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On the time-dependency of MAC curves and its implications for the EU ETS[☆]

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Abstract

Recently, several articles rely on marginal abatement cost (MAC) curves to analyze the EU ETS. While the assumptions on MAC curves drive the results, the prevailing literature on the EU ETS does not take the shape of MAC curves into account. This paper discusses the implications of MAC curve properties for the EU ETS. With a partial equilibrium model of the European power sector, we derive two essential properties of MAC curves: First, the shape of MAC curves is convex and depends on economic developments, e.g., fuel prices and interest rates. Second, MAC curves flatten over time, mainly due to enlarging investment opportunities. With convex MAC curves, marginal abatement costs in the EU ETS increase over time, which triggers higher banking of firms. On the contrary, flattening MAC curves over time lead to lower incentives for banking. In particular, short-term MAC curves are steep and thus, raise the price path.

Keywords: EU ETS, Marginal Abatement Cost Curves, Emission Abatement, Power Sector Modeling.
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1. Introduction

The mitigation of greenhouse gas emissions requires a fundamental overhaul of the capital stock, i.e., investments in low-carbon technologies. The efficient coordination of investment capital is essential to minimize overall abatement costs. Economists agree that the pricing of emissions is a suitable instrument for allocating capital efficiently (e.g., Coase (1960) and Borenstein (2012)). By introducing the European emissions trading system (EU ETS), the EU has implemented a quantity control system with an endogenous price on emissions. The EU ETS requires that firms in the power sector, energy-intensive industries, and inner-European aviation submit allowances to cover their emissions. Overall, the EU ETS regulates about 40 % of total European emissions.

The latest reform of the EU ETS has introduced the Market Stability Reserve (MSR) and the Cancellation Mechanism (CM), which have fundamentally changed the EU ETS to a system with restricted banking and responsive allowance supply (cf. Bocklet et al. (2019)). A comprehensive literature strand evaluates the reforms' impact via partial equilibrium models of the EU ETS (e.g., Perino and Willner (2016) and Bocklet et al. (2019)). Most of these articles do not model allowance demand endogenously.[1] They assume allowance demand exogenously based on marginal abatement cost (MAC) curves. MAC curves match emission mitigation with abatement costs and have been crucial tools to evaluate environmental policies for decades (e.g., Jackson (1991) or Aaheim et al. (2006)).

In the EU ETS related literature, the assumptions on MAC curves are heterogeneous. While some articles assume linear MAC curves (e.g., Perino and Willner (2016) or Bocklet et al. (2019)), others use convex MAC curves (e.g., Beck and Kruse-Andersen (2018) or Schmidt (2020)). Without evidence from the literature, papers usually presume a time-independent shape of MAC curves. Nevertheless, both the shape as well as its development over time drives results. In particular, these assumptions affect total emissions in the EU ETS due to the responsive allowance supply of the EU ETS.

This paper assesses the fundamental properties of MAC curves and their implications for the EU ETS. To this end, we carry out a case study to derive stylized MAC curves for the European power sector. Multiple runs of a partial equilibrium model map carbon price paths onto emission abatement. We find that MAC curves are convex. The curvature is subject to economic developments, such as fuel prices and interest rates. Further, MAC

[1] To the best of our knowledge, Bruninx et al. (2018) present the only approach that combines power market modeling with a depiction of the EU ETS regulation.

curves are time-dependent. In the short term, they are steep since coal-to-gas fuel switching is the only abatement measure. With enlarging investment opportunities and technological learning, MAC curves flatten over time.

Assuming convex instead of linear MAC curves increases banking since future abatement becomes relatively more expensive. On the contrary, flattening lowers incentives for banking. Under idealized assumptions, steep short-term MAC curves shift the equilibrium price path upward while also reducing short-term banking. This effect could cause strong price reactions in the short term when market frictions such as myopia are considered. For a numerical evaluation of these effects, we propose methodological approaches to account for the time-dependency of MAC curves.

The remainder of the paper is organized as follows: Section 2 reviews the prevailing literature on MAC curves. Section 3 derives stylized MAC curves for the European power sector. Section 4 discusses the implications of the identified properties of MAC curves for the EU ETS. Section 5 concludes.

2. Prevailing Literature on MAC Curves

This section sheds light on the properties of MAC curves discovered in the existing literature. We consider quantitative evaluations as well as qualitative discussions of MAC curves.

The prevailing literature uses four methodological approaches to quantitatively evaluate MAC (compare Huang et al. (2016)): (1) Estimations based on distance functions, (2) expert-based evaluations, (3) top-down models, and (4) bottom-up models.

MAC evaluation via distance functions estimates past and present marginal abatement costs based on historical data (Ma et al. (2019)). For example, Du et al. (2015) find that the marginal abatement costs in the Chinese energy system increase over time in a convex shape. However, these historical observations do not allow statements about future MAC or the construction of MAC curves.[2]

Expert-based evaluations, e.g., performed by McKinsey & Company (2013), derive MAC curves by gathering expert knowledge on abatement costs and potentials. While revealing abatement potential even at negative abatement costs, the derived MAC curve for 2030 is convex-shaped in its positive part.

[2] In particular, observed marginal abatement costs reflect rather the part of the MAC curve with low mitigation efforts, which likely do not represent MAC for extensive emission mitigation. For a comprehensive and critical review of MAC evaluation by distance functions, the reader is referred to Ma et al. (2019).

The use of top-down models, mostly integrated assessment models, covers economy-wide activities, their interactions, and the consequences on the natural environment at a global level.[3] For the EU ETS sectors, Landis (2015) finds that MAC curves are convex in abatement.

In contrast to top-down models, bottom-up partial equilibrium models abstract from global interactions between the different economic sectors but allow for more technical details. Kesicki (2013) finds that the MAC curve of the UK energy system in 2030 is convex-shaped and robust to changes in fossil fuel prices, but depends strongly on the underlying interest rate. Delarue et al. (2010) find that short-run abatement in the European power markets depends on the carbon price as well as on the price margin between coal and gas. Van den Bergh and Delarue (2015) compare two abatement options, namely fuel-switching from coal to gas and wind investments, with a model of the central-western European power sector. They point out that MAC of the different abatement options are not additive but impact each other.

Summing up, articles with different methodological approaches consent that MAC curves are convex. However, Kesicki and Ekins (2012) generally calls for caution when interpreting MAC curves. MAC curves depend on uncertain assumptions, which are often not transparent. Further, the concept of MAC curves takes the perspective of a perfectly informed central planner who decides cost-efficiently on abatement under perfect foresight. In reality, the decisions on abatement measures depend on individual preferences. If individuals decide solely based on abatement costs and their actions are coordinated in perfect markets, the cost-efficient MAC curve of the central planner coincides with the aggregation of individual decisions on abatement measures. However, individual decision-making is subject to non-financial costs and behavioral aspects. Consequently, MAC curves of a central planner often identify abatement measures with negative abatement costs, which are not realized yet. Moreover, MAC curves are always a static snapshot in time and do not reveal what abatement measures are taken before and after the reference year. Historic abatement and expectations about future abatement drive the shape of MAC curves.[4]

[3]Most integrated assessment models use a computable general equilibrium framework to depict economic interrelations via substitution elasticities. Kuik et al. (2009) provides a comprehensive meta-analysis on the derivation of MAC curves with integrated assessment models.

[4]At the same time, today's decisions on abatement also impact future's abatement costs, e.g., due to technological learning effects.

3. Case Study: MAC curves of the European Power Sector

To illustrate the different properties of MAC curves, this section carries out a case study for the European power sector.

3.1. Methodological approach

Power market model DIMENSION

We derive MAC curves with the partial equilibrium European power market model DIMENSION.[5] By assuming inelastic electricity demand in the short term and perfectly competitive markets without transaction costs, the decision making of individual, profit-maximizing firms under perfect foresight is equivalent to a central planner's cost minimization problem. The central planner minimizes the total discounted costs of investments in power plants and their dispatch to satisfy electricity demand. Appendix A presents the most relevant equations of DIMENSION.

Approach for deriving MAC curves

To obtain MAC curves for the European power sector, we feed different carbon price paths $\boldsymbol{\tau}$ into the model and derive the corresponding level of emissions $emissions(y)_{|\boldsymbol{\tau}}$ for each considered year y. The emissions of the baseline scenario (baseline emissions) $u(y) := emissions(y)_{|\boldsymbol{\tau}=0}$ are used to define the abatement level of a carbon price path $\boldsymbol{\tau}$ as $abatement(y, \tau) = u(y) - emissions(y)_{|\boldsymbol{\tau}}$. Figure 1 sketches the methodology to derive MAC curves using the power market model DIMENSION.

We assume that carbon prices develop according to the Hotelling rule (cf. Hotelling (1931)), i.e., they rise with the interest rate.[6] The model derives MAC curves in time period t anticipating this price development for a time horizon H of 15 years.

[5]The model DIMENSION has been developed by Richter (2011) and has been used in many analyses, e.g., Bertsch et al. (2016), Peter and Wagner (2018) and Helgeson and Peter (2020).

[6]Emission allowances are a scarce resource. Rational firms with perfect foresight use allowances so that the corresponding carbon price increases with their private interest rate. Otherwise, arbitrageurs could take advantage of inter-temporal price differences. Ex-post, prices develop differently due to external shocks or new information on future costs or demand (cf. Bocklet and Hintermayer (2020)).

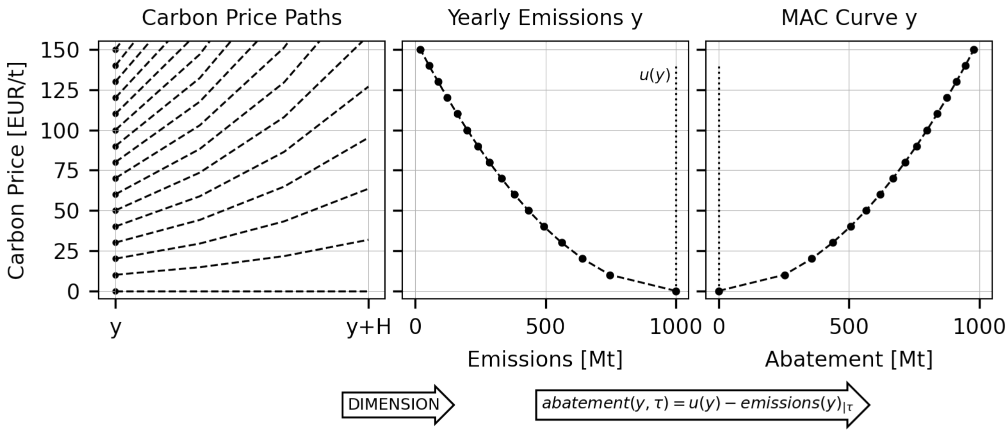

Figure 1: Schematic illustration of the approach for deriving MAC curves

Parametrization

This case study derives stylized facts on MAC curves, using the European power sector as an example. To isolate the impact of single restrictions or input parameter changes, we keep the parametrization as plain as possible. We fix the status quo of European power plants, i.e., we abstract from decommissioning due to technical restraints or political goals. We assume the existing fleet of power plants in 2019 according to the database developed at the Institute of Energy Economics at the University of Cologne, which is continuously updated based on Platts (2016), Bundesnetzagentur (2020) and ENTSO-E (2020). Net transfer capacities develop according to the ENTSO-E Ten-Year Network Development Plan 2018 (ENTSO-E (2018)). Fuel prices, investment costs, net trade capacities, and electricity demand are as of 2019. By default, we use an interest rate of 8%. Time-series rely on the historical weather year 2014. For keeping the model tractable, 16 representative days approximate the development for one year. Appendix B gives an overview of the considered technologies and their techno-economic parameters.

3.2. The Change of MAC curves over time

This section evaluates how different lead times for investment affect MAC curves. In the short term, the power plant fleet is fixed. Switching electricity generation from power plants with higher carbon intensity (e.g., hard coal or lignite) to power plants with lower carbon intensity is the only viable abatement measure (*Fuel Switching*). The existing capacity of the power plants with lower carbon intensity limits the abatement potential of fuel switching. With longer lead times, investment into generation capacities as a reaction to higher carbon prices is possible. Yet, installation capacities or necessary approval processes restrict the speed of changing the power plant fleet via investments. In the long term, freedom to invest is unrestricted. Additionally, demand can react to rising carbon prices, e.g., via investments into energy efficiency or carbon leakage.

For determining the development of MAC curves over time, we make the following stylized assumptions. In the short term, all capacities are fixed and only the dispatch of the generation portfolio can change with the carbon price. In the medium term, the expansion of RES capacities must not be higher than five times the average expansion between 2017 and 2019, reflecting investment lead times of five years. Investments into gas power plants are restricted to about 9 GW per year within the European electricity system. In the long term, investments are not restricted. Further, we assume that the development of long-term demand depends on the carbon price development.[7] Ceteris paribus, figure 2 depicts the resulting MAC curves for different time horizons and disaggregates the abatement into static fuel switching, (restricted) investment into power plants, and demand adjustment.[8]

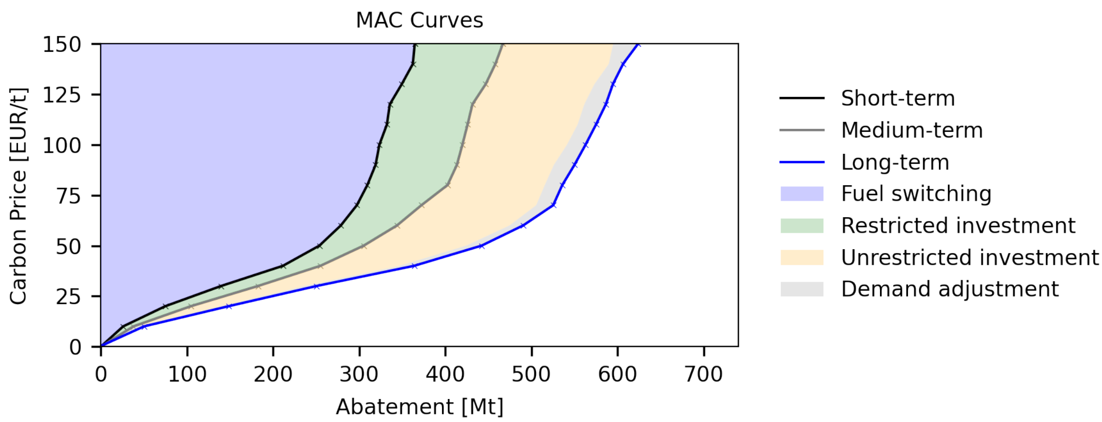

Figure 2: Short-, medium- and long-term MAC curves and disaggregation of the abatement measures

In line with the literature, MAC curves are convex independent of the time horizon. They further flatten over time, primarily due to the increasing investment possibilities. In the short run, replacing coal generation with gas-fired power plants allows to reduce emissions. The short-term MAC curve is convex since modern gas power plants drive inefficient coal

[7]We approximate the impact of rising carbon prices on electricity prices via the difference in marginal costs of modern Combined Cycle Gas Turbine Power Plants (CCGT) and assume a demand elasticity of 5 % with regard to the electricity price.

[8]Throughout this paper, the end of the x-axis depicts maximum abatement, i.e., zero emissions.

power plants out of the market already at low carbon prices. Later on, inefficient gas power plants replace modern coal generators at higher abatement costs.
Progressing in time, fuel switching is not the only abatement option but investments into modern gas power plants and particularly RES power plants are possible. As a result, the MAC curves flatten, i.e., the same carbon price results in higher abatement. While investment restrictions prevail in the medium term, unrestricted investment possibilities further flatten MAC curves in the long term. Besides developments on the supply side, adjustments of the electricity demand further bend MAC curves downward.[9]
While the MAC curves above consider variations in investment freedom and demand adjustment, the following section analyzes how developments in markets beyond the power sector (i.e., fuel prices and interest rates) or technological progress affect long-term MAC curves.

3.3. Drivers of long-term MAC curves

This section analyzes three exogenous parameters, which influence long-term MAC curves: fuel prices, interest rates, and technological learning.

Fuel prices

With regard to fuel prices, the power sector is mainly subject to the development of gas and hard coal prices. In particular, the margin between these fuels is considered a major driver. For a stylized illustration of the impact of fuel prices on the MAC curve, we compare three different levels of gas prices (10, 20, or 30 EUR/MWh_{th}, respectively), while the coal price is not varied. The variation of gas prices with constant coal prices alters the margin between coal and gas. Figure 3 depicts the corresponding MAC curves.
Lower gas prices affect MAC curves in two ways: First, gas power plants are more competitive against carbon-intensive coal generation. As a result, more abatement takes place at lower carbon prices, and the lower end of the MAC curve shifts downward. Second, investments into RES power plants are less competitive to gas power plants, since gas generation becomes cheaper. As a result, the MAC curve becomes steeper at the upper end. For higher gas prices, the same effects hold true vice versa.
The same reasoning holds with a variation of fuel prices in the short term. As there is no investment in the short term, the only effect is the altered margin of fuel switching (see Appendix C).

[9] Based on our stylized assumptions, demand adjustment is only a minor abatement measure. Whether it is more relevant in reality depends on the assumed elasticity.

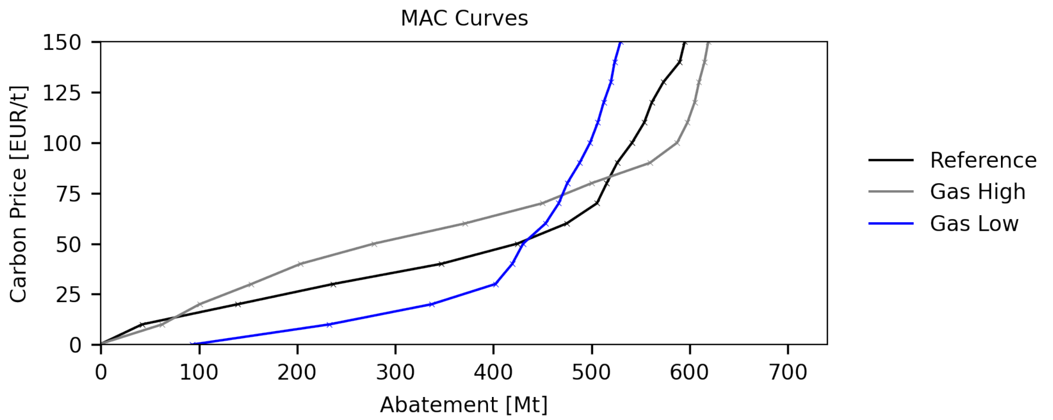

Figure 3: Long-term MAC curves for different coal/gas price spreads

Interest Rates

Apart from fuel markets, the development of financial markets affects the shape of MAC curves. The interest rate reflects the general development of financial markets, i.e., the risk-free interest rate, and the risk premium accounting for sector-specific uncertainty. Figure 4 depicts long-term MAC curves for different interest rates on long-term MAC curves.

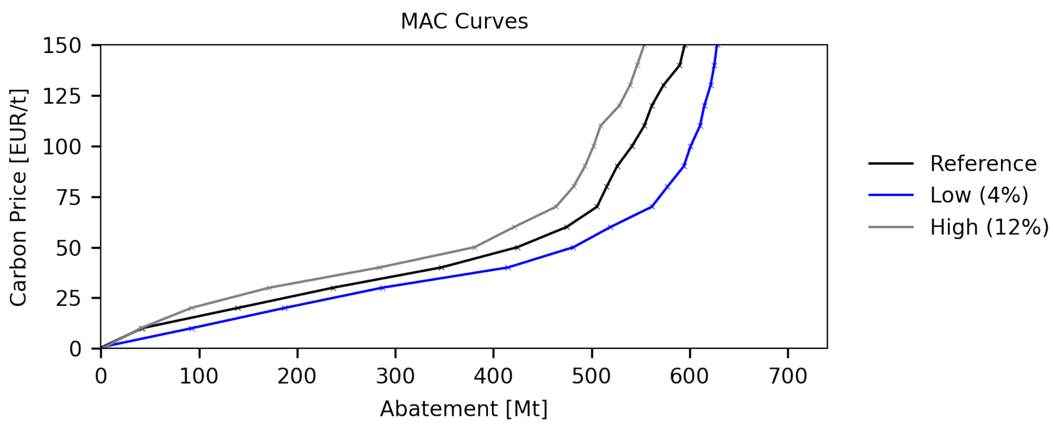

Figure 4: Long-term MAC curves for different interest rates

Interest rates primarily affect the weighted costs of capital. The transformation of the power sector requires capital-intensive installations of RES power plants. With lower interest rates, RES becomes cheaper. As a result, the MAC curve is lower at all abatement levels. Since the lower part of the MAC is dominated by fuel-switching, the effect increases with abatement so that it mainly affects the end of MAC curves. A higher interest rate mirrors the effect of lower interest rates.

Technological Learning

Until now, we refrain from technological learning. However, new technologies exhibit possibilities to drive down investment costs or improve technological parameters such as efficiency. Figure 5 depicts the change in long-term MAC curves with projected technological learning of RES power plants. The respective cost assumptions can be found in Appendix B.

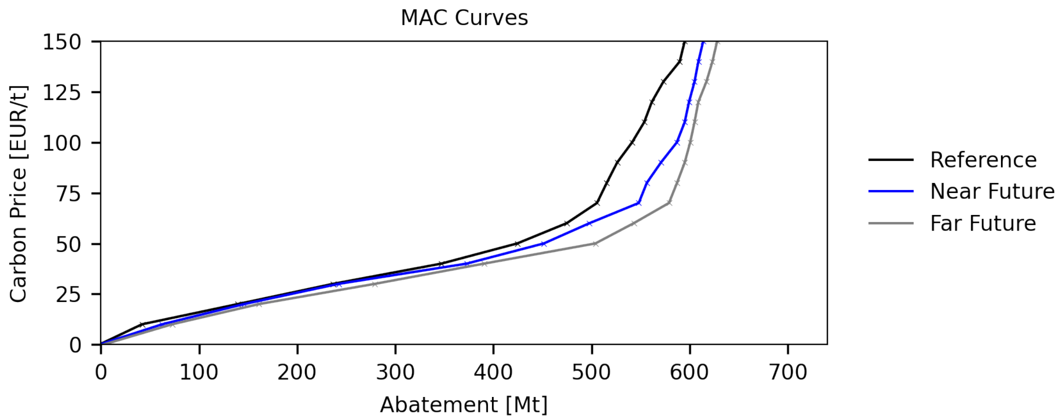

Figure 5: Long-term MAC curves for different assumptions on investment costs

The impact of technological learning is clear-cut: Lower investment costs drive down costs of RES generation. Hence, uncertainty about the future development of techno-economic properties mainly affects the upper part of MAC curves, i.e., beyond the potential of fuel-switching.

Beyond improvements of existing technologies, the cost development of so-called backstop technologies underlines this finding. These technologies are able to remove an arbitrarily large amount of emissions for a fixed price, the backstop price. In light of recent plans to establish a hydrogen economy, experts consider hydrogen-fueled gas turbines as a potential carbon-free and dispatch-able backstop technology in the power sector. In this case, the backstop price level is subject to future costs of hydrogen. The prevailing literature (e.g., Brändle et al. (2020)) projects costs of carbon-neutral hydrogen of roughly 1.5 to 3 EUR/kg. These prices equal about 45-90 EUR/MW_{th}, the marginal abatement costs to replace gas generation is thus approximately between 125 and 350 EUR/t compared to gas prices of 20 EUR/MW_{th}.[10]

Summing up, this case study of the European power sector reveals: first, MAC curves are convex. Their curvature depends on economic developments such as fuel prices and interest rates. Second, they flatten over time due to technological learning and investment restrictions.

4. Implications for the EU ETS

As pointed out in Section 1, model-based analyses of the EU ETS typically assume static MAC curves. On the contrary, MAC curves are dynamic. They are only a snapshot in time so that they conceal dynamic interactions. Further, MAC curves flatten over time due to restrictions on investments and technological advancements. This section discusses the implications of these findings for the EU ETS.

4.1. The functioning of the EU ETS

The EU ETS is a cap-and-trade system, which requires firms to buy allowances to compensate for their emissions. By reducing the yearly supply of allowances to the market, the EU ETS enforces abatement. Firms are allowed to bank allowances for later use while borrowing allowances from future allocations is prohibited.

Firms choose their abatement so that they minimize abatement costs. In equilibrium, carbon prices equal MAC in a friction-less market. In line with the Hotelling rule (cf. Hotelling (1931)), the carbon price rises with the interest rate as long as firms hold a positive bank of allowances. If the aggregate private bank is empty, the price increases at a lower rate according to the yearly issued allowances. (cf. Bocklet et al. (2019))

In this idealized setting, the market determines an initial price, which reflects the discounted backstop costs and fully sets up a price path that sooner (lower initial price) or later (higher initial price) leads to an empty private bank. Market equilibrium paths, which consist of a sequence of price-emission tuples, solve the trade-off between low initial prices and a late point in time where allowances are scarce so that overall (discounted) abatement costs are minimal.

The implementation of the Market Stability Reserve and the Cancellation Mechanism poses additional restrictions on the banking of allowances. First, if banking volumes exceed a

[10]The (direct) marginal abatement costs reflect the difference in fuel prices between natural gas and hydrogen, divided by the emission factor of natural gas of about 0.2 t_{CO2}/MWt_{th}.

pre-defined level, the MSR absorbs allowances from the market. The allowances from the MSR enter the market when the bank falls below the reinjection threshold.[11] Second, the size of the MSR is limited. If the MSR exceeds the previous year's auction volume, the CM invalidates overhanging allowances. As a result of the MSR and the CM, banking decisions affect both the timing and the total volume of allowance supply. In particular, higher banking volumes increase cancellation volumes and thus reduce total emissions within the EU ETS.

4.2. Implications of time-dependent MAC curves in the EU ETS

Chapter 3 reveals two properties of MAC curves, which should be considered in models of the EU ETS: MAC curves are convex and they flatten over time.

If the MAC curve is convex instead of linear, the MAC curve becomes steeper with higher abatement, which makes future abatement relatively more costly. Accordingly, firms bank more allowances to smooth the abatement in the steep upper part of the MAC curve. Due to the endogenous supply rules in the reformed EU ETS, a convex MAC curve causes higher banking volumes and more cancellation compared to a linear MAC. Osorio et al. (2020) provides quantitative evidence by comparing the cancellation volumes of several articles. Modeling approaches that consider convex curvatures (e.g., Bruninx et al. (2018) and Beck and Kruse-Andersen (2018)), exhibit comparatively high cancellation volumes.

Along the same lines, models of the EU ETS usually assume the shape of the MAC curves to be time-independent, neglecting that short-term MAC curves are steeper due to investment restrictions and technological learning. As a result, abatement is more expensive in the short term and becomes cheaper over time. Figure 6 visualizes the stylized impact of a steeper short-term MAC curve on the price path in comparison to the assumption of the long-term MAC curve for all points in time.[12]

[11] Allowances from the MSR enter the market in junks of 100 million allowances per year if the previous year's bank is below 400 million allowances.

[12] This stylized analysis assumes that there is only one banking phase. If, for example, the flattening of MAC curves overcompensates the firms' interest rate, a second banking phase is economically rational.

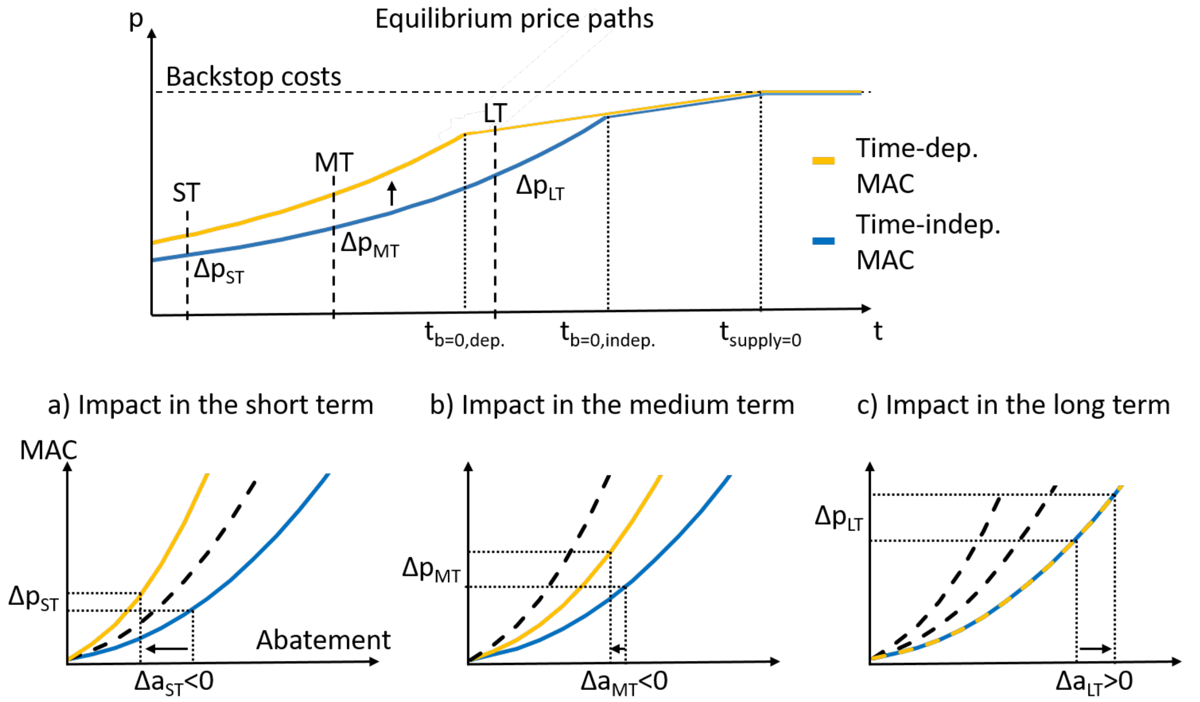

Figure 6: Stylized impact of time-dependent MAC curves on the equilibrium price path and implications for abatement in the short (ST), medium (MT) and long term (LT)

Under perfect foresight, the whole price path is determined already in the first period. Backstop costs are obtained when the last allowance is issued ($t_{supply=0}$ in the upper part of Figure 6).[13] The quasi-linear price development after the bank is emptied ($t_{b=0,dep.}$ and $t_{b=0,indep.}$), depends on the allowance supply and the shape of long-term MAC curves.[14] Firms choose a sequence of price-emission tuples that suffice the two fundamental rules, namely the price development with Hotelling until the bank is empty and the equivalence of MAC and carbon prices. Due to steeper short-term MAC curves (i.e., short-term abatement becomes more expensive), firms increase their short-term emissions, and thus, decrease banking volumes. At the same time, prices increase since the short-term MAC are higher even at the lower abatement level (see Figure 6a). In the medium term, the time-dependent MAC curve flattens and the difference in abatement decreases but abatement is still lower (see Figure 6b).

[13]This holds true as long as backstop costs decrease slower than the firms' interest rate. In general, backstop costs only shift the price path as long as the rest of the MAC curve is kept constant (compare Bocklet et al. (2019)). Abatement and banking remain unaltered.

[14]After the private bank is empty, abatement decreases linearly with the allowance supply. Correspondingly, the price increases in accordance with the upper part of the MAC curve.

As a result, the bank empties earlier ($t_{b=0,dep.} < t_{b=0,indep.}$). In the long term, firms need to increase their abatement with time-dependent MAC curves due to lower banking volumes (see Figure 6c). Summing up, with time-dependent MAC curves, the price level rises, and banking decreases in the short-term. Since cancellation volumes increase with short-term banking (see Herweg (2020)), the described effect increases total emissions due to lower cancellation volumes.

Beyond this theoretical analysis, myopia is considered important to understand the EU ETS market (compare Bocklet and Hintermayer (2020)). In a myopic setting, steep short-term MAC curves might be an additional driver of the price increase observed after the introduction of the MSR and the CM.

All in all, banking and cancellation volumes increase with convexity while flattening has the opposite effect. Accurate numerical models of the EU ETS should consider the shape and dynamic evolution of MAC curves to quantify the overall effects.

4.3. Approaches for time-dependent MAC curves in EU ETS models

In general, there are two approaches to account for the time-dependency of MAC curves: using exogenous but time-dependent MAC curves in EU ETS models or coupling of models for allowance demand and the EU ETS.

Exogenous dynamic MAC curves for the power sector can be derived via modeling, e.g., as described in Section 3. Deriving MAC curves for the energy-intensive industries - as the other large sector within the EU ETS - is more challenging, since industry processes are more heterogeneous and data availability is limited. Further, it is important to depict interactions between the sectors to account for the non-additivity of abatement measures. For example, the electrification of industry processes saves carbon in the industry sector but interacts with the MAC curves of the power sector. Feeding the derived time-dependent MAC curves into a model of the EU ETS improves the accuracy of the results. However, this approach neglects that MAC curves are interrelated, i.e., they are not a sequence of static curves but rather a family of curves, that depends on the carbon price path.

For considering interactions between the allowance demand and the EU ETS price path, it is worth to consider the coupling of an allowance demand-side model (covering the power sector and energy-intensive industries) and an EU ETS model. Via soft-coupling, the EU ETS model feeds the derived price paths to the allowance demand-side model, which then updates the MAC curves. By iterating these steps, a consistent model framework is set up if the model runs converge. Alternatively, the two models could be hard-coupled, i.e., a simultaneous equilibrium is calculated by an integrated approach. For example, the implementation as a mixed complementary problem (MCP) allows to derive a consistent solution with an endogenous depiction of allowance demand and the EU ETS market. Both variants of model-coupling open up possibilities to evaluate alternative EU ETS designs (e.g., the implementation of carbon price floors) or related environmental policies, such as electrification efforts.

5. Conclusion

Recent literature relies on MAC curves to analyze the design of the EU ETS as the key emission abatement instrument in Europe. While the assumptions on MAC curves drive the results, the literature on the shape of MAC curves within the scope of the EU ETS is scarce. Against this backdrop, this paper identifies implications of MAC curve properties for the EU ETS.

In a case study, we derive MAC curves for the European power sector. To this end, a partial equilibrium model is fed with carbon price paths to determine corresponding emission and abatement levels. We identify two fundamental properties of MAC curves of the European power sector: First, the shape of MAC curves is convex for all points in time. The curvature depends on economic developments, such as fuel prices and interest rates. Second, MAC curves flatten over time. In the short term, fuel-switching is the only abatement option and thus, the MAC curve is steep. With longer investment horizons, the degree of freedom for investment grows and enables the transformation of the capital stock. This additional abatement option flattens the MAC curve. Further, technological learning and demand adjustments lowers in particular the upper part of the MAC curve.

Idealized market equilibrium paths in the EU ETS consist of price-emission tuples that minimize overall abatement costs and comply with the allowance supply path. Emission decisions and thus market prices are a trade-off between emissions today and in the future. After introducing the Market Stability Reserve and the Cancellation Mechanism, the total allowance supply and thus total emissions decrease with banking volumes. With convex MAC curves, marginal abatement costs increase over time, which makes future abatement relatively more expensive compared to today's abatement. Thus, firms increase banking volumes compared to linear MAC curves. On the contrary, MAC curves flatten over time, which lowers the incentives for banking. Considering steeper MAC curves in the short term leads to a higher price path and an earlier depletion of the firms' bank. For quantifying these effects, the time-dependency of MAC curves should be depicted. A model of the allowance demand side could derive MAC curves, which are fed into a model of the EU ETS. Ideally, the allowance demand-side model is coupled with the EU ETS model to derive consistent equilibrium paths.

Beyond the power sector, MAC curves within energy-intensive industries should be analyzed to cover the whole scope of the EU ETS. Since MAC curves are only snapshots of a dynamic context, path dependencies and uncertainties are worth considering. In particular, the impact of global deep decarbonization and its implications for MAC curves are a subject of further research.

Appendix A. The Power Market Model DIMENSION

Table A.1 presents the notation used within this paper. Capitalized terms represent endogenous decision variables. Lower case terms denote exogenous parameters.

Table A.1: Sets, Parameters and Variables

Sets		
$i \in I$		Electricity generation and storage technologies
$m, n \in M$		Countries
$y \in Y$		Years
$t \in T$		Representative time steps
Parameters		
$d(y,t,m)$	[MWh]	Electricity demand
r	[-]	Discount rate
$avail(y,t,m,i)$	[-]	Availability of electricity generation technology
$ntc(y,m,n)$	[MW]	Net transmission capacity
$\eta(i)$	[MWh/MWh_th]	Generation efficiency
$\delta(y,i)$	[EUR/MW]	Annualized investment cost
$\sigma(i)$	[EUR/MW]	Fixed operation and maintenance cost
$\gamma(y,i)$	[EUR/MWh]	Variable fuel cost
$\tau(y)$	[EUR/tCO2eq]	Carbon price
$\nu(i)$	[tCO2eq/MWh_th]	Fuel-specific emission factor
$cap_{add,min}(y,m,i)$	[MW]	Existing or under construction capacity
$cap_{sub,min}(y,m,i)$	[MW]	Decommissioning due to lifetime or policy bans
$l(m,n)$	[-]	Relative transmission losses
Variables		
$CAP(y,m,i)$	[MW]	Electricity generation capacity
$GEN(y,t,m,i)$	[MWh]	Electricity generation
$EM(y,t,m,i)$	[tCO2eq]	Emissions
$CAP_{add}(y,m,i)$	[MW]	Investments in electricity generation capacity
$CAP_{sub}(y,m,i)$	[MW]	Decommissioning of electricity generation capacity
$TRADE(y,t,m,n)$	[MWh]	Trade flow of electricity from m to n
TC	[EUR]	Total costs
$FC(y)$	[EUR]	Invest and fixed operation & maintenance costs
$VC(y)$	[EUR]	Variable generation costs

The central planner minimizes total discounted costs for serving the electricity demand. Consequently, she decides on the investment in capacity and the dispatch of power plants. The total discounted costs consist of fixed (FC) and variable (VC) costs, i.e.,

$$TC = \sum_{y \in Y} (1+r)^{-(y-y_0)} \cdot [FC(y) + VC(y)], \tag{A.1}$$

where the fixed costs per year comprise the annualized investment costs and the fixed operation and maintenance costs for installed capacity. The variable costs embody generation-dependent costs, namely for fuel and emission allowances.The installed capacity of electricity generators develops endogenously according to equation A.2.

For a realistic depiction of European energy markets, equations A.3 and A.4 account for existing as well as under construction capacities ($cap_{add,min}$) and decommissioning due to end-of-lifetime or technology bans ($cap_{sub,min}$). Equation A.5 formally defines the fixed costs.

$$CAP(y,m,i) = CAP(y-1,m,i) + CAP_{add}(y,m,i) + CAP_{sub}(y,m,i) \tag{A.2}$$

$$CAP_{add}(y,m,i) \geq cap_{add,min}(y,m,i) \tag{A.3}$$

$$CAP_{sub}(y,m,i) \geq cap_{sub,min}(y,m,i) \tag{A.4}$$

$$FC(y) = \sum_{\substack{\tilde{y}: \\ y-\tilde{y}<lifetime(i)}} CAP_{add}(\tilde{y},m,i) \cdot \delta(\tilde{y},i) + \sum_{m \in M, i \in I} CAP(y,m,i) \cdot \sigma(i) \tag{A.5}$$

Further, technical constraints restrict the dispatch of installed capacities. First, for every time step, electricity generation has to balance the inelastic demand adjusted by the trade flows from and to neighboring countries (Equation A.6). Second, electricity generation of each technology and in each time step is bound by the available capacity (Equation A.7). The availability factor accounts for maintenance shutdowns of conventional power plants or the infeed profile of renewable energy. The trade flows are restricted by the net transfer capacities between countries and have to be symmetric, i.e., exports from m to n are imports from n to m (Equations A.8 and A.9). Variable costs comprise fuel costs and costs for emissions (Equation A.10). The former is calculated as the product of generation per technology and the technology-specific variable fuel costs. The latter is the product of the carbon price and realized emissions which are calculated through the fuel input and the fuel-specific emission factor (Equation A.11).

$$\sum_{i \in I} GEN(y,t,m,i) = d(y,t,m) + \sum_{n \neq m} (1 - l(m,n)) \cdot [TRADE(y,t,m,n) - TRADE(y,t,n,m)] \quad \text{(A.6)}$$

$$GEN(y,t,m,i) \leq avail(y,t,i) \cdot CAP(y,m,i) \quad \text{(A.7)}$$

$$TRADE(y,t,m,n) \leq ntc(y,m,n) \quad \text{(A.8)}$$

$$TRADE(y,t,m,n) = -TRADE(y,t,n,m) \quad \text{(A.9)}$$

$$\forall y \in Y, m,n \in M,\ i \in I$$

$$VC(y) = \sum_{m \in M,\, i \in I} \sum_{t \in T} [GEN(y,t,m,i) \cdot \gamma(y,i) + EM(y,t,m,i) \cdot \tau(y)] \quad \text{(A.10)}$$

$$EM(y,t,m,i) = GEN(y,t,m,i) \cdot \frac{\nu(i)}{\eta(i)} \quad \text{(A.11)}$$

The presented equations constitute the core functionality of DIMENSION: The objective function A.1 is minimized over the feasible region, which is defined by the constraints A.2-A.11.

Moreover, the model incorporates features such as ramping and storage constraints as well as area restrictions for RES. For a thorough introduction of DIMENSION and its characteristics, the reader is referred to Richter (2011).

Appendix B. Numerical Assumptions

Table B.2: Considered Technologies and their techno-economic characteristics based on Knaut et al. (2016) and Peter (2019)

Technologies	Efficiency	Fixed Operation Costs (EUR/kWa)
Nuclear	0.33	101 - 105
Lignite	0.32 - 0.46	45 - 60
Coal	0.37 - 0.46	40 - 60
Combined Cycle Gas Turbines (CCGT)	0.39 - 0.60	24 -30
Open Cycle Gas Turbines (OCGT)	0.28 - 0.40	12 - 17
Oil	0.4	7
Biomass	0.3	120
PV	1	15 - 17
Wind Onshore	1	13
Wind Offshore	1	93
Hydro	1	11.5
Pumped Storage	0.76	11.5

Table B.3: Assumptions on Fuel Prices [EUR/MWh_{th}]

Fuel	Price
Uranium	3
Lignite	3
Coal	10
Natural Gas	20
Oil	33

Table B.4: Assumed Electricity Demand per Country [TWh], based on 2019 levels according to ENTSO-E (2020)

Country	Demand	Country	Demand
AT	67	IE	29
BE	85	IT	307
BG	32	LT	12
CH	62	LV	7
CZ	63	NL	114
DE	530	NO	128
DK	35	PL	156
EE	8	PT	49
ES	248	RO	52
FI	86	SE	132
FR	456	SI	14
GR	51	SK	28
HR	17	UK	263
HU	41		

Table B.5: Technological learning regarding Investment Costs [EUR/kW], based on the World Energy Outlook 2019 (IEA (2019))

Technology	Status quo	Near Future	Far Future
Wind Onshore	1580	1503	1430
Wind Offshore	3985	3038	2600
PV (roof)	883	688	580
PV (base)	750	585	480
OCGT	412	412	412
CCGT	900	900	900

Appendix C. Impact of fuel prices on short-term MAC curves

Figure C.7 depicts the impact of different gas prices (10, 20 or 30 EUR/MWh$_{th}$) on short-term MAC curves, i.e., if no investments are possible.

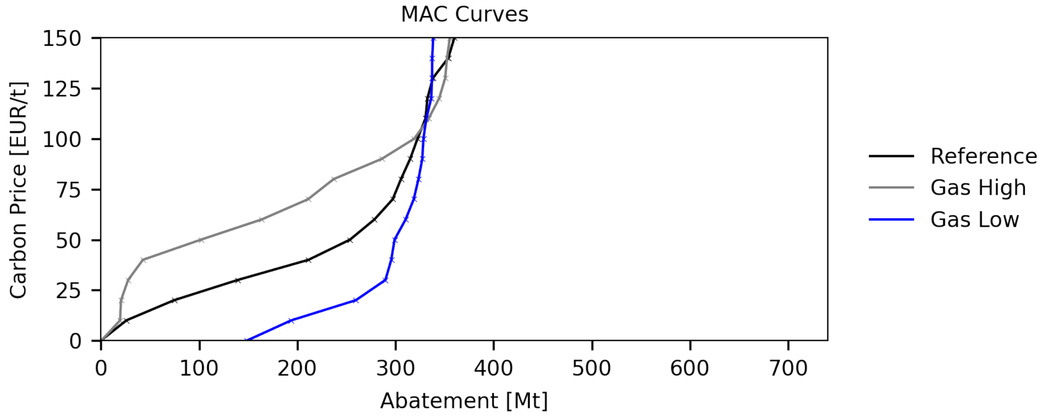

Figure C.7: Short-term MAC curves for different coal/gas price spreads

The lower part of the MAC curve reflects the margin between coal and gas prices. Under lower gas prices, modern gas power plants replace inefficient coal generation even without a carbon price signal. Higher gas prices have the opposite effect. Only below 10 EUR/t, higher gas prices do not impact fuel switching as the margin between coal and gas is not closed by such low carbon prices. The upper part of the MAC curve is similar since the fuel-switching potential is reached independently of the gas price. Only minor shifts in the dispatch of, e.g., biomass affect the MAC curve.

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