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A critical evaluation of the 2022 greenhouse gas mitigation quota in Germany from an environmental economics and policy perspective

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ABSTRACT

This study aims at identifying the strengths and weaknesses of the Greenhouse Gas Mitigation Quota trading as an alternative to allowance trading and carbon taxes. Information was gathered from the websites and publications of the responsible authorities and relevant legal texts. Moreover, literature on comparable environmental policy instruments was analyzed based on predefined criteria. Assumptions were made to create models for assessing cost effectiveness, Pareto efficiency, and dynamic incentive effects. The results show that the Greenhouse Gas Mitigation Quota trading only partially meets the basic criteria of environmental effectiveness, cost effectiveness, and Pareto efficiency, and has further weaknesses regarding legitimacy and practical feasibility. In order to reduce GHG emissions from fossil fuels as efficiently as possible, a key policy priority should therefore be to adapt the Greenhouse Gas Mitigation Quota and to combine it systematically with other environmental economics policies such as a carbon tax.

1. Introduction

The Paris Agreement, adopted in December 2015, contains three main goals: limiting the increase in global average temperature to no more than 1.5 °C; reducing emissions and adapting to climate change; and directing financial resources in line with climate policy goals. In order to comply with the Paris Agreement's enhanced ambition mechanism, Germany's climate protection policy uses various instruments, one of them being the Greenhouse Gas Mitigation Quota (GHGMQ) anchored in the German federal government's Emission Protection Act (BImSchG, 2013, sect. 37 a-h).

The GHGMQ legally obligates distributors of fossil fuels to reduce the average greenhouse gas (GHG) emissions of the diesel and gasoline fuels they put on the market by a certain percentage. To meet this obligation, distributors must sell low-emission fuels in addition to fossil fuels or pay other parties for replacing fossil fuels with low-emission fuels. There is renewed interest in GHGMQ trading, which has been fueled by several factors. Firstly, the quota level will increase from 8% in 2023 to 25% in 2030. Moreover, Austria and some other EU member countries are implementing instruments similar to the German GHGMQ trading. Additionally, the European Commission has plans to incorporate a standard that is akin to the GHGMQ into the regulatory framework through RED III (European Council, 2022).

Research has yet to critically evaluate the 2022 German GHGMQ trading from an environmental economics and policy perspective. This paper aims at identifying the strengths and weaknesses of the GHGMQ trading as an alternative to allowance trading and carbon taxes, at delivering results that can be applied in industry and policy making, and at providing a basis for further research. The focus is exclusively on the 2022 version of the German GHGMQ, as it differs significantly from the older versions and is of future relevance due to its expected duration until at least 2030, with increasing quota levels.

The remainder of this paper is structured as follows. The related literature is discussed in Section 3, while Section 4 describes the method used for the policy evaluation. Section 5 contains the political and regulatory framework of the GHGMQ. Section 6 presents the results of the evaluation. Section 7 concludes and presents some recommendations for future research.

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2. Related research

Even though no literature directly deals yet with the German GHGMQ as an environmental economics instrument, many existing studies in the broader literature have examined comparable instruments under different aspects. Several studies discuss performance standards, some of which focus on their ability to incentivize innovation (Klier and Linn, 2016; Nentjes et al., 2007), others on their overall impact on fuel consumption and GHG emissions (Greene et al., 2020; Jenn et al., 2019). Another active strand of literature concerns tradable performance standards. Yeh et al. (2021) compare different tradable performance standards, focusing specifically on low-carbon fuel standards, and assess the policies' effectiveness in reducing GHG emissions. Their study shows that low-carbon fuel standards only have minor price effects on products and provide strong incentives for innovation but, unlike emissions pricing, do not reduce consumption of polluting products. In addition, Holland et al. (2009) find that low-carbon fuel standards are much less efficient in reducing emissions than a carbon tax or a cap-and-trade scheme, and Holland et al. (2015) demonstrate that fuel standads are more costly than a cap-and-trade program in achieving the same emission mitigation. In contrast, Sperling and Yeh (2010) suggest that low-carbon fuel standards are the most practical approach to initiate the transition to alternative fuels. A recent qualitative meta-analysis by Axsen and Wolinetz (2023) concludes that low-carbon fuel standards have helped reducing GHG emissions, can effectively complement carbon pricing, and have received substantial public support in recent years. Other studies address challenges associated with low-carbon fuel standards, such as indirect land use change and energy supply security implications (Rubin and Leiby, 2013; Yeh and Sperling, 2010).

In our study, we present an exploratory investigation into the German GHGMQ, a unique environmental policy instrument in Europe. Our approach distinguishes itself through a comprehensive assessment of the GHGMQ that goes beyond the analysis of individual aspects. We apply established standard criteria and consider a multitude of additional criteria to provide a holistic understanding and a comprehensive evaluation of this innovative policy instrument. Consequently, our study makes a significant contribution to the discussion on the effectiveness and potential of the GHGMQ.

3. Methodology

First, various criteria for evaluating environmental economics policies were identified based on relevant literature. Second, these criteria were used to classify and evaluate the GHGMQ trading. Multiple sources of information were used to classify GHGMQ trading as an environmental policy instrument and conduct the subsequent evaluation.

Since little has been published about GHGMQ trading so far and this type of data gathering is open-ended, it was decided to use qualitative methods for the collection of data (Starr, 2014, p. 240). Due to the fact that the study was exploratory, no particular information needs could be identified. The data analysis was therefore inductive. Data collection was synchronized with that of Liepold et al. (2023), in which strengths and weaknesses of the GHGMQ trading as an alternative to allowance trading and carbon taxes were identified.

Six expert interviews were conducted as part of the field research. These interviews involved members of so-called "pooling firms". Such firms are service providers acting as intermediaries between low emission fuels distributors and quota obligated companies. The interviews had a semi-structured format, allowing for flexibility in exploring unknown topics and ensuring that not all questions were predetermined (Wilson, 2014).[1] Additionally, inquiries were made via email to the relevant customs administration and the German Federal Environment Agency (UBA) alongside the face-to-face interviews to gather additional information.

In addition to the field research, a qualitative literature review was conducted. On the one hand, the websites and publications of responsible authorities, as well as relevant legal texts, were used to gather further information. On the other hand, literature on comparable environmental policy instruments was analyzed based on predefined criteria.

For four criteria, assumptions were made in order to create models that could be used to check the conditions for fulfilling a criterion taken from literature. For some of the criteria, the extent to which they were met was also examined without the creation of a model.

[1] The key questions of the interviews can be found in the Appendix.

4. Political and regulatory framework

The 2022 version of the German *Greenhouse Gas Mitigation Quota Act* is based on Directive 2009/28/EC, known as the *EU Biofuels Directive*, and the revised *Renewable Energy Directive* (EU) 2018/2001, which requires a 14% share of renewable energy in the transport sector by 2030. Whereas, until 2014, the quota regulated the amount of energy used in biofuels as a proportion of total energy, from 2015 onwards the quota prescribes a GHG mitigation share for fuels placed on the market in relation to a fuel mix that is based purely on fossil gasoline and fossil diesel fuel.[2]

The use of conventional biofuels from food and feed crops for land conservation purposes, aiming to comply with the GHGMQ, is restricted. As an alternative, biogenic fuels, electricity for e-vehicle charging, biogenic liquified gases, and from 2020 until 2026, measures taken to reduce upstream emissions can be used to meet the quota.

5. Multi-criteria evaluation

There is no superior strategy for government intervention in the context of external effects, as the circumstances vary depending on the need (Goulder and Parry, 2008, p. 135). Over the past decade, most research on the performance of internalization strategies has emphasized the use of evaluation criteria (Goulder and Parry, 2008, p. 152). The criteria to be considered are not standardized and must be specified for each specific situation (Mickwitz, 2006, p. 29). In this study, as many criteria as possible were used for the evaluation in order to obtain the most comprehensive results.

The evaluation of the GHGMQ trading is based on the three main criteria of environmental effectiveness, cost effectiveness, and social compatibility. The latter is assessed based on social welfare. On the one hand, these criteria were chosen because they are frequently used in the literature on the evaluation of environmental economics policy instruments (Mickwitz, 2006; Perman, 2003). On the other hand, they are suitable for determining how strongly a criterion contributes to the three strands of sustainable development: Social, Environmental, and Economic (Purvis et al., 2019, p. 682). In addition to the basic criteria, further criteria can be used for a detailed evaluation of an instrument. These criteria promise the successful implementation of a policy (Vogel et al., 2018, p. 12). The additional criteria include dynamic incentive effect, dynamic effect over time, flexibility, practical feasibility, legitimacy, and social acceptability and international harmonization.

5.1. Environmental effectiveness

To evaluate the environmental effectiveness, it is necessary to look at the goal of the GHGMQ. If the GHGMQ is to increase the share of renewable energy in the transport sector to 14% by 2030, and thus meet

[2] Notice that the GHGMQ only applies to gasoline and diesel fuels. It does not apply to jet fuels. From 2026 onwards, however, legislation will prescribe a quota for jet fuels from renewable energies of non-biogenic origin (BImSchG, 2022, sect. 37a, para. 4a, cl. 1).

the requirements of RED II (EU, 2018/2001), then the GHGMQ is not the most efficient strategy. This is because the share of renewables in transport is measured by the amount of energy from renewables in relation to the amount of energy from fossil and renewable fuels. In contrast, GHG mitigation is measured by real emissions in relation to those from a 100% fossil fuel mix. As a result, if the quota remains the same and the goal is to keep the amount of renewable energy as high as possible, renewable energy with comparatively high specific GHG emissions (e.g., biodiesel from soybeans with 58 kg CO_{2eq}/GJ) should be used, since a larger amount of renewable energy is needed to meet the quota. However, firms are inclined to market fuels with the lowest possible emissions as a compliance option because the quota can be met more cost-effectively by distributing or purchasing a smaller amount of energy, thus also resulting in a smaller amount of renewable energy. At the same time, the quota tends to favor renewable energy over more emission-intensive options, while still increasing the overall share of renewable energy. An instrument based on the amount of energy from renewables would be better in increasing the share of energy from renewables (if the goal was simply to maximize the share of renewables). However, both the EU-mandated renewable energy share and the GHGMQ aim at reducing GHG emissions to limit global warming. For this reason, the relationship described above works in reverse. Since the quota requires mitigation of GHG emissions by a certain factor, compliance options that produce particularly low specific emissions are favored.

To further assess environmental effectiveness, it is necessary to determine whether the fine is sufficiently high to induce firms to comply. If the expected benefit of undercutting the quota is less than the benefit of meeting the quota, it can be assumed that in the presence of rational behavior the quota will actually be met. The quota mandates a certain amount of GHG mitigation. A fine is imposed for each ton that is not abated. Complying with the GHGMQ has the benefit of avoiding the fine. Undercutting the quota has the benefit of saving abatement costs. The compliance option certificate (COC) price is assumed to be equal to the firm's marginal abatement cost (see subsection 5.2). This assumption is made because the price is negotiated by GHG traders and quota obligators, with quota obligators having significant control over the price. A lower-cost mitigation would be achieved by themselves.

However, a lower COC price than the fine does not guarantee that GHG emissions actually decrease. Two aspects limit the effectiveness of the quota. First, the fact that electricity and other advanced fuels can be counted more than once against the quota means that the actual emission mitigations do not match those suggested by the quota. Furthermore, the GHGMQ is, as the name implies, a quota-based, i.e., relative, instrument and therefore not suitable for reducing the amount of GHGs in absolute terms since the quota can be met either by reducing total emissions or by increasing low-emission energy production (Zhang et al., 2018, p. 4). Using low-emission fuels reduces GHG emissions by the difference between the specific GHG emissions of the fossil fuel and the low-emission fuel, multiplied by the energy content of the low-emission fuel. This conclusion is based on the assumption that the use of low-emission fuel prevents fossil fuel use. Therefore, a constant fossil fuel demand, despite a quota, can only be justified by an increased total fuel demand. As a result, there has not been a proportional increase in emissions because low-emission fuels have been used instead of fossil fuels (for an example see section A.1 in the Appendix).

The GHGMQ is an absolute cap on emissions only if fuel consumption remains constant or decreases. For this to be the case, the total demand for fuel must also be kept constant or reduced through other environmental policy instruments or, alternatively, a correspondingly high quota level.

In practice, the demand for fossil fuels has a low price elasticity (Dahl, 2012, p. 4). For this reason, price increases resulting from the quota are prolonged to reduce fossil fuel sales. Furthermore, firms will only reduce their production of fossil fuels to a limited extent as long as the demand for fossil fuels exists and it is more economical for them to either produce and sell compliance options themselves or to buy compliance options certificates. This can lead to a situation where there is little mitigation of GHG emissions in absolute terms, even though the quota suggests the opposite. Fig. 1 shows this effect, particularly until 2019.[3]

Significant mitigation in absolute GHG emissions is only possible if the level of the quota is so costly that the highly inelastic demand for fossil fuels is also reduced or if the "subsidy" introduced into the compliance option markets by compliance option trading is so large that it significantly influences demand in these markets. In addition, there is another aspect that limits the environmental effectiveness. The fact that electricity and other advanced fuels can be counted multiple times against the quota means that the real emission mitigations do not match those suggested by the quota. In contrast, emission certificate trading that sets a sufficiently low cap on the amount of emissions allowed will ensure that GHG emissions are limited in absolute terms, because a market response does not drive the mitigation of emissions and will therefore only be effective in absolute terms if the quota is sufficiently high. This suggests that the more directly the quantity determined by the target is influenced by the measures of the instrument, the faster the target will be achieved. A tax or subsidy, in contrast, would have a similar short-term effect as the GHGMQ trading. However, the level of the tax could be used to control the amount of fossil fuel reduction. In contrast, the quota initially only indirectly generates costs that can have the same effect.

5.2. Cost effectiveness

The cost effectiveness criterion is considered to be met if the marginal abatement costs are the same for all firms (Mickwitz, 2006, p. 30; Perman, 2003, p. 203). p_h is the price for one unit of fossil fuel, $c_{h,i}$ are the costs of firm i for one unit of fossil fuel, p_l is the price for one unit of low-emission fuel and $c_{l,i}$ are the costs of firm i for one unit of low-emission fuel. Assuming that the quota is environmentally effective and that there is only one form of fossil fuel and one form of low-emission fuel, the marginal abatement costs MAC of the firm i can be calculated as:

$$MAC_i = (p_h - c_{h,i}) - (p_l - c_{l,i}). \tag{2}$$

It is assumed further that there are only two fossil fuel distributors. This assumption can be justified by a study of the German Federal Cartel Office, which showed that in the filling station business, there is a dominant group of non-competing distributors of fossil fuel that have access to refinery capacity, and other distributors of fossil fuel that do not have access to refinery capacity (German Federal Cartel Office, 2011, pp. 18–22). In the context of this model, it is assumed that the second non-dominant group can replace fossil fuels with low-emission fuels at lower costs. This assumption results from the marginal cost of fossil fuels being lower for the first group due to the accessibility of refineries, which makes the minuend of eq. (2) significantly larger. For simplicity, it is assumed further that both firms' marginal abatement cost curves are linear.

Fig. 2 shows the marginal abatement cost curves of the two fuel firms. The firms' MACs are plotted on the abscissa axis. The ordinate shows the amount of low-emission fuel produced. As in the GHGMQ trading, the firms can either purchase the certificates or sell the low-emission fuels themselves. Once a certain price for COCs is established, firms respond to that price by buying additional COCs, depending on their marginal abatement costs, producing until their GHGMQ is met and the fine f is avoided, or producing more and generating certificates that they sell. Fig. 2 also illustrates this mechanism.

[3] GHG emissions in 2020 and 2021 were affected by Corona pandemic mitigation measures (UBA, 2021).

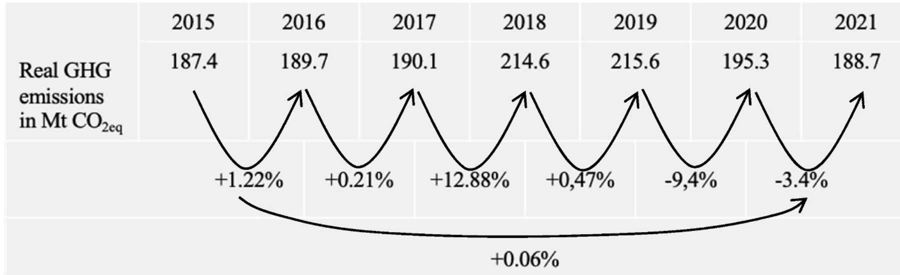

Fig. 1. Development of the total GHG mitigation, including emissions from compliance options, based onGerman Central Customs Authority, 2023a

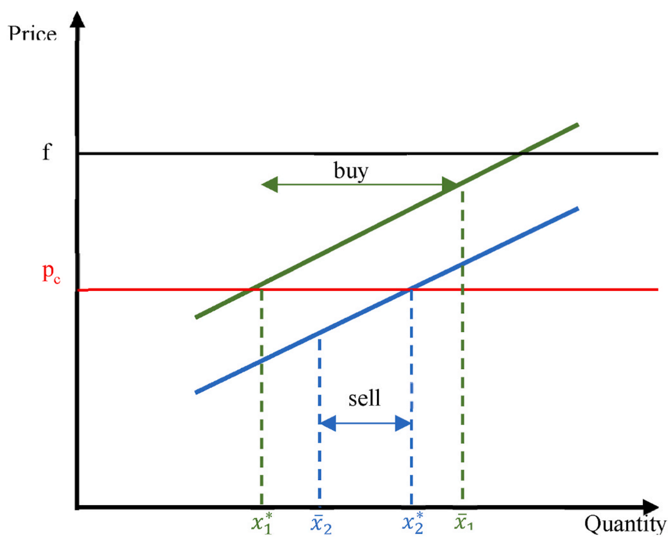

Fig. 2. Compliance option trading mechanism.

Provided that it can be ruled out that the firms subject to the GHGMQ would rather pay the fine than fulfill the GHGMQ, the following model can be used to demonstrate the cost effectiveness of the firms. Both firms produce as many units of the low-emission fuel until the *MAC* equal the certificate price c_p. In this example, firm 1 produces x_1^* units and firm 2 x_2^* units under c_p. Both firms must maintain different quantities of low-emission fuel due to the GHGMQ. The different quantities are caused by different amounts of fossil fuels put into circulation. Firm 1 needs $\bar{x}_1$ units of low-emission fuel, and firm 2 needs $\bar{x}_2$ units. If firm 2 produces x_2^* units of low-emission fuel, but only needs $\bar{x}_2$ units, it can sell the difference at the price of p_c. Firm 1 needs $\bar{x}_1$ units of low-emission fuel but only produces x_1^* units because it is cheaper to buy COCs on the certificate market. Conversely, all firms pay p_c for the required amount of low-emission fuel. The criterion of cost effectiveness is therefore met.

Loosening the constraint so that the fine and the price of the COC varies results in twelve different scenarios (S), depicted in Table 1. It is important to note that x_i^* is different in all scenarios and corresponds to the actual number of COCs sold or purchased. The analysis shows that the cost effectiveness criterion is met for each COC price and fine. However, the likelihood of these scenarios occurring varies.

Scenarios 1 and 2, in which both groups of firms completely avoid compliance, are not realistic because there is a market for COCs. Scenarios 4, 8, 9, and 10, in which the fine is so low that both groups of firms do not fully comply, are also unlikely, as discussed in subsection 5.1. The remaining scenarios show that it is irrelevant for the behavior of firms whether the fine is above or below $MAC(\bar{x}_1)$ if the certificate price is below the fine. Outside of this model, the price of certificates can be expected to be lower than the fine, since the price of certificates is determined in a supply and demand market, and it is obvious that there will be no trading if firms can violate the quota at a lower cost. In scenarios 5 and 7, firm 1 produces until the marginal abatement costs equal the certificate price. It then purchases any additional energy needed to meet the quota. Firm 2 produces more than it needs to meet the quota.

Table 1
Behavior of fossil fuel distributors influenced by varying COC prices and fines,described for twelve scenarios

S						Firm 1	Firm 2
1		$MAC(\bar{x}_2)$	$<$	$MAC(\bar{x}_1)$	$< p_c < f$	Generates $\bar{x}_1$	Generates $\bar{x}_2$
2		$MAC(\bar{x}_2)$	$<$	$MAC(\bar{x}_1)$	$< f < p_c$	Generates $\bar{x}_1$	Generaters $\bar{x}_2$
3		$MAC(\bar{x}_2)$	$< f <$	$MAC(\bar{x}_1)$	$< p_c$	Abates until $MAC(x_1^*) = f$ Pays fine for $\bar{x}_1 - x_1^*$	Abates $\bar{x}_2$
4	$f <$	$MAC(\bar{x}_2)$	$<$	$MAC(\bar{x}_1)$	$< p_c$	Abates until $MAC(x_1^*) = f$ Pays fine for $\bar{x}_1 - x_1^*$	Abates until $MAC(x_2^*) = f$ Pays fine for $\bar{x}_2 - x_2^*$
5		$MAC(\bar{x}_2)$	$< p_c < f <$	$MAC(\bar{x}_1)$		Abates until $MAC(x_1^*) = p_c$ Buys $\bar{x}_1 - x_1^*$	Abates $\bar{x}_1 - x_1^* + \bar{x}_2 \dot{\vee}$ until $MAC(x_2^*) = p_c$ Sells $\bar{x}_1 - x_1^* \dot{\vee} x_2^* - \bar{x}_2$
6		$MAC(\bar{x}_2)$	$< f < p_c <$	$MAC(\bar{x}_1)$		Abates until $MAC(x_1^*) = f$ Pays fine for $\bar{x}_1 - x_1^*$	Abates $\bar{x}_2$
7		$MAC(\bar{x}_2)$	$< p_c <$	$MAC(\bar{x}_1)$	$< f$	Abates until $MAC(x_1^*) = p_c$ Buys $\bar{x}_1 - x_1^*$	Abates $\bar{x}_1 - x_1^* + \bar{x}_2 \dot{\vee}$ until $MAC(x_2^*) = p_c$ Sells $\bar{x}_1 - x_1^* \dot{\vee} x_2^* - \bar{x}_2$
8	$f <$	$MAC(\bar{x}_2)$	$< p_c <$	$MAC(\bar{x}_1)$		Abates until $MAC(x_1^*) = f$ Pays fine for $\bar{x}_1 - x_1^*$	Abates until $MAC(x_2^*) = f$ Pays fine for $\bar{x}_2 - x_2^*$
9	$p_c < f <$	$MAC(\bar{x}_2)$	$<$	$MAC(\bar{x}_1)$		Abates until $MAC(x_1^*) = p_c$ Buys $\bar{x}_1 - x_1^*$	Abates until $MAC(x_2^*) = p_c$ Buys $\bar{x}_2 - x_2^*$
10	$f < p_c <$	$MAC(\bar{x}_2)$	$<$	$MAC(\bar{x}_1)$		Abates until $MAC(x_1^*) = f$ Pays fine for $\bar{x}_1 - x_1^*$	Abates until $MAC(x_2^*) = f$ Pays fine for $\bar{x}_2 - x_2^*$
11	$p_c <$	$MAC(\bar{x}_2)$	$< f <$	$MAC(\bar{x}_1)$		Abates until $MAC(x_1^*) = p_c$ Buys $\bar{x}_1 - x_1^*$	Abates until $MAC(x_2^*) = p_c$ Buys $\bar{x}_2 - x_2^*$
12	$p_c <$	$MAC(\bar{x}_2)$	$<$	$MAC(\bar{x}_1)$	$< f$	Abates until $MAC(x_1^*) = p_c$ Buys $\bar{x}_1 - x_1^*$	Abates until $MAC(x_2^*) = p_c$ Buys $\bar{x}_2 - x_2^*$

On the one hand, it is possible that firm 2 produces exactly as much as firm 1 needs, which happens if the COC price is particularly high and close to $MAC(\overline{x}_1)$, because firm 1 then self-provides a large part of its demand and only has to purchase a few more certificates. Theoretically, this scenario is possible, but once the certificate market is taken into account, it becomes very improbable. The reason for this improbability is that if the demand for COCs is low, there will only be trading between firm 1 and firm 2, and not with a third party, because firm 1's demand could be met by firm 2 alone, even below the certificate price. It would be more economical for firm 2 to offer more than the quantity initially demanded by firm 1 at a lower price, which would inevitably lower the certificate price. On the other hand, the certificate price ranges between $MAC(\overline{x}_2)$ and $MAC(\overline{x}_1)$ such that firm 1 buys $\overline{x}_1 - x_1^*$ and firm 2 sells $x_2^* - \overline{x}_2$ as in the previous case. In addition, the quantity $\overline{x}_1 - x_1^* - (x_2^* - \overline{x}_2)$ is then purchased by a third party in the COC market. If the certificate price is lower than the *MAC* of the firms, as in Scenarios 11 and 12, then both firms purchase the required quantities in excess of what they would have produced at marginal costs equal to the certificate price. These scenarios could occur if a large amount of compliance options is available, i.e., the supply of COCs significantly exceeds the demand. In practice, that is the case when the quota is particularly low, when a large amount of energy from low-emission fuels is available, for example, due to multiple crediting, and when fossil fuels significantly lose importance in the fuel mix.

Let the limitations of this model be considered again. At the outset, it was assumed that quota trading is environmentally effective. Subsection 5.1 shows that this is not the case in practice. Thus, instead of looking at the cost of real abatement, firms are concerned with the cost of meeting the quota. To keep this cost minimal, firms will try to save as much fossil fuel as possible, so that the cost of the resulting quota improvement is equal to the cost of purchasing or producing low-emission fuels with the same effect on the quota. Each firm, therefore, has three specific cost curves, depending on its impact on the quota. Analogously to the mechanisms described in the model, it can be assumed that the specific marginal costs, which are co-determined by the effect of the cost-causing measure, are set such that they correspond to the certificate price. As a result, the GHGMQ trading scheme formally meets the criterion of cost effectiveness.

The cost effectiveness criterion addresses a key question: Is there an instrument that can achieve the same effect at a lower cost? Taken in isolation, there is none. However, quota trading cannot be considered in isolation (Liepold et al., 2023). Reducing emissions incurs costs. These costs are distributed efficiently. In this respect, the GHGMQ trading does not differ from other environmental policy instruments. The unique characteristic of the GHGMQ trading is that part of the costs work as a subsidy in other markets. In other words, a classical subsidy such as the Environmental Bonus is a burden on the government budget with the purpose of reducing the costs of low-emission technologies. The GHGMQ trading works similarly but is financed directly by the fossil fuel distributors and therefore reduces the sale of fossil fuels, just like an Energy Tax. The GHGMQ trading thus combines two environmental policy instruments. This reduces administrative and bureaucratic costs and makes the GHGMQ trading more cost-effective than a tax and a subsidy each in two different markets.

5.3. Pareto efficiency

A market is Pareto-efficient if no market participant can improve its situation without worsening the situation of another market participant (Pareto, 1897). To see whether the GHGMQ trading can make GHG mitigation Pareto-efficient, it is helpful to consider the welfare of avoiding and emitting GHGs.

In the case of pollution, social welfare π consists of the benefits to all firms from the emissions (equal to the avoided abatement costs) and the damages D caused by the emissions (equal to the benefits from abatement). Assuming that there is only one low-emission fuel Q_l and one fossil, high-emission fuel Q_h and that the marginal benefit of abatement per ton of GHG is constant. With the level of the GHGMQ q being given, the benefit B of using low-emission fuel with specific emissions of β_l instead of high-emission fuel with specific emissions of β_h results from avoided emissions, and can be calculated as:

$$\begin{aligned} B &= D((Q_h + Q_l)\beta_h - Q_h\beta_h - Q_l\beta_l) \\ &= D(\beta_h - \beta_l)Q_l \\ &= D(x_h + x_l)\beta_h q \end{aligned} \tag{3}$$

The avoidance cost is the integral of the marginal cost function $MAC(Q_l)$. With this information and eq. (3), social welfare W can be described as:

$$W = \int_0^{Q_l^*} D\,(\beta_h - \beta_l) - MAC(Q_l)\, dQ_l. \tag{4}$$

To determine the maximum social welfare, eq. (4) must be derived and set equal to zero.

$$\frac{\partial W}{\partial Q_l} = D\,(\beta_h - \beta_l) - MAC(Q_l) = 0. \tag{5}$$

It can be observed that welfare is maximized when the marginal production cost Q_l is equal to the marginal benefit multiplied by the specific GHG emissions saved by using low-emission fuel instead of high-emission fuel.

With this information, knowing the aggregated marginal cost curve $MAC(Q_l)$ and the marginal damage cost, the optimal quantity Q_l^* can be determined. It is easy to verify that this condition is Pareto-efficient. If firms were to emit less than the optimal quantity, this would reduce abatement costs, but the benefit of abatement would also decrease. Conversely, a quantity greater than Q_l^* would lead to an increase in abatement benefits but a decrease in marginal costs.

In practice, however, several problems arise. First, it is usually impossible to precisely put a monetary value on marginal damage since the damage caused by pollutant emissions often takes several years to manifest itself. This problem is common to all other environmental policy instruments (Vogel et al., 2018, p. 14). In addition, the marginal damage is unlikely to be constant. The higher the annual emissions, the greater the benefit of abatement will be, since only a limited amount can be emitted to avoid reaching or exceeding a tipping point.[4] The last ton before a tipping point is, therefore, infinitely valuable. Therefore, it is not possible to test which instrument is Pareto-efficient, but only which instruments are closer to Pareto efficiency than others. If we consider the other side of the Pareto efficiency condition, marginal costs as a function of Q_l, another problem arises. The GHGMQ level would have to be set just sufficiently high to replace the right amount of Q_l^* with the minimal aggregate cost to firms. However, due to the numerous compliance options and multiple impact mechanisms, it is impossible to determine the exact quota level, neither within the scope and analysis of this paper nor in reality. For this reason, the GHGMQ is dominated by taxes and certificate trading from a Pareto efficiency perspective, as the information requirements are significantly higher.

Instead of aiming for Pareto efficiency, a different approach is adopted to set the optimal quota level. A vaguely estimated quota level is established based on the projected set of compliance options. The goal of the quota is to reduce GHG emissions sufficiently to limit global warming to 1.5 °C. The compliance options and the quantities of fuels placed on the market are used as indicators to check whether and how much improvement is needed. If the information from these indicators is

[4] If a tipping point is crossed, it could prevent stabilization of the climate at intermediate temperature rises and cause continued warming due to cascaded feedback effects (Steffen et al., 2018).

insufficient, a questioning of the associations and firms concerned is also carried out (Federal Government, 2022, p. 31). This approach is similar to the standard-pricing approach by Baumol and Oates (1971). The climate target corresponds to the standard of thestandard-pricing approach, the quota to the indirect form of pricing. The pricing (quota level) is controlled to be sufficient to meet the standard (climate target), rather than based on the unknown value of marginal net damages. A high quota level effectively ensures that fossil fuel costs rise to the point where it is cheaper to forgo some of the fossil fuel products and thus meet the quota than to emit even more compliance option fuels. In this case, there is also an absolute GHG mitigation. That way, it can be indirectly ensured that the benefits are more significant than the total costs since the costs, whatever they may be, are offset by the benefits of meeting the 1.5 °C target. The value of the latter, although not precisely quantifiable in monetary terms, is very high.

5.4. Dynamic incentive effect

The incentive to reduce GHG emissions comes from the increased cost of the GHGMQ and the revenue from the sale of COCs. Certificate trading schemes and tax schemes create an incentive for technological improvement. In contrast, standards create an incentive to meet the standard at lower cost but not exceed the standard (Harris and Roach, 2017, p. 196). The GHGMQ trading, as a combination of certificate trading and standards, creates both an incentive to reduce costs and an incentive to overfulfill the quota by realizing a profit from over-fulfillment and is thus at least equivalent to a certificate trading scheme covering the fossil fuel market. In this context, the addition of a minimum price for the *COCs* could strengthen the incentive to innovate (Aldy, 2017, p. 6).

Given the COC price p_c, the energy quantity of a fuel Q, the specific GHG emissions of this fuel β, the specific emissions of a fossil fuel β_h and the quota level q, the fuel price changes Δp resulting from the quota can be calculated as follows (Yeh et al., 2021, p. 9):

$$\Delta p = p_c(\beta - (1-q)\beta_h)Q. \quad (6)$$

Since $\beta - (1-q)\beta_h$ is negative for low-emission fuels, the price of these fuels falls as a result of the GHGMQ trading. On the one hand, this creates a reward for using low-emission fuels; on the other hand, this aspect ensures that the average fuel price is lower than in the presence of a GHG tax of the same level as the *COC* price. This is because, in comparison, a GHG tax increases the price of both fossil fuels and low-emission fuels, although the price increase for the latter is significantly lower. Accordingly, the quota provides less of an incentive to reduce overall fuel consumption. However, this would be necessary to come as close as possible to environmental effectiveness (see subsection 5.1).

The incentive to replace fossil fuels with low-emission fuels results from the difference in the change of the prices of different fuels (Yeh et al., 2021).

In principle, it can be said that a tax of the same amount as the certificate price would create a stronger dynamic incentive since this tax would provide an identical incentive to replace fossil fuels with lower-emission fuels and simultaneously creates a stronger incentive to reduce overall demand. Nevertheless, the latter leads to an increased burden on consumers, which is why, in practice, GHG tax rates are significantly lower than the prices of the COCs, making the dynamic incentive effect weaker than under the GHGMQ trading (Pizer, 1999; Yeh et al., 2021, p. 12).

5.5. Dynamic effect

It can be assumed that the impact of the GHGMQ on total emissions is initially limited and increases over the decade.[5] However, as the importance of fossil fuels declines, the quota's impact diminishes because GHG mitigation is measured in relation to a lower amount of fossil fuels. Accordingly, if the fuel mix is no longer dominated by fossil fuels but by compliance options, the absolute emissions avoided as a result of the quota will be lower, even if the quota is met. In order to achieve significant further mitigation in total emissions, the quota obligations would have to be adjusted or replaced by other environmental economics instruments.

5.6. Flexibility

From the point of view of flexibility, it is necessary to assess whether, how quickly, and at what cost an instrument can be adapted (Perman, 2003, p. 203). For the group held accountable by the instrument, it is more advantageous to adapt to a change in the law if it is known in advance that the law could be adapted and those affected can prepare in advance for any changes (UNITI, 2020, p. 3). To a limited extent, this possibility exists because requirements at the European level are first announced, then adopted, and only then implemented at the national level. For example, since summer 2022, there have been public plans for RED III, which will no longer require EU Member States to achieve a 14% share of renewable energy in transport. Instead, Member States can either enforce a 29% renewable energy share in transport by 2030 or reduce GHG intensity by 13% (European Council, 2022),the latter being equivalent to the GHGMQ. The plans have yet to be finalized, but firms in the transport sector may already be considering the implications of such a regulation. Meanwhile, as far as the effect of the quota is concerned, higher costs for quota-obligated parties lead to an increase in the price of fossil fuel, which can lead to a decrease in demand, which in turn reinforces the mitigation of GHGs. In perspective, a long implementation lead time is not necessarily favorable.

Other implemented environmental policy instruments, such as the National Emission Trading System (NETS), also provide for a regular evaluation of the act, but the fixed prices in the introductory phase remain unaffected. The fixed prices not being affected make the instrument less flexible until 2025. However, the temporary reduction of the Energy Tax to ensure social justice has also shown that legislative changes can be made quickly (Müller, 2022).[6] This example shows that each instrument can be adapted with a comparable financial outlay within a shorter timeframe in urgent cases.

5.7. Practical feasibility

As described in subsection 5.1, the GHGMQ trading scheme follows the trial-and-error method. The advantage of this procedure is that the statistics on fuels placed on the market are collected anyway as part of monitoring the quota. Most of the costs are borne by the quota obligators. They incur bureaucratic costs that arise in the form of reporting costs and due to preparing information for the standardized format of

[5] With limited capacity for sustainable biomass, green hydrogen, and advanced biofuels, as well as the expansion of electromobility in the first half of the 2020s, the GHGMQ will increase moderately to 12% by 2026. After that, the increase accelerates, and the quota level rises to 25% within four years (BImSchG, 2022, sect. 37a, para. 4).

[6] First reading in the Bundestag was on May 13, 2022, the hearing of the responsible committee on May 16, 2022. The bill was passed by the Bundestag on May 20 and confirmed by the Bundesrat on May 21, 2022. It entered into force on June 1, 2022. Compared to the timeframe for the further development of the GHGMQ (see section "Adherence to democratic principles"), this legislation was enacted very quickly (Müller, 2022).

the authority (German Central Customs Authority, 2023b). Data collection costs are not expected to be high, as most of the information has to be collected in other contexts. The costs depend crucially on the complexity, which essentially results from the product portfolio of the quota obligators and usually correlates with the size of the responsible party. A large part of the administrative costs is likely to be incurred in concluding contracts with other compliance option providers, especially if the contracts are concluded via brokers and pooling firms.

Compared to other abatement instruments, administrative and bureaucratic costs are likely to be lower or equal. Under the NETS, obligated parties must at least prepare a monitoring plan that discloses the methods used to determine emissions (sometimes in a simplified form) and have it verified by the authorities (German Federal Council, 2019, p. 29). Preparing and verifying this data is costly and time-consuming for both the government and the firm. The reports must be submitted once a year (German Federal Council, 2019, p. 29). This effort is comparable to the bureaucratic effort required by the GHGMQ obligation (German Federal Council, 2019, p. 30). Firms must also ensure that the appropriate infrastructure is in place (German Federal Council, 2019, p. 25). In contrast, it can be assumed that standardized certificate trading via the European Energy Exchange will result in lower costs compared to the quota trading. In addition, there is a social benefit in the form of increased transparency.

The Energy Tax reporting is usually done monthly. This tax must be calculated and reported by the taxpayer independently. The declaration can be made either via an online form, which is filled in, printed, and sent to the main customs office or electronically. The main customs office checks whether the calculations are understandable and correct. If this is not the case, tax assessment notices are sent. The taxpayer must pay the tax independently within the second month following the sale of the fuel (BMI - German Federal Ministry of the Interior and Community, 2023). The complexity of tax reporting is less than the complexity of quota and NETS reporting. This reduced complexity results, for example, from the fact that certain fuels are treated in the same way as under the energy tax law, while in the other instances, they must be considered in a differentiated manner. Taxation is based on volume, whereas reporting in quota trading and NETS is based on GHG intensity (German Federal Council, 2019, p. 26). Nevertheless, the administrative and bureaucratic costs of the Energy Tax are likely to be higher than those of the other two instruments, as recording and auditing are much more frequent. However, if the Energy Tax were to be dropped, the bureaucratic costs of the other two instruments would increase significantly, as it would no longer be possible to benefit from synergies in reporting.

5.8. Legitimacy

The sub-criteria of transparency, predictability, evidence-based decision making, equity and impartiality, and adherence to democratic principles are decisive for assessing the legitimacy criterion and, thus, crucial to an effective policy implementation. It appears that the implementation of the GHGMQ trading is mainly seen as illegitimate by the public.

5.8.1. Transparency

The goal of the GHGMQ to reduce GHG emissions is obvious. However, the reference value the quota refers to is not immediately apparent. The term GHGMQ is ambiguous.[7] The formulation of the actual calculation can only be found on a legal basis and requires reading several sections of law and different acts and regulations. The extent to which misconceptions about the definition of the GHGMQ are widespread requires further research.

The GHGMQ trading scheme is also not fully transparent. In particular, the sale of certificates from electricity for e-vehicle charging by private individuals has created market players who have no GHGMQ trading expertise.

5.8.2. Predictability

There is no time limit on the quota. The GHG mitigation required by the quota is to be achieved at least at the same level from 2031 onwards (Federal Government, 2022, p. 20). For all three planning horizons, the level of the GHGMQ can be assumed to have medium to high planning reliability, taking into account the information usually available for these horizons. The actual GHG emissions avoided cannot be predicted with certainty because, as described in subsection 5.1, more GHG may be emitted in absolute terms, and it cannot be assumed with certainty that (fossil) fuel consumption will remain constant.

Regarding the quantity of compliance options, no predictability can be assumed on either the supply or the demand side. If fossil fuel consumption remains constant, more compliance options will be needed as the quota increases until 2030, which could lead to an increase in the demand for COCs, which would be reflected in a price increase. At the same time, the number of available compliance options is expected to increase due to, among other things, efficiency improvements and cost degression in production, but also as a result of the GHGMQ. An increase in supply is likely to lead to a decrease in demand, leading to a decrease in price.

Unlike for the NETS, there are no price controls for the COCs. However, the fine for non-compliance acts as an indirect price constraint, as firms will prefer to pay the fine rather than avoid compliance if marginal abatement costs are exceeded, and COC prices are higher (see subsection 5.1). Such price frameworks lead to stronger stakeholder support. In general, environmental economists favor the addition of a floor price to achieve a higher level of ambition (Jotzo et al., 2018). Meanwhile, fossil fuel industry interests prefer adding a maximum price to protect against high compliance costs. If the limits of a price framework were undercut or exceeded, quota trading would become equivalent to a tax (Aldy, 2017). As a result, there is little planning certainty for the costs incurred by firms due to the quota

5.8.3. Evidence-based decision making

Significant mitigation in GHG emissions to achieve the 1.5 °C target is based on scientific evidence. Therefore, mitigating GHG emissions that contribute to achieving the target is scientifically justified. The fact that experts have a say in the development of the legal basis (see paragraph “Adherence to democratic principles”) helps to ensure that GHGMQ trading is evidence-based. However, the scientific basis for multiple crediting of certain compliance options is controversial among scientists. The level of the GHGMQ is also controversial (e.g. Naumann et al., 2021). In addition, the specific GHG emissions and energy quantities of accountable electricity for e-vehicle charging are not generally published with sources and calculation descriptions, and so it often remains unclear where these values originally come from.

[7] It is reasonable to assume that the mitigation refers to a baseline from a previous year because that is how GHG mitigations are often reported. For example, the German federal government’s greenhouse gas reduction target is stated as follows: By 2030, greenhouse gas emissions are to be reduced by at least 65 percent compared to 1990 levels (KSG, 2019, Sect. 3). Alternatively, it could be assumed that the mitigation is calculated from the average emissions of a mix of low-emission and fossil fuels and the average emissions of an all-fossil fuel mix.

5.8.4. Equity and impartiality

A market is not necessarily equitable even if it is Pareto-efficient and internalizes external costs or benefits. Under the assumptions made in subsection 5.2, it could be shown that the criterion of cost effectiveness is met, i.e., fairness between firms is partly given. However, this is contradicted by the fact that firms without access to refineries cannot generate any upstream emission reduction, which limits the number of compliance options. It is possible that a different COC price would result if all firms would face the same framework conditions. As described in subsection 5.1, the instrument also leads to a reduction in the costs of GHG emissions for society. In the optimal case, the Pareto efficiency criterion is met, which is not the case here.

Preliminary, the firms required to meet the quota pay for compliance, but they pass the costs on to the end-consumers of the fuels. This way, the GHGMQ partly follows the benefit principle (Mankiw, 2011). However, it cannot be guaranteed that all end-consumers receive the same relative benefits from consumption. Therefore, the benefit principle is not fully satisfied. In addition and in compliance with the ability to pay principle, the cost of meeting the quota, and thus internalizing the external effect, could be borne by the wealthiest. This principle is not applied because all consumers are burdened in the same way if they consume the same amount. Measures such as a climate premium or specific subsidy programs for vulnerable households that facilitate the switch to compliance options could help in this regard (Burger et al., 2022, p. 14).[8] Furthermore, individual compliance options are not considered at their actual energy quantities and GHG emissions but at a factor of two or three. As a result, individual compliance option markets are not treated equally.

5.8.5. Adherence to democratic principles

The act went through the rules of the Federal Republic of Germany for the passage of legislation and was confirmed by a majority of a democratically elected parliament. Throughout the process, there were repeated comments on requests for amendments. Various stakeholder groups (incl. NGOs) were given the opportunity to exert influence. On this basis, it can be concluded that the environmental policy instrument of the GHGMQ trading meets the evaluation criterion of adherence to democratic principles.

5.8.6. International harmonization

To meet the international harmonization criterion, a scheme must ensure that the risk of eco-dumping is limited (Babiker, 2005, p. 422). Since fuel consumption is subject to constraints and costs, and this consumption for most cannot be shifted locally, there is no significant danger of emissions being shifted across German borders to avoid being GHGMQ obligated. This also applies to the Energy Tax and the NETS.[9]

The law is compatible with European legislation, and modified forms of the GHGMQ are also used, e.g., in Austria, France, and the Netherlands. However, cross-border trading of compliance options is not possible and would involve challenges. First, cross-border trading would encourage the purchase of compliance options from countries where the share of renewable energy is already significantly higher. Furthermore, the Effort Sharing Regulation (EU) 2018/842 sets nationally binding emission targets for sectors outside the EU ETS, including road transport. The targets are staggered according to relative gross domestic product per capita, so Germany must make a significantly above-average contribution. Assuming that the GHGMQ is environmentally effective, imposing the same quota on countries whose GHG intensity in transport is already lower would result in these countries approaching a zero-emissions target faster and in high-emission countries failing to meet the EU emissions targets. At the same time, however, it would lead to greater cost effectiveness since emissions would be avoided first where the abatement costs are the lowest.

6. Conclusions and policy implications

This study aimed to understand the German GHGMQ trading scheme better and evaluate it from an environmental economics perspective. Based on quantitative and qualitative data from surveys, expert interviews, and a review of literature on similar environmental policy instruments, it can be concluded that the GHGMQ trading does not meet several predefined criteria for evaluating internalization strategies and is therefore not unreservedly superior to other instruments.

The findings of this study suggest that the GHGMQ trading only partially meets the basic criteria of environmental effectiveness, cost effectiveness, and Pareto efficiency. Fig. 3 summarizes the evaluation of the GHGMQ trading in comparison to GHG pricing, certificate trading, and traditional emission standards.

This study is the first attempt to thoroughly examine the German GHGMQ trading as a further development of the former biofuel quota. However, the assumptions made require a critical, fact-based assessment. The most important limitation is that the market participant acts as a *homo economicus*. However, as there may be different behavioral motives in practice, which have not yet been sufficiently researched, it is possible that some results, such as cost effectiveness, do not match well with reality. A natural progression of this work is to determine the efficient combination of the GHGMQ trading and other environmental economics policies. Yet another possible area of future research would be to investigate the extent to which a unified cross-border instrument related to the GHGMQ is preferable to national solutions from an environmental economics perspective.

In addition to minor policy adjustments, such as introducing price caps and reducing administrative costs through digitalization, there are major adjustments that have a significant impact on the overall effectiveness of the instrument.

Firstly, it should be ensured that the quota favors the most promising technology, not by multiple counting, which would take into account false emission mitigation quantities, but by limiting the permissible compliance options. Furthermore, it should be ensured that green certificates or self-generated electricity from distributed solar power systems can be used to credit lower specific GHG emissions (Fabianek et al., 2020), as this would increase the incentive to use low-emission electricity.

As there is no Pareto efficiency, it is also important to ensure that the quota level is high enough for the quota to be effective. This effect needs to be monitored regularly. In order to achieve significant further mitigation in total emissions in the long term, quota obligations would have to be adjusted or replaced by other environmental economics instruments.

If the plans for RED III are implemented in such a way that EU Member States are no longer required to achieve a 14% share of renewable energy in transport, but are instead given the option of either enforcing a 29% share of renewable energy in transport by 2030 or reducing GHG intensity by 13%, it is likely that other countries will also use an instrument similar to the GHGMQ. The extent to which a uniform instrument related to the GHGMQ is preferable to national solutions from an environmental economics perspective requires further research.

Taken together, the results suggest that to reduce GHG emissions from fossil fuels as efficiently as possible, it is advisable to adapt the GHGMQ trading scheme and combine it with other environmental economics instruments.

[8] The climate premium works like this: Every household receives a fixed premium. Those who produce less greenhouse gases pay less in absolute terms through the prices and benefit more from the premium (Burger et al., 2022, p. 14).

[9] However, there is a small risk of fuel tourism due to lower fuel prices in neighboring countries, especially in border regions (Destatis, 2022).

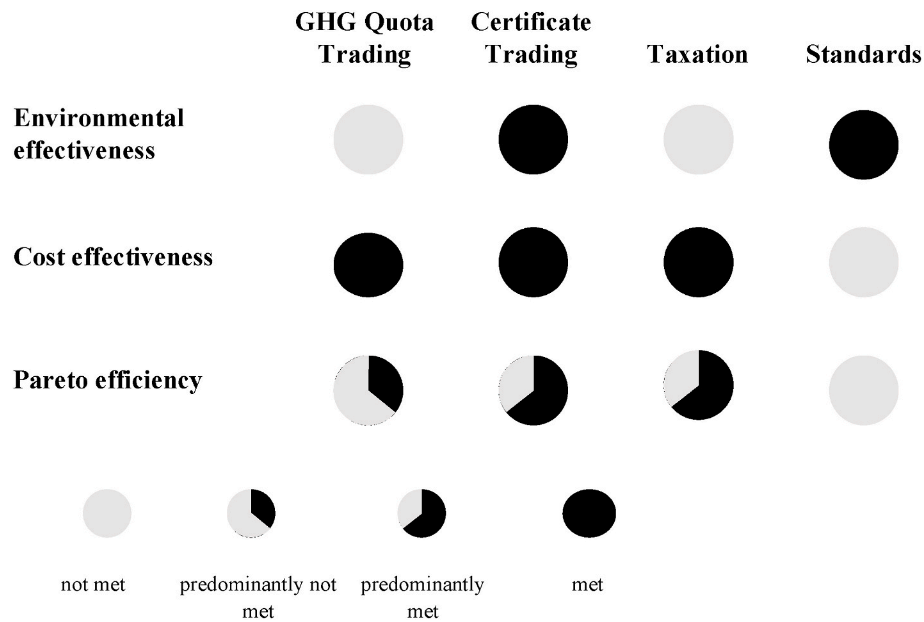

Fig. 3. Evaluation of the GHGMQ trading based on basic criteria compared to other internalization strategies.

CRediT authorship contribution statement

Constanze Liepold: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Resources, Validation, Visualization, Writing – original draft. **Paul Fabianek:** Conceptualization, Investigation, Methodology, Supervision, Validation, Visualization, Writing – review & editing. **Reinhard Madlener:** Conceptualization, Methodology, Project administration, Supervision, Validation, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Appendix

Table A.1
Guiding questions for the semi-structured interviews

	Guiding question (in the original German language)	English translation by the authors
1	Wie läuft der THG Quotenhandel ab?	How does the GHGMQ trading work?
2	Wie würden Sie die Rolle der Zwischenhändler beschreiben?	How would you describe the role of pooling firms?
3	Wie beschreiben Sie den Preisbildungsmechanismus? Wer setzt die Preise fest?	How do you describe the pricing mechanism? Who sets the prices?
4	Welche Kritik (positiv und negativ) haben Sie am Instrument „THG Quotenhandel"?	What criticisms (positive and negative) do you have of the "GHGMQ trading" instrument?
5	Wo sehen Sie noch Forschungsbedarf?	Where do you see a need for further research?

A.1 Example for the GHGMQ not being environmentally effective

This relationship is illustrated below by using a purely hypothetical example. Table A.1 provides an overview of the scenarios run. For simplicity reasons, it is assumed that there is only one form of high-emission, fossil fuel *h*, and one form of low-emission fuel *l*. The specific emissions of the fossil fuel β_h of 94.1 $\frac{kg\ CO_{2eq}}{GJ}$ correspond to the GHG emissions of the German fossil fuel mix as specified in the BImSchG. The specific GHG emissions of the low-emission fuel β_l are fictitious since the real average emissions of the low-emission fuels are subject to significant fluctuations. Based on these assumptions and knowing the amount of energy from fossil fuels Q_h, of low-emission fuels Q_l, and accordingly also in total Q_{total}, the quota q can be calculated as follows:

$$q = \frac{Q_{total}\beta_h - Q_h\beta_h - Q_l\beta_l}{Q_{total}\beta_h} = \frac{(Q_l + Q_h)\beta_h - Q_h\beta_h - Q_l\beta_l}{(Q_l + Q_h)\beta_h}. \quad (1)$$

By rearranging eq. (1), it is possible to determine either the total amount of energy, the amount of energy from the low-emission fuel, or the amount of energy from the fossil fuel, provided the quota level and one of the aforementioned variables are known.

Considering the different scenarios, we first assume that a firm sells 100 GJ of fossil fuel (Reference Scenario *Ref*). Its combustion results in GHG emissions of 9410 kg CO_{2eq}. In the first example scenario *S1*, fossil energy remains constant, but a GHGMQ of 6% is introduced. In order to meet the quota, 115 GJ of total energy must be demanded since 15 GJ of low-emission fuels must be sold to meet the quota. Consequently, total energy demand must have increased for the fossil energy demand to remain the same. In this scenario, total GHG emissions increased by about 8% despite of the quota. Without the quota (*S1.2*), the increased demand would have been satisfied exclusively by fossil fuels, and emissions would have increased by about 15% compared to the Reference Scenario.

The total energy demand has remained constant in the second scenario (*S2*). In this case, 13 GJ of fossil fuel must be replaced by low-emission fuel to meet the quota. This results in a 6% mitigation in GHG emissions compared to the Reference Scenario. If the quota is 7% instead of 6% (*S3*) and the total demand is constant, 7% of the GHG emission are saved compared to the Reference Scenario.

If the demand for fossil fuels decreases to 90 GJ (*S4*), for example, due to GHG pricing or cost increases resulting from the GHGMQ, the firm must sell 13 GJ of the low-emission fuel to meet the quota. This assumes that overall fuel demand has increased and that there is demand for low-emission fuel. If this is not the case, the firm is forced to reduce its sales by 3 GJ despite of the fossil fuel demand to meet the quota.

If there is a decrease in total energy demand, e.g., due to efficiency improvements, the firm must limit its sales to 78 GJ. Otherwise, it will miss the quota (*S5*). In this case, the absolute emission mitigation compared to the Reference Scenario would be the highest at about 15%.

Table A.2
Interdependencies between quota and fuel quantities

Scenarios	Q_l	Q_h	Q_{total}	β_l	β_h	GHG_l	GHG_h	GHG_{ges}	Reference value	GHG mitigation	GHGMQ	GHG compared to *Ref*
	GJ			$\frac{kg\ CO_{2eq}}{GJ}$		$kg\ CO_{2eq}$						
Ref.	0	100	100	50	94.1	0	9410	9410				
S1	15	100	115			734	9410	10,144	10,792	647	6%	8%
S1.2	0	115	115			0	10,822	10,822	10,822			15%
S2	13	87	100			640	8205	8845	9410	565	6%	−6%
S3	15	85	100			747	8004	8751	9410	659	7%	−7%
S4	13	90	103			661	8469	9130	9712	583	6%	−3%
S5	12	78	90			576	7385	7961	8469	508	6%	−15%

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