tCO_2^{-1} to a plateau at €20–30 tCO_2^{-1} in 2019–2020 and then a second, even sharper, rise during which prices repeatedly reached almost €100 tCO_2^{-1} in 2021 and 2022[2]. The question of why prices have risen so steeply is still unanswered, though, and a subject of debate among the scientific and policy community.

The literature so far identifies various factors as playing a potential role in carbon price developments in general: (1) regulatory changes (such as the introduction of the Market Stability Reserve (MSR) or changes in the linear reduction factor)[3–5], (2) actors' behaviour (foresight horizon, hedging or participation in trade)[6,7] and (3) speculation and external financial investors[8–10]. However, most work focuses on one of those aspects, provides only qualitative assessments and covers only the period before the recent reforms and price increases.

With a view on understanding what has driven prices in the recent period, the following puzzle arises. It is economically straightforward that a tightening of the long-term cap should increase current and expected prices. However, past research suggests that market participants in the ETS are myopic[7,11]. Whereas myopia can always have an impact on energy sector investments, it is especially relevant when the power sector is covered by an intertemporal emissions trading system with a cap that strongly tightens over time, so that future certificate scarcities can influence current investments. If most market actors were myopic, a long-term tightening of the cap should thus only have modest effects on current prices, much lower than the observed increase after the reforms.

In light of that, we hypothesize that the reform could have had another important effect on actors: making them more farsighted. The reason is that through the reform EU policymakers substantially firmed up the credibility of their commitment to the ETS overall. They did this both explicitly, by emphasizing that the 'ETS is front and centre to all our efforts'[12], and implicitly, by investing a lot of political capital in the political negotiation. More broadly, a recent empirical study also shows that the European Union has currently the world's highest climate policy credibility[13].

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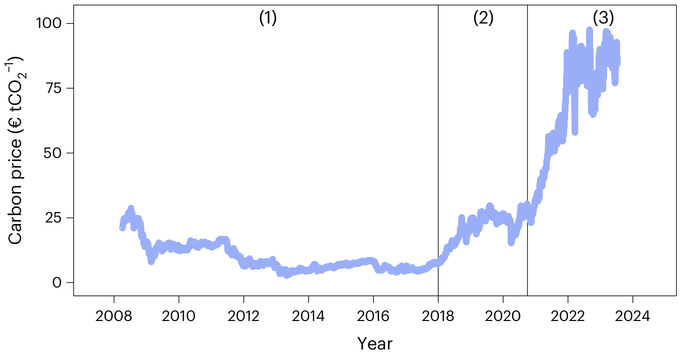

Fig. 1 | Evolution of carbon prices on the EU ETS from 2008 to 2023. Prices correspond to historical EU ETS allowances (EUA) prices on the EEX spot market[2,68]. The year tick marks the beginning of a year. We categorize the price evolution into three periods: (1) initial decline and stabilization, (2) first rise and (3) second rise.

Such instilled credible commitment is essential to shape firms' expectations about the durability of long-term policies such as the ETS[14], and indeed studies suggest that low policy credibility can be associated with decreased green investments[15], and that policy credibility can enhance actors' farsightedness[16]. The main reason is that low credibility creates high regulatory uncertainty regarding a future softening of the cap or interventions to dampen high carbon prices—a major reason for myopia. Correspondingly, increasing credibility implies that actors become more farsighted.

Research is still outstanding on whether myopia remains a prevalent influence within the current EU ETS. Equally, there has been no investigation into whether any shifts in the foresight horizon have occurred and their potential impact on the recent surge in carbon prices.

We fill this gap by providing a model-based analysis of the EU ETS with a specific emphasis on the influence of actors' foresight horizon. The contribution of our work is threefold. We first analyse the past: bringing together the impact of political reforms, the foresight of compliance actors and the role of external investors, we show which mix of those mechanisms could explain the observed strong rise in carbon prices. We discuss the present: by computing marginal carbon prices necessary to drive the decarbonization of the electricity and industry sectors in line with the new EU's 2030 goals as set in the 'Fit for 55' package, we assess that current ETS prices correspond to the optimal market-efficient carbon price trajectory. We turn to the future: having understood the mechanisms that could plausibly have led to the observed increase in carbon prices, we explore in how far this positive development is vulnerable and potentially could be reversed. We close with policy recommendations on how to secure the energy transition in light of our results.

From past to present

When analysing past carbon prices (Fig. 1), one can broadly break down the timeline into three periods with distinct price regimes: (1) the period of 2008–2017, in which prices first dropped and then stabilized at a low level below €10 tCO_2^{-1}, (2) the period of 2018–2020, the first rise up to a plateau of €20–30 tCO_2^{-1} and (3) the period since late 2020, the second rise, in which prices increased strongly and are now stabilizing around €70–90 tCO_2^{-1}. What might have been the main mechanisms driving these three regimes, and, in particular, what role could actors' foresight have played?

Regarding the first period (1), the common understanding is that prices dropped because of a high surplus of allowances that accumulated since 2008. The financial crisis reduced emissions more than anticipated, leaving compliance actors with a high number of unused allowances, hence limiting incentives to decarbonize[17].

Different publications furthermore suggest that the limited foresight of compliance actors contributed to low carbon prices[4,6,7,18]. To understand the role of foresight, one needs to consider that the EU ETS allows for almost unlimited forward bankability: any certificate not used today can be used in the future. Hence, expected future prices may have a strong influence on today's prices. In contrast, in a market without bankability, a surplus of certificates over emissions would mean the certificate price in that year is zero, as the unused certificates become worthless at the end of the year.

Now, many firms might not consider the long-term future (inherently, or due to regulatory uncertainty and lack of policy credibility) but rely on short-term planning horizons of for example, five to ten years[19]. If allowances scarcity occurs outside their planning horizon, they will not anticipate it and hence don't have incentives to bank certificates for the future nor decrease emissions in the short term. Consequently, the carbon price will stay lower and decarbonization will be slower than if actors were farsighted (Fig. 2).

Thus, for many years the EU ETS failed in establishing a carbon price that would drive deep decarbonization. In period (1), actors presumably acted myopically, a behaviour leading to low carbon prices. However, just a few years later, EU ETS prices are stronger than ever[2]. What happened since 2017? Which mechanisms drove the rise in carbon prices observed in periods (2) and (3)? A plausible explanation would be that prices simply increased because reforms tightened the cap[20]. Here we present a more comprehensive explanation: the reforms had the side effect that market actors also became less myopic, which drove prices up. Therefore, we first give an overview of the most relevant reforms from the past years and then present our modelling results.

The past years were marked by numerous reforms and rapid EU climate policy developments[21–27]. While it is challenging to pinpoint one specific regulation with the highest impact on carbon prices, we can, generally, speak about an intensive period in climate policy since 2015 with two crucial ETS reform periods: the 'MSR reform' and the 'Fit for 55' package, as summarized in Table 1.

Our modelling findings are divided into two segments. We first present results supporting our hypothesis that actors have extended their foresight, which strongly impacted historical carbon prices. Hereafter, we turn to the role of external financial investors, who have been gaining attention throughout literature and media[8–10,28–30], to delimit their possible impact on the carbon price surge.

Figure 3 shows our modelling results on the impact of reforms and actors' foresight on carbon prices (see also Extended Data Figs. 1–6). First of all, one can see between period (1) and period (2), when the MSR reform was negotiated and implemented, actors presumably started to look further into the future. When turning to period (1) before 2018, one notices that observed ETS prices are closer to the modelled prices for myopic actors than to the modelled prices for farsighted actors. It seems therefore plausible to assume that market actors behaved at least partially myopically, which is in line with earlier assessments[7]. For periods (2) and (3), one observes the opposite: both, the 2019–2020 observed ETS prices of €20–30 tCO_2^{-1} and the 2021–2022 ones of €70–90 tCO_2^{-1}, are consistent with the modelled prices for farsighted actors (that is, perfect foresight trajectories for old 'MSR reform' targets, and new 'Fit for 55' targets, respectively). We also calculate the Mean Average Percentage Error (MAPE) between the modelled and historical prices (Extended Data Tables 1–4), which confirms the visual conclusions drawn from Fig. 3.

Hence, regarding the first rise at the beginning of period (2), a hypothesis following our results is that prices increased due to a gradual switch from actors' short- to long-term foresight, which might have been triggered, among other things, by the MSR reform tightening the cap and strengthening the MSR. Whereas our results indicate that the direct effect of the reform—the tighter emissions budget—cannot explain the substantial increase in prices under the assumption of continued myopia, the reform might have had a strong indirect impact:

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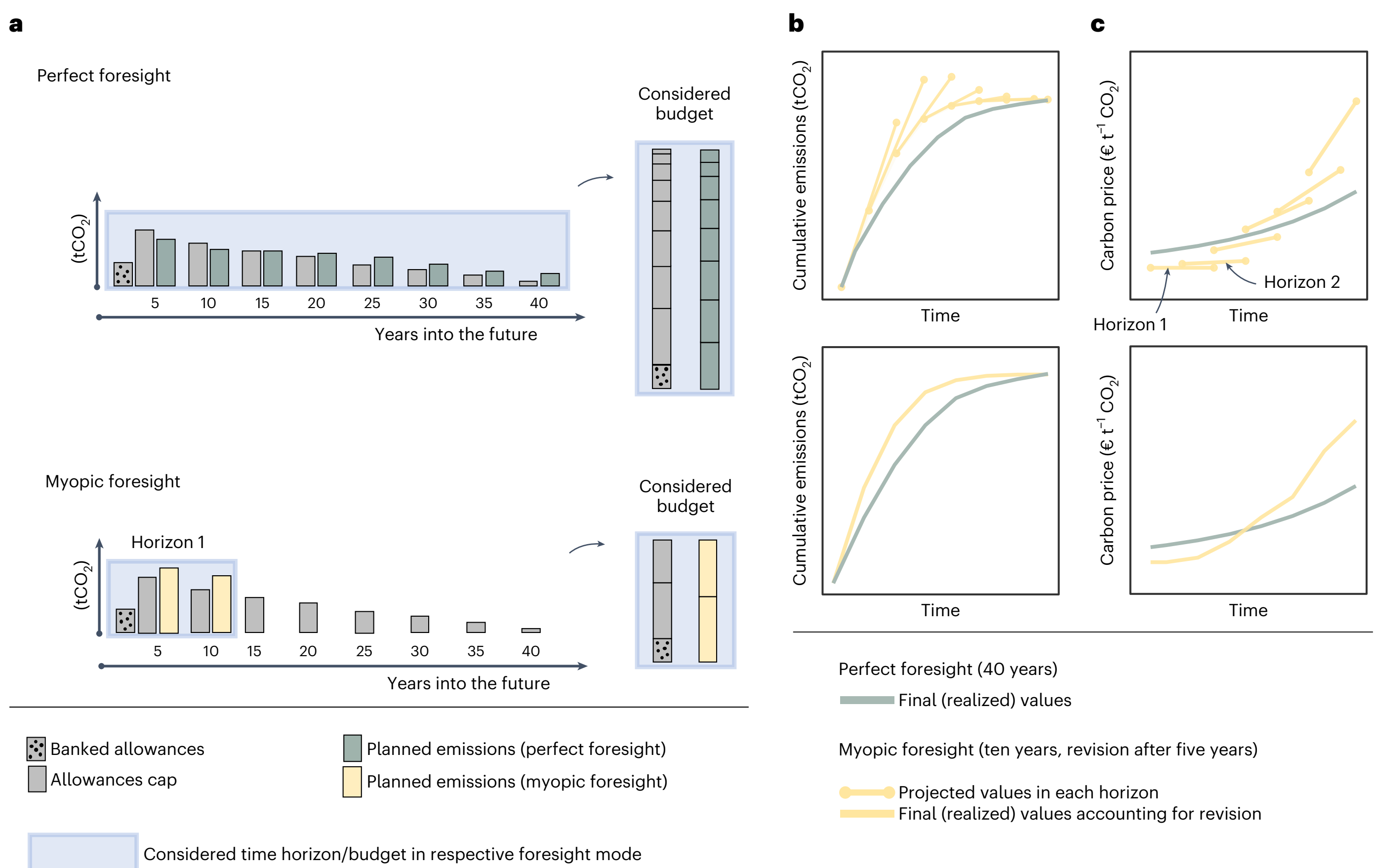

Fig. 2 | Stylized emissions and carbon price trajectory with short-term, myopic, and long-term, perfect, foresight. Simple cap and trade system without the Market Stability Reserve, for illustrative purposes. **a**, Example of a planning horizon at the beginning of the transformation. With a myopic foresight of ten years, there is no (or very weak) incentive to reduce planned emissions. With a perfect foresight, future scarcity is anticipated and planned emissions get reduced already in the near-term. **b**, Cumulative emissions over the whole transformation period. Myopic foresight leads to delayed decarbonization. **c**, Carbon prices over the whole transformation period. Myopic foresight leads to very low carbon prices in the near term. Short lines correspond to the specific horizons: every five years a new foresight horizon of ten years starts.

the negotiations and ultimate implementation of the reform over 2017 and 2018 (Table 1) emphasized the will of EU policymakers to 'repair' the ETS (showing 'the doctor has not given up on the patient'[31]), which strongly increased its long-term credibility, inspiring market actors to show longer foresight. These findings align with previous assessments, which, on the one hand, demonstrate that the MSR can lead to increased carbon prices[32,33], whereas, on the other hand, argue that the effect of the MSR reform on the emissions budget alone is unlikely to fully explain the surge in carbon prices[6,34].

Secondly, Fig. 3 shows that the 'Fit for 55' package sharply increases the stringency of the EU ETS. Optimal carbon prices (that is, obtained under the assumption of perfect foresight) to reach the new targets are substantially higher than those that were necessary for achieving previous goals. In fact, modelled prices for the 'Fit for 55' targets for 2020–2023 are in the order of €70–90 tCO_2^{-1}, corresponding well to observed 2021–2023 prices on the EU ETS, thus supporting the hypothesis that actors have transitioned towards a more farsighted perspective.

Figure 4 discusses the final point of this section: could an influx of long-term investors explain the strong rise of carbon prices if other actors had remained myopic? Here we assume external investors temporarily block a part of the allowances on the market, which then cannot be used by compliance actors to cover their emissions during the period (Methods). This influences the price trajectory: when external investors buy, prices go up; when they sell, prices can go down.

In reality, it is estimated that external investors currently hold only around 5–10% of allowances futures[9], consistent with the scenario in which 5% of auctioned allowances are bought by external financial investors. This scenario shows only a small price increase of less than €10 tCO_2^{-1} in 2025 compared with the pure myopic scenario (Fig. 4). Thus, following our results, a major contribution of external investors to the price rise seems unlikely. What is on the other hand possible, is that they acted as a catalyser, speeding up the process of compliance actors switching to longer foresight and anticipating the consequences of the 'Fit for 55' package.

To summarize, we provide a possible explanation of the past: we show that the two price rises (first to €20–30 tCO_2^{-1} and more recently to €70–90 tCO_2^{-1}) are consistent with a first regulatory reform that had limited impact on the cumulative certificate budget but contributed to a switch of actors' behaviour from myopic to farsighted and a second reform that substantially tightened the emissions cap. Whereas external investors may have accelerated the transition, it seems improbable that prices are artificially high solely due to their activity.

Furthermore, our results provide insights about the present state of the EU ETS. Our modelling indicates that observed 2022 and 2023 prices of around €80 tCO_2^{-1} put the ETS sectors on track to achieving their reduction targets set by the Climate Law, a result in line with earlier findings[35].

Our findings suggest that actors became farsighted, which is consistent with the initially formulated hypothesis that the ETS reform heightened policy credibility. Overall, there are thus reasons for careful optimism: trust in the EU ETS revived, policy credibility seems high, actors are therefore farsighted and current prices are in line with EU's

Table 1 | An intensive period in climate policy between 2015 and 2022. Developments and reforms relevant for the EU ETS

Date	Event	Impact on climate policy/the EU ETS
Dec. 2015	Adoption of the Paris Agreement[21]	Global climate policy: 'goal to limit global warming to well below 2, preferably to 1.5 degrees Celsius, compared to pre-industrial levels'.
Oct. 2015	Decision on the establishment of an MSR[22]	**EU ETS design**: new mechanism with pre-defined rules addressing the high surplus of allowances. Depending on the total number of allowances in circulation (TNAC), allowances get placed in the reserve or released from the reserve. However, as all certificates are to be released in the long term, this reform implies NO tightening of the intertemporal emission cap and thus had little impact on market prices.
Oct. 2016	Ratification of the Paris Agreement[23]	EU climate policy: all parties (including the EU) having adopted the Paris Agreement are required to submit an NDC till 2020, outlining their post-2020 climate actions.
Feb. 2017	'**MSR reform**' Proposal of ETS/MSR reform for trading period IV (2021–2030)—strengthening the MSR and tightening ETS targets[24]	**EU ETS design**: Parliament and Council formulate their ETS/MSR reform proposals. Council proposes automatic cancellation of certificates in the MSR above a threshold.
Nov. 2017	'**MSR reform**' Final agreement on ETS/MSR reform for trading period IV (2021–2030)[25,26]	**EU ETS design:** after six trilogues, Commission, Parliament and Council reach an agreement on the ETS/MSR reform. Tightening of the cap: linear reduction factor of allowances (in percentage points of 2005 cap) increases from 1.74 to 2.2. Strengthening of the MSR: higher intake and certificate cancellations from 2024 on.
March 2018	**'MSR reform'** ETS/MSR reform for trading period IV (2021–2030) officially adopted[27]	**EU ETS design:** directive with the ETS/MSR reform officially published.
Dec. 2019	Presentation of the European Green Deal[62]	EU climate policy: EU Commission presents EU's new climate action strategy including the goal of climate neutrality in 2050 and an emissions reduction of 50–55% until 2030, compared with 1990 levels.
March 2020	Proposal for a European Climate Law[63]	EU climate policy: EU Commission presents legislative proposal of a law setting the objective for the EU to become climate neutral by 2050.
Sept. 2020	Proposal to set an EU-wide 55% emissions reduction target for 2030[64]	EU climate policy: EU Commission amends the Climate Law proposal by introducing the updated 2030 climate target of a net reduction of at least 55% of EU's greenhouse gas emissions compared with 1990 levels.
Dec. 2020	The Council agrees on the 55% reduction target for 2030[65]	EU climate policy: The Council of the EU reaches an agreement on an approach on the climate law proposal, including an agreement to the updated 2030 climate target of a net reduction of at least 55% of EU's greenhouse gas emissions compared with 1990 levels.
April 2021	Final agreement on Climate Law[66]	EU climate policy: Parliament, Council and Commission agree in trilogue negotiations on the −55% 2030 reduction target, enabling the formal adoption of the Climate Law in June 2021.
July 2021	'**Fit for 55' package**[54,67]	**EU ETS design:** EU Commission publishes package of legislative proposals to meet the 2030 emissions reduction target of 55%. For the EU ETS it includes: steeper annual emission reductions, strengthening of the MSR, gradual removal of free allowances for the aviation sector and the inclusion of the maritime sector into the current EU ETS.
Dec. 2022	Agreement on EU ETS '**Fit for 55**' proposal[39]	**EU ETS design:** Parliament, Council and Commission reach final agreement during trilogue negotiations on the EU ETS 'Fit for 55' proposal. Ambitions are kept high: all main elements from the initial proposal remain; the emissions cap gets slightly more tightened compared to the initial proposal.

Highlighted in bold are events directly affecting the EU ETS design.

goals. However, the question arises: are these changes principally reversible? In particular, could credibility plummet again, implying that actors return to myopic behaviour? If yes—why? And what would it mean for carbon prices and the energy transition?

A look into the future

The previous section has shown that the recent rise in ETS prices does not result from an acute scarcity of allowances—as their surplus is still vast—but can rather be explained by market actors having turned more farsighted. A plausible interpretation is that this was due to the long-term cap becoming considerably more credible. This may suggest that from this point on, ETS prices would only increase. However, what would happen if policy credibility gets shaken again due to a crisis or political backlash? How much would prices plummet and what would it imply for the energy transition? This is what we analyse in the following with a scenario considering a shock—for illustrative purposes—in 2025.

Before turning to numerical results, to underpin our motivation for analysing a shock scenario, we develop a conceptual model on how policy credibility, actors' foresight and carbon prices influence each other (Fig. 5). The left side schematically represents the events from 2017 to 2021. It starts from a state with low policy credibility due to the huge certificate surplus, myopic market actors and ensuing low carbon prices. Then, the MSR reform and the higher ambition in the 'Fit for 55' package substantially strengthened the policy credibility and set in motion a reinforcing cycle: actors extend their foresight horizon, which in turn increases carbon prices, which (1) may increase the policy credibility and (2) attracts non-compliance actors to the market with at least partially more long-term investment strategies.

The right side shows a path, how the current situation could unravel again: a price shock or a crisis and the ensuing political reactions could potentially reduce policy credibility and trigger a relapse into myopic behaviour and hence lower prices. The recent energy crisis serves as an illustrative example: the tenfold increase[36] of European gas prices in 2022 put pressure on the EU ETS from several directions.

First of all, rising energy prices created strong liquidity problems for many firms[37]. Under liquidity problems, firms might sell assets not required in the short-term—such as banked CO_2 certificates, which could decrease prices and scare away external investors. Secondly, the rising energy prices directly created pressure to weaken climate policies. As an example, Poland repeatedly proposed to freeze

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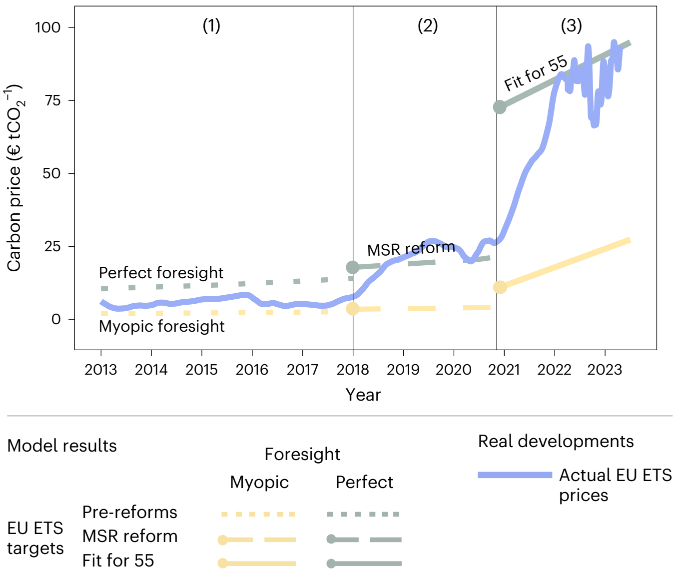

Fig. 3 | Impact of reforms and actors' foresight on carbon prices. Historical carbon prices on the EU ETS and modelled carbon price trajectories with the assumption of either perfect or myopic foresight over the three periods (1)–(3) as defined in Fig. 1. For each period, we show the carbon price trajectories required to reach the target that was valid during that period. Thus, jumps in same-coloured trajectories between one period and the next show the effect that the change in the ETS targets and MSR parameters has under unchanged actor foresight. Myopic foresight corresponds to a rolling foresight horizon of ten years (Methods provide underlying model assumptions). Historical prices are historical allowances (EUA) prices on the EEX spot market[2,68]. The mean average percentage error between modelled and historical prices is available in Extended Data Table 1. The interaction between the foresight horizon and the MSR is shown in Extended Data Fig. 1. Prices are nominal until 2023 and real EUR2023 from 2023 on (Methods 'Carbon prices').

carbon prices at €30 tCO_2^{-1} (ref. 29) or even temporarily suspend the EU ETS[38]. If the EU were to give in to such proposals, it would decrease its long-term policy credibility, and hence, following our hypothesis, compliance actors' foresight. Given the trilogue results in late 2022[39], it appears the European Union managed to overcome this critical situation without weakening the ETS and undermining its long-term policy credibility.

Nevertheless, the future remains uncertain, with the energy crisis serving as just one recent illustration of potential risks. Political crisis can happen anytime and history has repeatedly shown that all policy reforms face the threat of being undone or weakened over time[40]. This emphasizes the importance of exploring the risks of undermined policy credibility and actors returning to myopia. More specifically, to safeguard against such a turn of events, it is important to quantify what would be lost in terms of price degradation, and how this would slow down the energy transition.

Figure 6 shows the price trajectory of such a 'reversal to myopia' scenario. It presumes actors were myopic in the past, became farsighted around 2020 and turn fully myopic again in 2025. Prices could then start falling, reaching a level below €30 tCO_2^{-1} in 2025. There is currently no mechanism ensuring prices stay high in the next years. Assuming such a relapse into myopia really happens and prices fall in the near future below €30 tCO_2^{-1}, what would it mean for the energy transition? The general impacts of myopic foresight in the energy sector have been studied in previous literature[41–46]. Nerini et al.[47] show using the cross-sectoral capacity expansion model UK Times that myopia might result in delayed climate action and higher total transformation costs, compared with the pathway set by a perfect foresight model. On the one hand, emissions abatement gets delayed. On the other hand, the solutions chosen are focused on the near-term, creating lock-ins and not the most efficient ones from a long-term perspective.

To illustrate the delayed action, we focus on the electricity sector. The major problem we identify under the relapse to myopia is that, as seen in Fig. 7, delayed investments into wind capacity in turn delay the phase-out of coal power generation. As illustrated in Fig. 7a, our modelling shows that myopia could massively slow down wind capacity expansion in the next ten years, with yearly investments reduced by a factor of three, compared with the cost-optimal (that is, perfect foresight) trajectory. The missing wind power in combination with low carbon prices would strongly delay the phase-out of coal (Fig. 7b).

These risks are examples of what can happen in the electricity sector. Any delay poses the risk of climate targets becoming out of reach or being reachable only at very high costs, as feasible roll-out rates can be limited, for example, due to the availability of skilled workers or production capacities[48]. Likewise, the required steeper carbon price in the long-term might increase the likelihood of a political backlash that dismantles the policy[49]. Hence, it is crucial to be aware that carbon prices could principally fall again in the near future, with strong consequences for the energy transition. Exploring potentials of a price floor in the ETS, proposed in the past to address the problem of myopia[18] and designing complementary policy instruments to shore up the energy transition thus remains critical—despite currently high carbon prices.

Conclusions

This work proposes a quantitative explanation behind the observed rise in carbon prices on the EU ETS since 2017. We use a numerical model (see Methods) to simulate different foresight horizons of compliance actors and to depict the role of external investors. We show that the combination of stricter EU ETS policies and changed behaviour of compliance actors from myopic to farsighted can explain the rapid increase in carbon prices over the past years, underpinning with a quantitative analysis earlier scholarly work emphasizing the role of myopia[7,19]. Our results indicate that external investors probably only played a minor role by, for example, accelerating the price rise.

We discuss the hypothesis that policy credibility impacts actors' foresight and hence carbon prices. Consequently, a glimpse into the

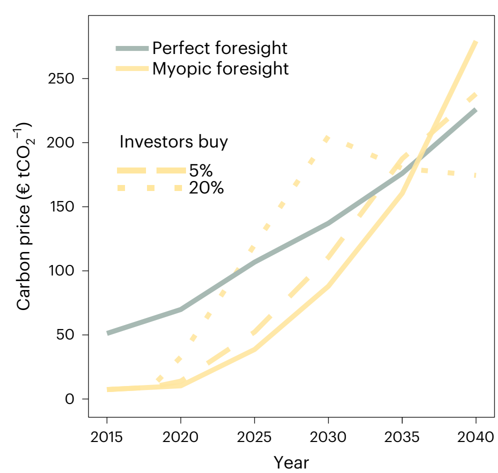

Fig. 4 | Impact of external financial investors on carbon prices. Carbon price trajectories assuming perfect foresight, myopic foresight and myopic foresight with external investors buying 5% or 20% of yearly auctioned allowances and reselling them once carbon prices reach the theoretical value from the perfect foresight path. If external investors had started buying 5% or 20% of auctioned allowances from 2018 onwards, they would own, respectively, around 10% or 40% of today's (as of 2022) total number of allowances in circulation. All trajectories correspond to newest targets from the 'Fit for 55' proposal with an active MSR. Exact assumptions on the number and timing of allowances bought and sold by external investors is available in Extended Data Fig. 2.

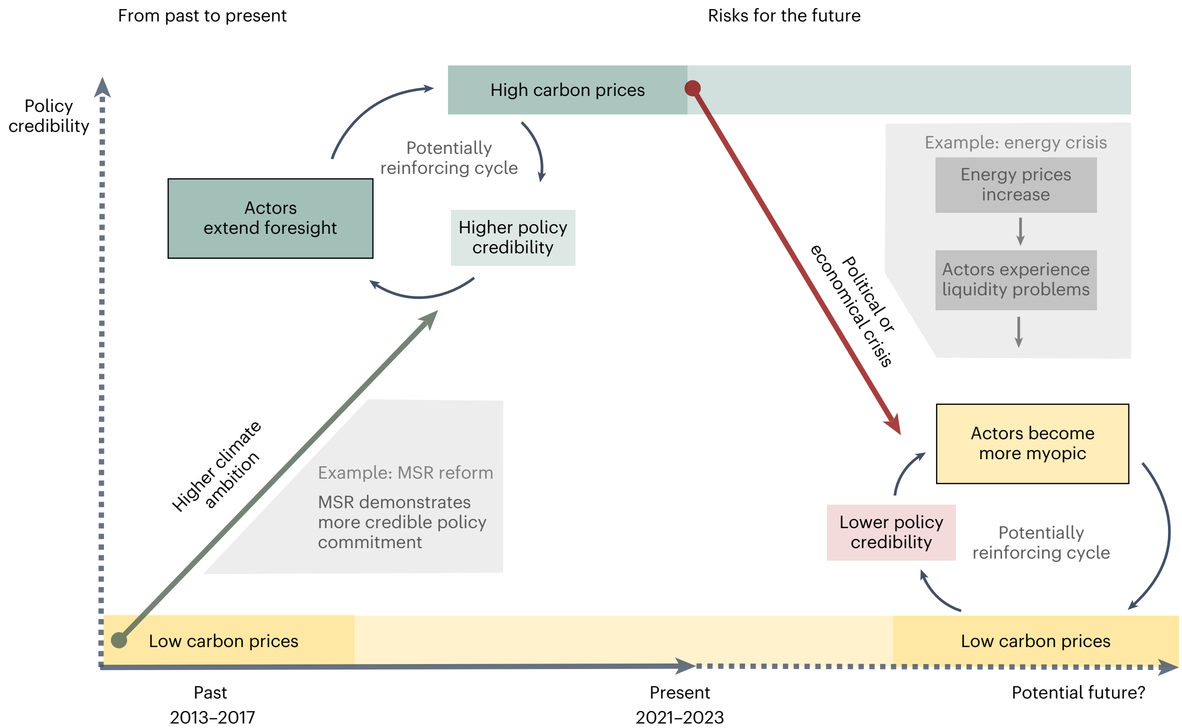

Fig. 5 | Role of actors' foresight and policy credibility in carbon price formation. A distortion from a high or low prices level can enchain a potentially reinforcing loop leading to a fall, or rise, in prices, respectively. Policy credibility plays a major role in how actors react to a distortion. The theoretical hypothesis is complemented by two examples: the introduction of the MSR as an example of increased commitment to climate targets and the current energy crisis, as an example of a potential shock. Following studies highlighting the importance of climate policy credibility for an acting private sector[13,69], we assume actors' foresight depends on policy credibility.

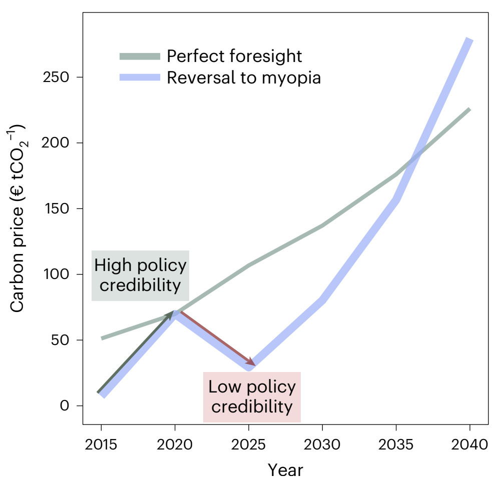

Fig. 6 | Risk of falling EU ETS prices due to undermined policy credibility. Carbon price trajectories assuming perfect foresight and reversal to myopia (that is, actors are first fully myopic, become farsighted around 2020 and then fall back fully into myopia until 2025). Both trajectories correspond to newest targets from the 'Fit for 55' proposal with an active MSR. The carbon price trajectories are complemented by the hypothesis that actors' foresight strongly depends on policy credibility.

future shows that carbon prices could fall again if actors become myopic again (for example, due to a price shock and reduced policy credibility). A fall back into myopia and low prices can threaten short-term decarbonization efforts. To prevent such a development, additional policy instruments seem advisable to stabilize expectations of agents. As an example, a price floor would limit the drop of carbon prices in the short term when long-term policy credibility is temporarily reduced and could even keep prices higher without being binding[50].

Overall, we find that observed 2022 and 2023 prices of around €80 tCO_2^{-1} are in line with EU Climate Law reduction targets and should not be artificially lowered. Compliance actors seem to trust the political commitment and act farsighted—a good sign for the reachability of EU's 2030 climate targets of the ETS sectors, if the current energy crisis and related policy reactions do not undermine this mindset.

Methods

The model LIMES-EU

All quantitative results in this work are obtained using the model LIMES-EU (Long-term Investment Model for the Electricity Sector), version 2.38. LIMES-EU is a linear optimization modelling framework that simultaneously determines cost-minimizing investment and dispatch decisions for generation, storage and transmission technologies in the European electricity sector. Although its clear focus is the electricity sector, the energy-intensive industry and district heating are also represented through marginal abatement cost curves. Compared with simple emissions trading models with static exogenous cost abatement curves, using an energy system model such as LIMES-EU allows to assess not only market developments (for example, prices or allowances in circulation) but also the investment dynamics and path dependencies within the electricity sector.

LIMES-EU allows to fully simulate the EU ETS including the Market Stability Reserve (MSR)[51]. Hence, one can analyse figures such as the number of allowances in circulation, the intake by the MSR and resulting carbon prices. By varying the cap and MSR parameters, one can reproduce the state of the EU ETS between different political reforms.

A comprehensive description of the LIMES-EU model, including parameters, equations and assumptions, is provided in the documentation available from the model's website[52].

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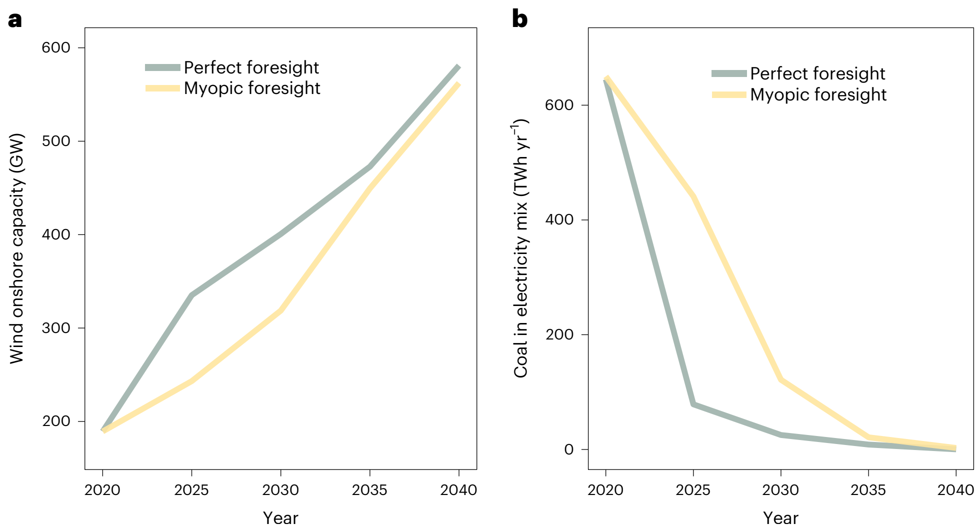

Fig. 7 | Delays in decarbonization due to myopia. a, Expansion of wind onshore capacity in the European Union under perfect and myopic foresight. **b**, Yearly electricity generation in the European Union from black and brown coal under perfect and myopic foresight. Trajectories in both **a** and **b** correspond to newest targets from the 'Fit for 55' proposal with an active MSR. Note that in both **a** and **b**, the 2020 year is fixed to match real 2020 values. Additional data (solar capacity expansion and total electricity mix) on perfect and myopic foresight scenarios can be found in Extended Data Fig. 3.

All changes to LIMES version 2.38 made for the purposes of this study are described below.

A myopic version of LIMES-EU

Rolling horizon as operationalization of myopia. Originally, LIMES-EU was formulated as a perfect foresight model running in five-year steps from 2010 until 2070. For the purpose of this study, to simulate the effect of myopic behaviour of decisionmakers, we extend the model with the option to use rolling time horizons instead of full intertemporal foresight. Mathematically this means that instead of solving one optimization problem over the whole time period from 2010 until 2070, we solve multiple (consecutive) optimization problems, covering shorter time periods.

In our choice to implement a rolling horizon, we follow several other publications from our field: the rolling horizon approach (that is, short foresight with overlapping time steps) has already been used extensively as a way to represent myopia in the context of energy systems modelling[41,43,44,47]. Although principally other approaches would be possible (for example, by varying the discount rate), we are not aware of any publication in our field representing myopia in a different manner.

Foresight length. All myopic foresight results in this work assume ten-year horizons with an overlap of five years between the horizons. Practically it means, actors have foresight of ten years but can revise their decisions every five years. As LIMES-EU runs in five-year time steps, one optimization horizon comprises always two time steps (for example, (2020, 2025), covering years 2018–2027).

The literature provides different estimations on planning horizons of manufacturing companies, ranging between three and 12 years[6]. Bocklet and Hintermayer[6] and Quemin and Trotignon[7] show that a horizon of around ten years can best replicate EU ETS developments (these analyses were conducted around the time of the MSR reform). Hence, we also chose a foresight horizon of ten years. As our model runs in five-year time steps, ten years is also the shortest foresight horizon we can meaningfully implement (that is, which allows for an overlap) in LIMES-EU. Varying the length of the foresight horizon impacts the results but not the general trends: the shorter the foresight, the lower the near-term carbon prices and higher the delays in decarbonization[47].

When running in myopic foresight, the model solves consecutively several individual optimization problems. Still, some variable values computed in one optimization horizon need to be transferred into the next optimization horizon. It concerns all previous capacity additions and decommissioning (needed to correctly compute current capacities) and emissions and banked certificates (needed for the ETS/MSR simulation). For instance, for the optimization horizon (2020, 2025) capacities will be fixed for 2020 and all time steps before 2020. We assume that dispatch decisions can still get revised every time step (five years), so for example, for the optimization horizon (2020, 2025), emissions and banked certificates values get fixed only for all time steps before 2020 but not 2020 itself.

What do actors neglect and what do they still consider. In our study, we use rolling horizons as a tool to represent actors' myopia due to low trust in the long-term stability of the EU ETS. Hence, our main aim is to depict actors that are myopic with regards to the ETS. Our modelling approach implies that actors don't consider any information outside of their ten years foresight horizon (that is, the future ETS cap and the future demand for certificates).

Nonetheless, as ETS actors are mostly large power system or manufacturing companies and salvage values ('book values') are traditionally part of companies balance sheets, we still assume that they consider the future value of capacities also beyond the foresight horizon. Therefore, a salvage value for the capacity stock remaining at the end the optimization horizon is subtracted from the cost function. In the myopic version, the salvage value is considered in each time horizon. This means that when we run a diagnostic scenario where we turn off the ETS and keep technology prices constant over time, the results of the myopic mode exactly reproduce the results of the perfect foresight mode.

MSR simulation. The MSR, which is originally implemented iteratively as a loop around the main optimization problem[51], runs in the myopic model version around each time horizon.

Specific modelling aspects

Carbon prices. Reported carbon prices (in € tCO_2^{-1}) represent the marginal abatement costs in a given year, which are equal to the dual value (shadow price) associated with the banking constraint in LIMES-EU. Transaction costs are neglected. Reported historic carbon prices are nominal, so given in € of the year in which they occurred. LIMES runs in real $€_{2010}$, but all reported prices from LIMES until 2023 in this paper were converted to nominal prices until 2023, adjusted for inflation using inflation rates provided by the Organization for Economic Co-operation and Development[53]. Computed prices after 2023 are in real $€_{2023}$.

External investors. To depict external investors in our model, we assume that the impact on carbon prices of buying/holding/selling EUA futures can be approximated by the assumption, external investors buy/hold/sell physical allowances. As we are interested in long-term price developments, we focus on external investors holding long open position on EUA futures.

To model the impact of external investors, we implement a one-step iteration approach. Hence, we implicitly assume that both compliance actors and external investors can't react the other group's action.

(1) In a first instance, a LIMES-EU run with full myopic foresight without external investors is conducted.

(2) The resulting carbon price trajectory $p_{\mathrm{price,CO_2}}(t_y)$ serves as input to the optimization problem from the external investors' perspective:

$$\max_{\upsilon_{\mathrm{bought}},\upsilon_{\mathrm{sold}}} \sum_{t_y\in T} (\upsilon_{\mathrm{sold}}(t_y)p_{\mathrm{price,CO_2}}(t_y) - \upsilon_{\mathrm{bought}}(t_y)p_{\mathrm{price,CO_2}}(t_y)) \times e^{-i(t_y-t_{y_0})} \quad (1)$$

$$\mathrm{s.t.}\ \mathrm{v}_{\mathrm{bought}}(t_y) \le \alpha p_{\mathrm{auction}}(t_y) \quad (2)$$

$$\sum_{0}^{t_y} \upsilon_{\mathrm{sold}}(t_y) \le \sum_{0}^{t_y-1} \upsilon_{\mathrm{bought}}(t_y) \quad (3)$$

$$\upsilon_{\mathrm{sold}}(t_y) \le \gamma \sum_{t_y\in T} \upsilon_{\mathrm{sold}}(t_y) \quad (4)$$

Equation (1) is the profit function: external investors want to maximize their profit by buying allowances and selling them at a later time step t_y. Herein, $t_y \in [2018, \ldots, 2040]$ are yearly time steps. T is the set containing all yearly steps part of the optimization. Further, $\upsilon_{\mathrm{bought}}(t_y)$ and $\upsilon_{\mathrm{sold}}(t_y)$ stand for the number of allowances bought and sold in time step t_y. The profit gets discounted by discount rate i. We assume $i = 5\%$, same as in the core model assumptions of LIMES-EU. Finally, $p_{\mathrm{price,CO_2}}(t_y)$ corresponds to the carbon price from a myopic run, which grows at a higher rate than the discount rate of 5%.

Equation (2) sets a limit on the number of allowances external investors can maximally buy. Herein, α is the share of auctioned allowances $p_{\mathrm{auction}}(t_y)$. We assume p_{auction} to be the final number of allowances auctioned, after subtraction of allowances transferred into the MSR. In our work, α is varied between 5 and 20%. Equation (3) ensures the number of allowances sold is below the number of allowances external investors bought prior to time step t_y.

Finally, equation (4) limits the number of allowances that can be sold in a given time step t_y, to prevent all of them being sold in a single year. Results assume an γ of 0.2, meaning allowances need to be sold over minimum five years.

(3) Having solved the optimization problem from the perspective of external investors, one can now conduct a new LIMES-EU run with full myopic foresight and additional input on the number of allowances blocked by external investors.

$$p_{\mathrm{investors}}(t) = \upsilon_{\mathrm{bought}}(t) - \upsilon_{\mathrm{sold}}(t) \quad (5)$$

$$\upsilon_{\mathrm{tnac}}(t) - \upsilon_{\mathrm{tnac}}(t-1) = p_{\mathrm{cap}}(t) - p_{\mathrm{investors}}(t) - \upsilon_{\mathrm{emi}}(t) \quad (6)$$

Here $p_{\mathrm{investors}}$ is the absolute number of allowances bought or sold by external investors. These influence the level of allowances, as shown in equation (7). Here $\upsilon_{\mathrm{tnac}}(t)$ is the total number of allowances in circulation (TNAC) at the end of time step t, $p_{\mathrm{cap}}(t)$ the total number of allowances auctioned and freely allocated and $\upsilon_{\mathrm{emi}}(t)$ the total emissions in time step t. Here $t \in [2010, 2015, \ldots, 2040]$ are five-year time steps.

To capture the unpredictability of external investors on the price formation, we assume compliance actors can't see the realization of $p_{\mathrm{investors}}(t)$ before time step t. Hence, even though they have a foresight of ten years regarding all other model inputs, they only have a foresight of one LIMES-EU time step (five years) when it comes to $p_{\mathrm{investors}}(t)$.

It is important to note that the way our approach is implemented, external investors behave as farsighted actors and have incentives to enter the market, only if compliance actors are myopic (carbon prices initially lower than under the perfect foresight scenario). Hence, all results showing the impact of external investors presume myopic foresight from compliance actors.

As we conduct only one iteration, we implicitly assume that external investors plan all their future behaviour only once and base it on myopic carbon prices. In the real world, there is a constant feedback between prices and investors' buying/selling strategy. Hence, our methodology does not aim to provide realistic predictions regarding possible behaviour of external investors. It is, however, suitable to show the order of magnitude of the increase in carbon prices, assuming external investors block a certain number of certificates.

Future. In the 'Reversal to myopia' scenario from Fig. 5b, similar to the full myopic version, several consecutive optimization problems with ten years foresight horizons are solved, with the exception that the horizon [2020, 2025] gets replaced by [2020,…, 2070] to simulate perfect foresight in time step 2020. Afterwards, from time step 2025 on, actors have again only myopic foresight.

MACC curves representing industry and heating sectors. As described in the LIMES-EU Documentation[52], the industry and heating sectors are not modelled explicitly in LIMES-EU, but the cost of emissions abatement is approximated by marginal abatement cost curves (MACCs). Originally, as they have been designed for runs starting in 2020, both MACCs assumed a minimum cost of €8 tCO_2^{-1}, being a well-suited assumption for benchmark modelling, in which modelled carbon prices always exceed €8 tCO_2^{-1} for relevant ETS scenarios. As in this work certain counterfactual scenarios yield prices below €8 tCO_2^{-1}, we extrapolate the MACC curves to also cover the price regime of €0–8 tCO_2^{-1} by analysing the change in industry and heating emissions upon implementation of the ETS. We thus estimate two additional emissions steps of 45 Mt CO_2 in industry and 15 Mt CO_2 in heating that would be emitted additionally compared to historic industry/heating emissions when ETS prices remain below €5 tCO_2^{-1} and again when they remain below €3 tCO_2^{-1}.

Scenarios

Modelling assumptions regarding calibration, policy targets and technology costs. The key assumptions behind our study's main scenario types are summarized in Extended Data Table 3. In Fig. 3, we align scenarios with historical conditions as closely as possible, adjusting variables such as ETS modelling start year and technology cost assumptions. Due to the five-year time steps in our model, complete historical replication and path dependency coverage may be limited (for example, 'Fit for 55' scenario starts in 2018).

For Figs. 4, 6 and 7, we exclusively use the 'Fit for 55' scenario, representing the current EU ETS state. This simplification serves the purpose of preventing information overload, aligning with the figures' primary objective. In Fig. 6, we extrapolate our results to 2015.

'Fit for 55' Commission's proposal vs final agreement. Extended Data Table 4 summarizes the relevant parameters used in this study defining the emissions cap and MSR functionality for the ETS state between different reforms.

All results in this study related to ETS targets from the 'Fit for 55' package assume parameters from the Commission's proposal published in July 2021[54]. As this study takes into account real ETS prices until December 2022, it is plausible to assume that until then market actors were basing their decisions on the Commission's proposal, not being aware yet of the upcoming changes in the final negotiations.

For completeness reasons, we provide a comparison of modelled carbon prices according to the emissions cap from the Commission's proposal (used in this study) and according to the emissions cap from the final ETS 'Fit for 55' agreement[39,55] in Extended Data Fig. 4. The emissions cap corresponding to the final agreement can be found in Extended Data Table 2.

Model validation

General modelling choices, for example, the clustering approach and the representative days choice, are described in the LIMES-EU model documentation. Here we present additional validation points for the scenarios presented in this study. First, we show that our model can approximate historical developments in 2015 and 2020. Then, we provide references demonstrating that our future estimates for the EU ETS align with other literature.

Reproducing historical developments in time step 2015. The capacity spin up of LIMES-EU is fixed so that it matches the 2015 historical mix of installed generation capacities in EU ETS countries. Extended Data Fig. 5 illustrates that based on this standing capacity, the model-calculated dispatch then reasonable matches the historic power generation dispatch in EU ETS countries. The total modelled emissions from electricity generation in the year 2015 for EU ETS countries covered by LIMES-EU amount to 981 Mt CO_2, closely aligning with the historical emissions of 967 Mt CO_2 reported by Mantsos et al.[56] Because emissions from industry, heating and aviation are also calibrated to match their historical 2015 levels (as described in LIMES-EU documentation[52]), this calibration ensures that our model generates meaningful values for total emissions in the 2015 time step. Also, the model-endogenous investments in 2015 lead to standing capacities in 2020 that match historic wind and solar capacities in 2020. To this aim, we additionally assume subsidies for electricity generated from solar or wind sources (€0.04 kWh^{-1} for solar and €0.015 kWh^{-1} for wind) to represent the various renewable subsidies that were in place in most EU member states. Our model, however, underestimates the capacity additions of offshore wind until 2020, which took place mostly in the United Kingdom.

Reproducing historical developments in time step 2020. To validate the 2020 model results, we first fix capacity spin up so that our model matches the installed generation capacities for both 2015 and 2020 in EU ETS countries. In Extended Data Fig. 6, we show that this calibration enables our model to approximate EU-wide dispatch and total emissions from the electricity sector in 2020. It's important to note that our model operates in five-year steps, with time step 2020 representing the actual years 2018–2022. However, due to the exceptional circumstances of the COVID-19 pandemic, the year 2020 deviates from the typical trends of 2018–2022. Hence, to validate time step 2020, we provide real values for the years 2019 and 2020.

With respect to electricity dispatch, our model estimates lower generation from biomass compared with the International Energy Agency (IEA) historical data. This discrepancy may be attributed to several factors, including our reliance on the European Network of Transmission System Operators for Electricity (ENTSO-E) dataset for total capacities, whereas using the IEA dataset for generation values (as ENTSO-E lacks a Statistical Factsheet covering generation for the years 2019 and 2020). Differences in values from different sources can often be substantial. Regarding biomass, variations may be due to, for example, the way biomass co-firing in coal power plants is accounted for. Nevertheless, despite minor deviations in our 2020 electricity dispatch from historical data, our model still provides a meaningful estimate of emissions. This aspect is critical for validating EU ETS models, as it directly impacts CO_2 prices, the total number of allowances in circulation and the functioning of the MSR.

Estimating future developments. While validating future projections is inherently impossible, we observe that LIMES-EU generally aligns with findings in the literature and does not produce results that are far outliers compared with other models. Osorio et al. discuss that LIMES-EU's estimates of MSR cancellations are consistent with other studies[51]. Furthermore, a recent model comparison study led by Henke et al. revealed that LIMES-EU's projections for various EU electricity sector variables from 2020 to 2050, such as final energy demand and the share of renewable energy sources in electricity generation, are in line with the range provided by ten other energy systems and integrated assessment models[57]. In another model comparison study assessing EUA prices until 2030, LIMES-EU's estimate of €140 tCO_2^{-1} falls within the range of €80 to €160 tCO_2^{-1} produced by six different models[58].

Methodological contribution

Whereas the primary focus of this work lies in providing insights for the ongoing debates surrounding the EU ETS, we also make a notable methodological contribution. There have been other studies using EU ETS models that explicitly simulate the electricity sector[33,59,60], and there have been energy systems analyses using myopic energy system models[41,43,44,47]. Also Nerini et al.[47] pioneered the idea to compare myopic and perfect foresight modes of a capacity expansion model to formulate more robust policies. Our study extends their approach and employs both types of foresight to evaluate ex post a concrete policy reform to test whether the change in the observable variable—in our case, the EU ETS price—can better be reproduced in the myopic or perfect foresight mode.

Data availability

Data for core model assumptions (investment costs, fuel costs and so on) are provided in the LIMES-EU documentation (Methods). The dataset containing all results displayed in this paper is publicly available via Zenodo at https://doi.org/10.5281/zenodo.10363561 (ref. 61).

Code availability

The LIMES-EU model code is available upon request from the authors. Moreover, a process has been started to make the model available under an open-source license. When this process will be completed, the code will be available for download from the PIK webpage at http://pik-potsdam.de/limes.

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Author contributions

R.P. and G.L. suggested the research question. J.S. and R.P. jointly conceived and designed the study in consultation with S.O. and G.L. J.S. extended the model, conducted scenario runs and created visualizations. J.S., R.P., M.P., G.L. and S.O. interpreted the results. J.S. wrote the manuscript with contributions from R.P., M.P., S.O. and G.L.

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Competing interests
The authors declare no competing interests.

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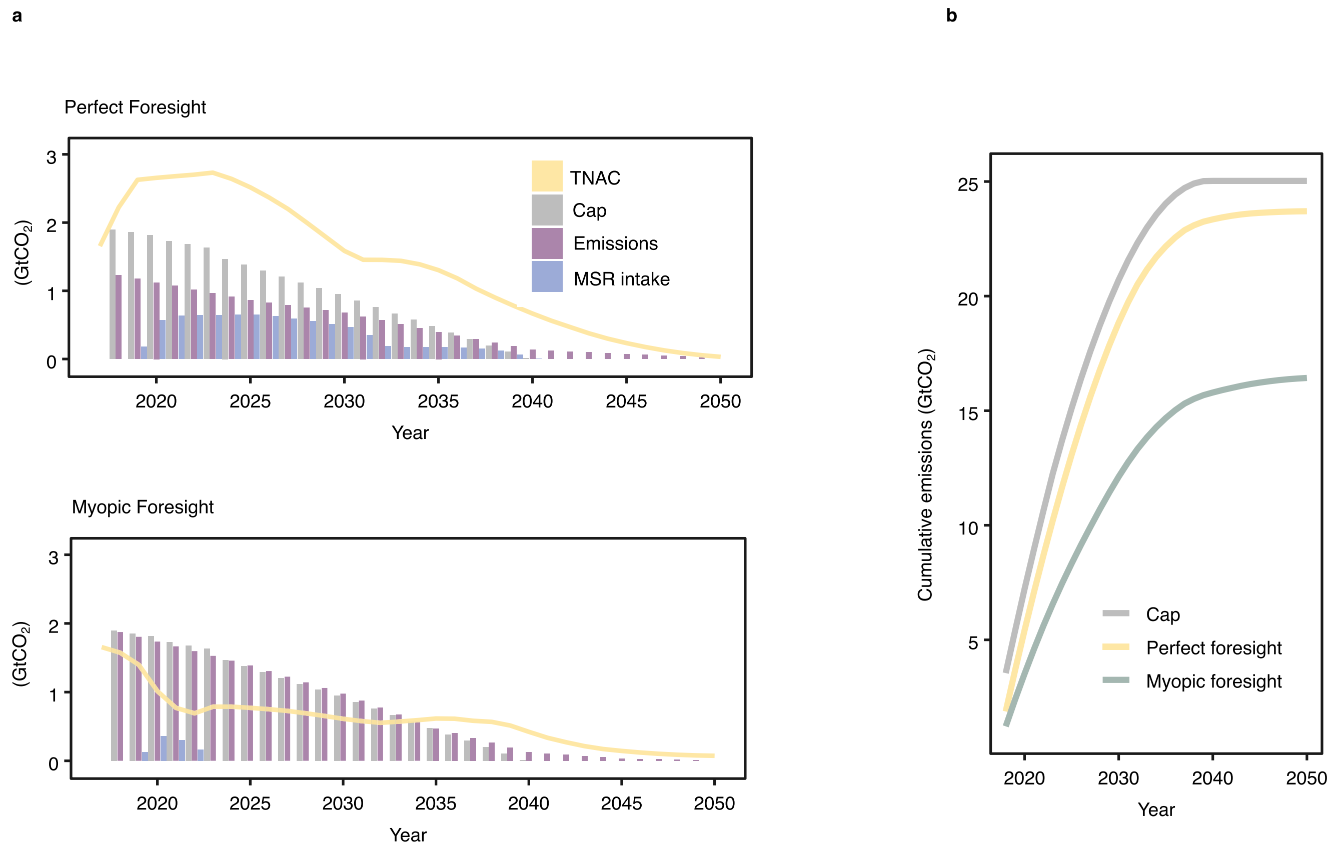

Extended Data Fig. 1 | Interactions between foresight horizon and MSR. a, Total number of allowances in circulation (TNAC), theoretical cap (allowances to be freely allocated and auctioned before accounting for MSR intake or outtake), total emissions, allowances taken in by the MSR for both perfect and myopic foresight. **b**, Cumulative emissions over transformation period for perfect and myopic foresight. The difference between cumulative theoretical cap and cumulative emissions corresponds to total number of allowances cancelled by the MSR. All results in this figure complement Fig. 3 and correspond to runs with newest targets from the 'Fit for 55' proposal with an active MSR.

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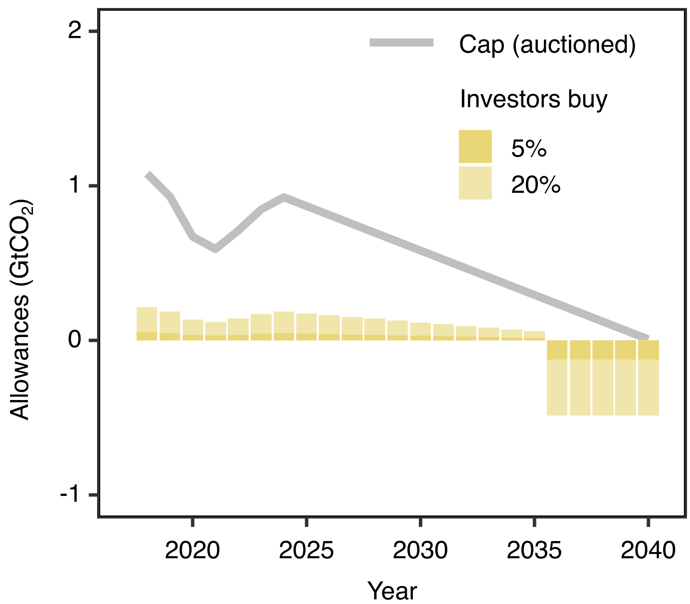

Extended Data Fig. 2 | Optimization problem from external financial investor's perspective. Investors optimize their profit till 2040 by buying up to 5% or 20% of yearly's auctioned allowances and reselling them later. Obtained buying and selling strategy corresponds to assumption on external investors from Fig. 4. Before entered to the LIMES-EU model, all values are transformed to 5-year time steps. Cap trajectory corresponds to allowances auctioned, assuming an MSR intake deducted from cap in years 2019–2023, as seen in Extended Data Fig. 1 (myopic foresight).

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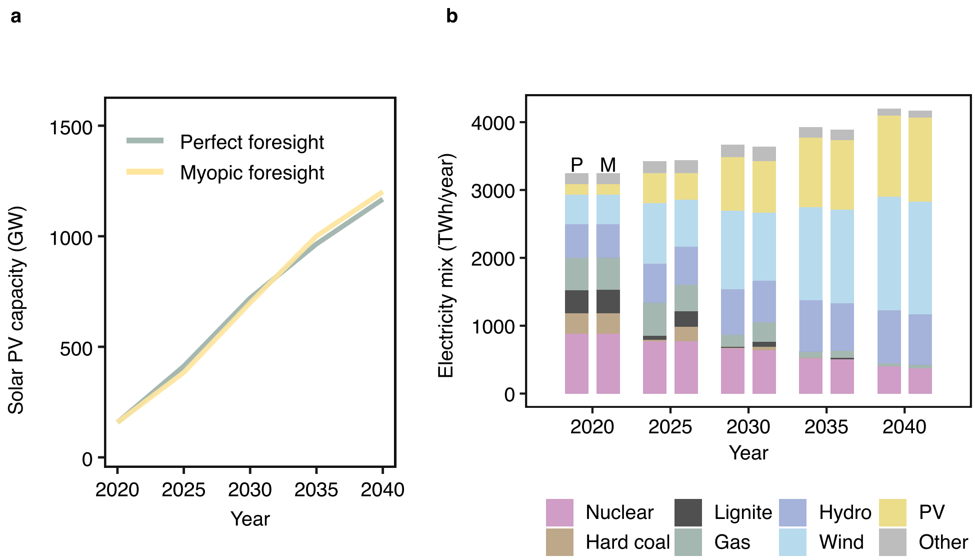

Extended Data Fig. 3 | Delays in decarbonization due to myopia. All results in this figure complement Fig. 7 and correspond to runs with targets from the 'Fit for 55' proposal with an active MSR. **a**, Expansion of solar capacity in the EU under perfect and myopic foresight. **b**, Total electricity mix. P: perfect foresight, M: myopic foresight.

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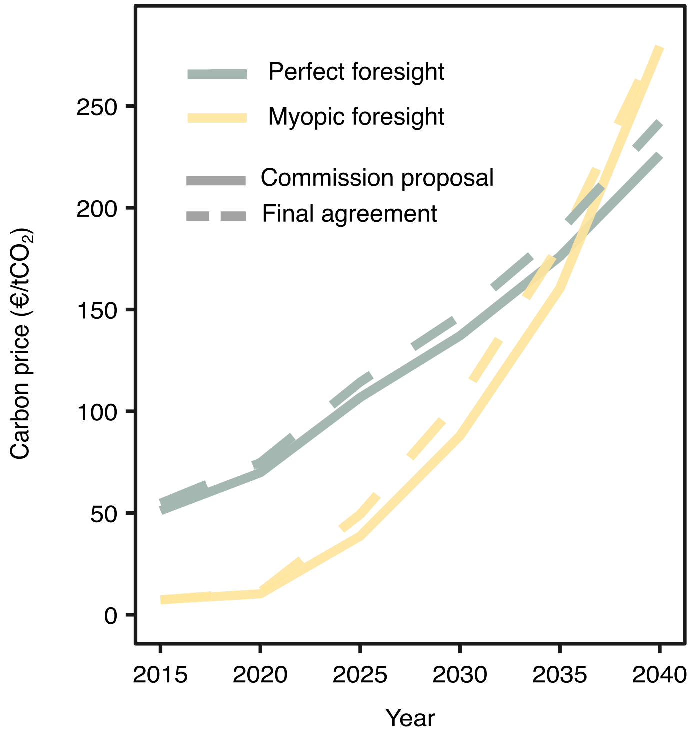

Extended Data Fig. 4 | 'Fit for 55' Commission proposal vs. Final agreement. Carbon prices corresponding to targets from the Commission's proposal (used throughout the whole study) and carbon prices corresponding to targets from the final agreement after trilogues. All scenarios include the MSR.

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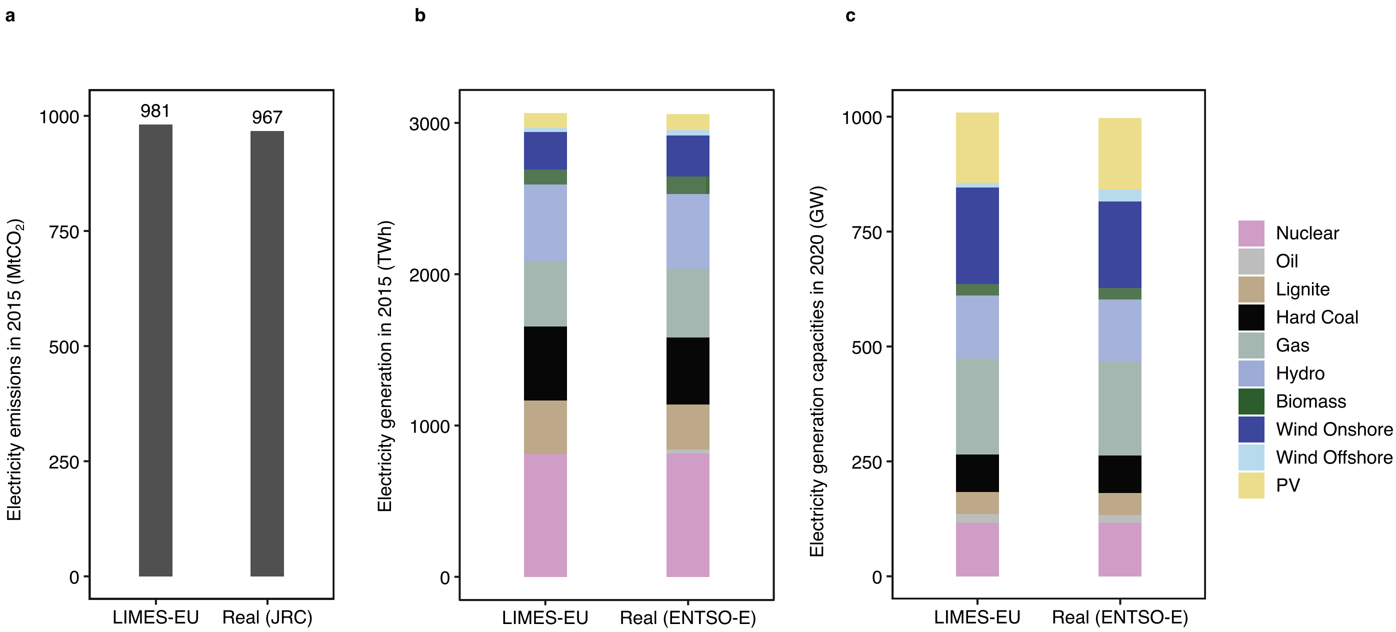

Extended Data Fig. 5 | Comparison of 2015 model results with historical data. Scenario: myopic foresight, EU ETS pre-MSR reform. **a**, Emissions from electricity generation in year 2015. Real emissions from the Joint Research Center (JRC) Dataset IDEES[56]. **b**, Electricity dispatch in 2015. Real dispatch from ENTSO-E Power Statistics[70]. **c**, Planned capacities for year 2020. In myopic mode, the model takes this investment decision in time step 2015, hence the 2020 generation capacities serve to validate decisions in time step 2015. Real capacities from ENTSO-E Transparency Platform[71]. All results for EU ETS countries (EU28 and Norway).

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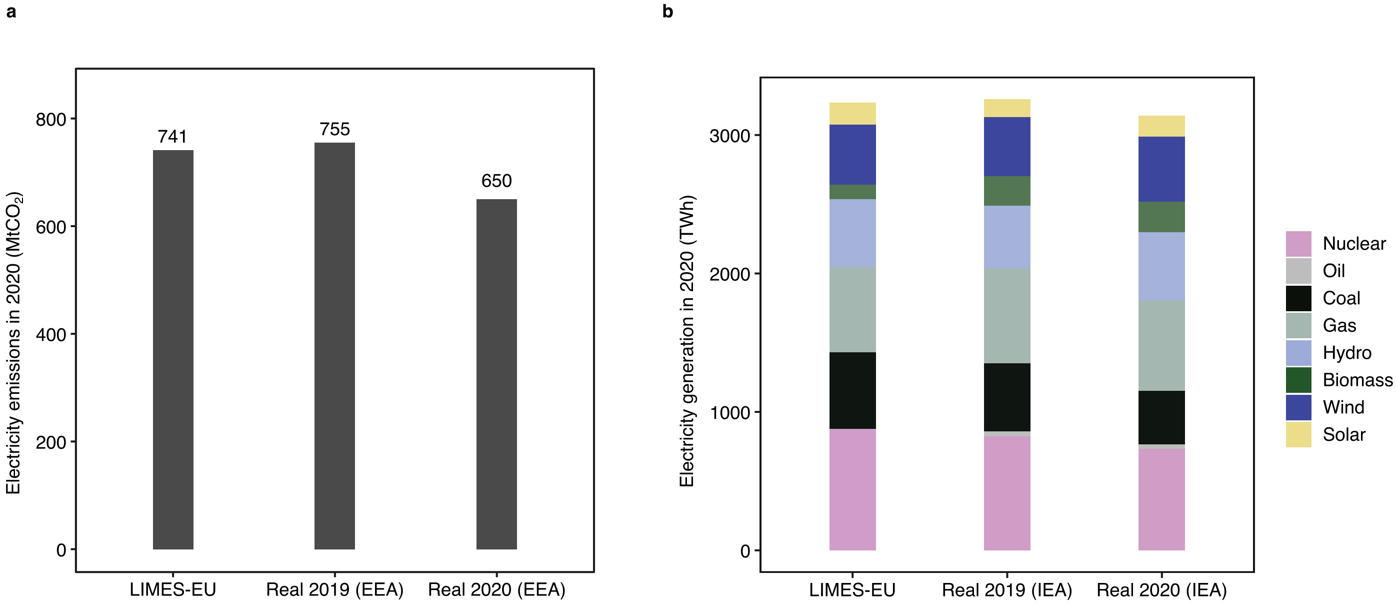

Extended Data Fig. 6 | Validation of historical time step 2020. Scenario: perfect foresight, EU ETS post-MSR reform. **a**, Emissions from electricity generation in year 2020 and 2019. As we are not aware of a data source providing 2019 and 2020 emissions for the electricity sector, we estimate real electricity sector emissions by taking EEA ETS emissions data for 'combustion of fuels' and assuming that electricity generation accounted for 79% of this (in 2015, emissions from electricity generation reported by the JRC constituted 79% of emissions from 'combustion of fuels' reported by the EEA). **b**, Electricity dispatch in 2020. Real dispatch from IEA dataset[72,73]. All results for EU ETS countries (EU28 and Norway).

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Extended Data Table 1 | Mean absolute percentage error (MAPE) of modeled CO2 prices assuming myopic or perfect foresight

Period	(i) Jan 2013 – Dec 2018	(ii) Jan 2018 – Sept 2020	(iii) Oct 2020 – July 2023
Modeled EU ETS	Pre-reforms	MSR reform	Fit for 55 reform
Myopic Foresight	**0.58**	0.8	0.8
Perfect Foresight	1.15	**0.25**	**0.38**

This table supplements Fig.3 by providing values of the MAPE error between modeled CO2 prices and real historical EUA prices. Highlighted in bold are the runs with the lower MAPE, hence lower error compared to real historical EUA prices. MAPE is calculated as the average absolute percent difference between two numeric vectors[73].

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Extended Data Table 2 | Differences in EU ETS caps and MSR parameters between 'Fit for 55' initial proposal and final agreement

Parameter	(i) Commission's proposal "Fit for 55"	(ii) Final agreement "Fit for 55"
Target 2030 with respect to 2005	-61 %	-62 %
Linear reduction factor (*LRF*)	4.2 % (Rebasing of 117 Mio [not specified, assumed in 2024])	4.3 % from 2024-27 and 4.4 % from 2028 onwards (Rebasing, of 90 Mio in 2024 and 20 Mio in 2026)
Cancellation mechanism	Only after 2023: Cancellation defined as the difference between MSR level and the EUA volume auctioned the previous year	Only after 2023: Cancellation defined as the difference between MSR level and 400 Mio
Free certificates	No specified but intended to remain at ~43% of the cap	Path defined and to be phased out by 2034

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Extended Data Table 3 | Modeling assumptions across different scenarios

Scenario	Figure(s)	ETS state	ETS modeling running from	Technology costs	Calibration
1.	3	Pre-reforms	Time step 2015 (= real year 2013)	Future capex costs of solar and wind generation technologies based on LIMES-EU documentation from year 2014[74].	> Electricity generation capacities fixed for time step 2015 > TNAC value fixed prior to time step 2015
2.	3	MSR reform	Time step 2020 (= real year 2018)	Future capex costs of solar and wind generation technologies based on the average of 2014[74] and current[52] LIMES-EU documentation.	> Electricity generation capacities fixed for time steps 2015 and 2020 > TNAC value fixed prior to time step 2020
3.	3, 4, 7	"Fit for 55" proposal	Time step 2020 (= real year 2018)	Future capex costs of solar and wind generation technologies based on current[52] LIMES-EU documentation.	

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Extended Data Table 4 | Parameters used in this study representing the state of the EU ETS between different reforms

<table>
<tr><th>Parameter</th><th>Pre-reforms</th><th>MSR reform</th><th>“Fit for 55” proposal</th></tr>
<tr><td>Linear reduction factor

(LRF)</td><td>1.74 %</td><td>2.2 %
(from trading phase 4 on starting in 2021)</td><td>4.2 %</td></tr>
<tr><td>Additional measures</td><td>'Backloading', of 900 Mio EUAs between 2014-2016</td><td>-</td><td>'Rebasing', of 117 Mio EUAs
(not specified, assumed in 2024)</td></tr>
<tr><td>EUA intake</td><td>-</td><td>When TNAC > 833 Mio:
▪ Intake is 24 % of TNAC until 2023
▪ Intake is 12 % of TNAC after 2024</td><td>When TNAC > 1096 Mio:
▪ Intake is 24 % of TNAC until 2030
▪ Intake is 12 % of TNAC after 2031
When 1096 > TNAC > 833 Mio:
▪ Intake is TNAC – 833 Mio</td></tr>
<tr><td>EUA outtake</td><td>-</td><td colspan="2">When TNAC < 400 Mio:
▪ 200 Mio until 2023
▪ 100 Mio after 2024</td></tr>
<tr><td>Cancellation mechanism</td><td>-</td><td>Only after 2023: Cancellation defined as the difference between MSR level and the EUA volume auctioned the previous year.</td><td>Only after 2023: Cancellation defined as the difference between MSR level and 400 Mio.</td></tr>
</table>