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Implications of Design Choices in the Allocation of Carbon Contracts for Difference

A Review of the Literature

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Implications of design choices in the allocation of Carbon Contracts for Difference – a review of the literature

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Abstract

Carbon Contracts for Difference (CCfDs) have emerged as a key economic policy instrument for industrial decarbonization in Europe and increasingly worldwide. They are contractual agreements between governments and developers of low-carbon projects that guarantee a fixed carbon price over the duration of the contract, serving both as a hedge and a subsidy. A key aspect of implementing CCfDs is the design of their allocation, which significantly impacts both the achievement of policy objectives and the associated costs. While several studies touch upon aspects of CCfD allocation, most existing literature addresses these topics only briefly or focuses on individual elements in isolation. Our work contributes to this emerging field by integrating the existing literature into a comprehensive analysis of CCfD allocation design and its associated implications. We present a structured review that categorizes key allocation design aspects according to predefined policy evaluation criteria (effectiveness, static efficiency, dynamic efficiency, and practical and legal feasibility) and practical design considerations. Our analysis highlights important trade-offs, such as those between static and dynamic efficiency, and identifies synergies in allocation design. Additionally, it draws attention to topics not yet explored in depth in the literature, including pricing methods in auctions, penalties and bidding strategies, and the interplay between allocation design options and broader CCfD design.

Keywords: Carbon contracts for difference, Industrial decarbonization, Instrument design, Climate policy, Green industrial policy

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1. Introduction

Global efforts to combat climate change require deep emission reductions in energy-intensive industries, such as the steel and chemicals sector, which account for a significant share of global greenhouse gas (GHG) emissions.[1] However, the adoption of low-carbon processes in these industries is hindered by their higher production costs compared to conventional, emission-intensive manufacturing methods [2]. Additionally, fluctuating and often low carbon prices, along with missing markets for green industrial products, fail to provide stable incentives for manufacturers to switch to clean technologies.

To address these challenges, various policy instruments have been suggested to incentivize investments in low-carbon industrial production processes [3]. One particularly prominent instrument is the Carbon Contract for Difference (CCfD), a contractual agreement between low-carbon project developers and governments, proposed by Richstein [4] in 2017. CCfDs are two-sided contracts that compensate the difference between the prevailing CO_2 market price and a pre-defined CO_2 price for the emission reduction achieved, thereby reducing carbon price uncertainty and bridging the cost gap with conventional industrial processes.

Since their theoretical introduction in 2017, CCfDs have quickly moved from theory to practice, with several large-scale programs established, especially in Europe. Examples of implemented programs include the Netherlands' Stimulating Sustainable Energy Production and Climate Transition program, Germany's CO_2-Differenzverträge program and the UK's Industrial Carbon Contracts. Furthermore, interest in CCfD schemes is growing beyond Europe: in Canada, the first CCfDs have been signed, and South Korea is preparing a national CCfD scheme.

As governments move forward with CCfD implementation, practical design considerations are receiving increasing attention, particularly within the European Union (EU). One of the key design aspects of CCfD programs is their allocation, i.e., determining who receives contracts and under what conditions. The purpose of this paper is to provide a comprehensive review of CCfD allocation and to discuss its implications. To that end, our research assesses the existing literature on CCfD allocation, offering a structured review that categorizes key aspects based on their relevance to predefined evaluation criteria and practical design considerations. The review has the following objectives: i) consolidate the current state of research on CCfD allocation, ii) clarify relevant CCfD allocation design aspects and respective options, iii) shed light on the potential implications of CCfD allocation design choices, including trade-offs and synergies[2] of design choices, and iv) identify key challenges and under-explored aspects in CCfD allocation design.

To achieve this, we review the rapidly expanding literature on CCfDs. Our analysis considers publications that focus on practical aspects of CCfD implementation, as well as more general literature on CCfDs. The first stream covers aspects such as the interactions of CCfDs with other climate policy instruments and regulations [e.g., 5, 6], and potential funding sources for CCfDs [e.g., 7, 8]. Furthermore, a significant

[1] Industry contributed to 22% in 2024, excluding emissions from industrial electricity use [1].
[2] Understood as complementary implications.

part of the literature discusses contract design aspects and respective options. Key considerations[3] include the calculation of the contract price [5, 10], the establishment of a benchmark for emissions [11], the dynamic adjustment of contractual payments to cover additional risks [e.g., 10, 12], as well as the allocation of CCfDs [e.g., 13, 14], which is the primary focus of this paper.

The second, more general stream of literature on CCfDs addresses broader conceptual and policy-related issues. Early work in this area primarily focuses on introducing the concept of CCfDs to academic and public audiences [e.g., 15, 16]. Another strand of literature highlights the benefits associated with CCfDs, including their de-risking capabilities that reduce financing costs [e.g., 17, 18, 19]. Other discussed benefits include the opportunity for governments to recuperate costs under high carbon prices [4] and the incentive compatibility for investment and operation [20]. Discussed risks of CCfDs include substantial and uncertain public expenditures [e.g., 7, 21], impacts on market competition within the EU [7] and a potential waterbed effect and reduced liquidity in the EU Emission Trading System (EU ETS) [e.g., 10, 21].

The way CCfDs are allocated has significant implications for achieving climate policy objectives while managing the associated costs. It is therefore crucial for policymakers and stakeholders to understand the various allocation options and assess their implications. However, to the best of our knowledge, while several studies touch upon the aspect of CCfD allocation, none of them provides a comprehensive review of different allocation design options and the design challenges associated. Moreover, much of the existing literature on CCfDs falls under the category of grey literature, in the form of a mix of qualitative discussions, case studies, and analytical analyses. This study's novelty and central contribution lies in integrating the existing elements into a comprehensive analysis on CCfD allocation and its associated implications.

Beyond its contribution to CCfD research, this paper also relates to broader literature on allocation trade-offs associated with environmental policy instruments. For example, there are notable parallels with the discussions on carbon permit allocation in the early 2000s. Prior to and throughout the evolution of the EU ETS, there has been considerable debate about how allowances should be distributed and the associated trade-offs [e.g., 22, 23]. More generally, CCfDs are implemented as part of wider climate and industrial policy mixes, alongside instruments such as carbon pricing and demand-formation measures. Analyzing CCfD allocation design therefore also contributes to the wider literature on policies for industrial decarbonization and governance of industrial decarbonization [e.g., 24, 25, 26].

This review is structured as follows. In the next section, we review the logic of CCfDs and present the main design aspects considered in the analysis. Section 3 outlines the methodology for the literature review. Section 4 reviews the allocation aspects covered in the literature on CCfDs. Finally, the findings are discussed in section 5, and conclusions are drawn in section 6.

[3] An overview of the most frequently discussed design elements is provided in [7, 9].

2. Background

2.1. The functioning of CCfDs

This paper uses an example of steel production to illustrate how CCfDs incentivize investments in low-carbon technologies [6, 27]. Figure 1 compares conventional blast furnace steelmaking with an alternative process that uses hydrogen to produce direct reduced iron (DRI), which is then converted to steel in an electric arc furnace (EAF). The DRI–EAF route faces higher capital and operating costs, with a cost gap of €477 per ton of steel (excluding carbon pricing). A carbon price of approximately 65€/tCO_2, comparable to the price level of EU ETS allowances observed in 2024, is insufficient to bridge the cost gap.[4]

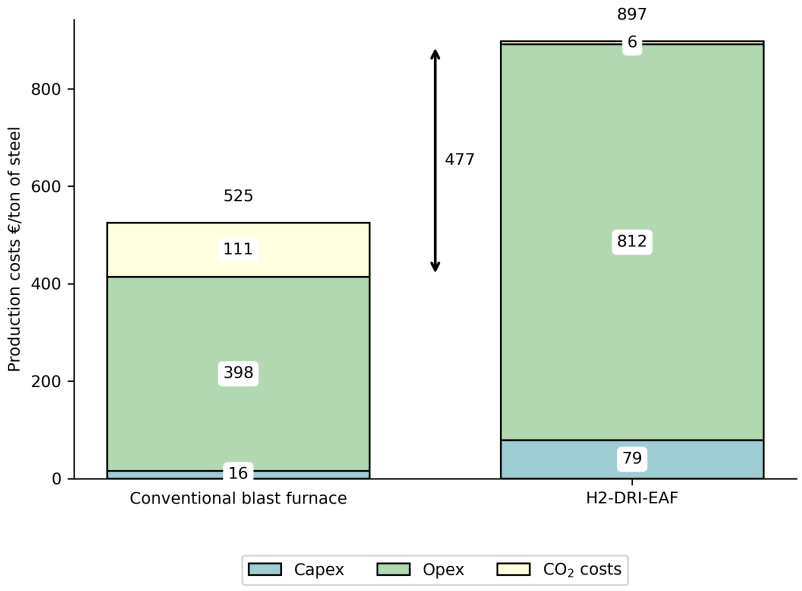


Figure 1. Comparison of conventional and low-carbon steel production costs.
Note: Based on [27], with updated price assumptions for electricity, natural gas, hydrogen and emission allowances. Average electricity and natural gas spot market price in 2024; hydrogen price in 2024 according to [28]; average price for EU ETS allowances in 2024. Without considering the free allocation of emission allowances.

Alongside insufficient carbon pricing levels, investments in low-carbon industrial processes are exposed to risk[5] due to the variability of carbon prices, the uncertainty of future energy prices and general regulatory risks regarding climate policy [14]. CCfDs aim to incentivize investments in low-carbon industrial production processes by addressing those risks [12, 14]. They are contracts between governments and low-carbon project developers agreeing on a fixed carbon price, the so-called strike price, over a defined period. By doing so, CCfDs provide carbon price certainty and, depending on the fixed carbon price, can help bridge or eliminate the cost gap between low-carbon and conventional production processes. CCfDs can hence be

[4]Assuming emission intensities of 1.71 tCO_2eq/ton of steel (conventional) and 0.09 tCO_2eq/ton of steel (low-carbon) as in [27]. This results in carbon costs of 111€/ton of steel and 6€/ton of steel, respectively.

[5]Both conventional and low-carbon producers face those risks. However, the risks of low-carbon producers can be regarded higher compared to those faced by conventional producers (see [2, 29]).

regarded as a hedging and subsidy instrument [14].

CCfDs are awarded for several years and cover the gap between the market price of CO_2, such as the price of EU ETS allowances, and a pre-defined strike price. For each contract year, the difference is paid per unit of emission reduction achieved by the project relative to a conventional technology. If the market price is below the strike price, the project receives a payment; if it rises above, the project repays the difference to the government. Figure 2 presents the basic functioning of a CCfD, using the example displayed in Figure 1. With an emission reduction of 1.62 tCO_2eq per ton of steel compared to a conventional production process, the strike price would need to be set at €294 per tCO_2eq to cover the full abatement cost of the low-carbon project. The strike price corresponds to the cost differential between the two production methods of 477€/ton of steel, divided by the avoided emissions per ton of steel.

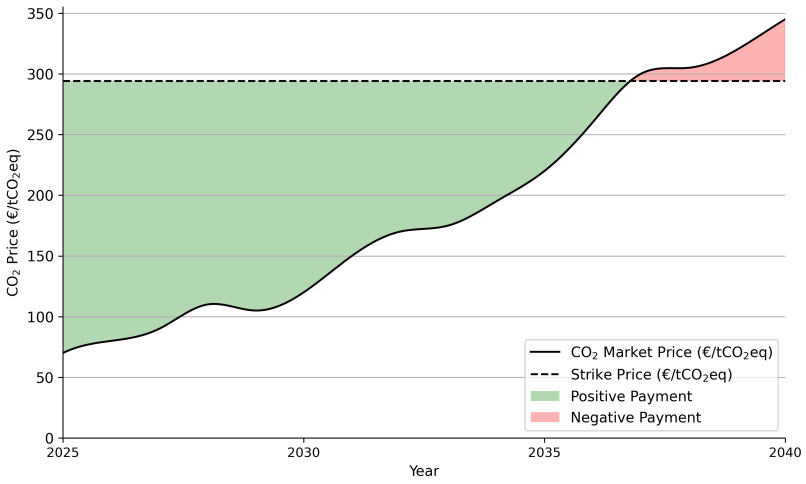


Figure 2. Illustration of the basic functioning of CCfDs. Note: Based on [6, 27, 30].

While the original form of a CCfD is a two-sided contract-for-difference, meaning that negative payments for the project developer are possible, modified forms of CCfDs include contracts that are designed as one-sided CCfDs. Other potential modifications include the coverage of other price risks apart from the CO_2 price risk, such as energy prices[6], or the adjustment of yearly payments by green premiums.[7]

2.2. Overview of CCfD allocation design options

As outlined in the introduction, CCfD schemes can be designed in many ways. A critical component of a CCfD scheme is its allocation design, which is the focus of this paper. Various design options for CCfD allocation exist and have been described in the literature, generally falling into three main categories: eligibility rules, award procedures, and award criteria. Table 1 provides a broad overview of the allocation design options discussed in the literature and covered in this paper. These options will be presented in greater detail in section 4, particularly in relation to policy evaluation

[6]Through the indexation of the yearly payments to the energy costs, as in the German CCfD scheme [2].
[7]Price premium for the additional cost of a green product paid by the consumer [31].

criteria to assess their implications.

Table 1. Allocation design categories and respective options.

Category	Explanation	Options
Eligibility rules	Eligibility criteria define which entities or projects qualify for a CCfD scheme. They describe the specific conditions that must be met by applicants for CCfDs to be eligible. Eligibility criteria for CCfDs can be applied to multiple dimensions.	Sectors Technologies Project size GHG emission reduction Commercialization level Financial capacity Innovation grant winners Prequalification stage Third-party verification
Award procedure	The award procedure denotes the process by which CCfDs are allocated to eligible applicants. Options for the award process include the awarding to all eligible projects, negotiations and auctions. There are several additional relevant design options, such as choosing between clustering options, which refers to the aggregation of technologies and/or sectors into separate allocation groups.	All eligible projects Auctions Negotiations Combinations of auctions & negotiations National vs. international allocation Risk buffer in the reserved budget Price ceiling Ex-ante sector/technology clustering Ex-post technology pots Joint clearing algorithm Bid scaling factors Funding round frequency
Award criteria	Award criteria specify the specific conditions and metrics used in the award procedure to evaluate and select applicants.[a] These criteria can include both price and non-price factors, and can be either numeric or qualitative.	Support cost efficiency Risk propensity GHG emission reduction Promotion of green lead markets Technological maturity Financial maturity Operational maturity Positive spillover effects Employment impact Verification of criteria fulfillment

[a]Eligibility and award criteria could also be interchanged [14]. For clarity, this possibility is not considered in the following sections.

3. Methodology

While various publications offer insights on CCfD allocation design aspects and the implications of design choices, most only discuss these topics briefly or address individual aspects in isolation. This study reviews the existing CCfD literature, whereby information on the allocation of CCfDs is filtered out and summarized.

To construct the review corpus, a two-step search and screening process is applied. First, publications referring to CCfDs are identified through keyword searches in both English and German[8] in academic databases (e.g., ScienceDirect, IEEE Xplore, Scopus) and Google Scholar, supplemented by targeted searches of publications from think tanks (e.g., Agora Industry, Bruegel, IDDRI). The search covers documents published up to the end of 2025 and does not apply any lower bound on the year of publication. Keywords include, for instance, "carbon contracts for difference", "CCfD" and "CO_2-Differenzvertrag". In addition to peer-reviewed articles, conference papers, working papers, policy briefs and other grey literature are considered. The reliance on grey literature reflects the fact that CCfDs are a relatively new policy instrument and that much of the detailed design discussion currently takes place in non-peer-reviewed reports and working papers.

[8]German publications are included because a substantial share of early work on CCfD design has been published in German, particularly with respect to the German CCfD scheme.

Second, all identified publications are screened to determine whether they cover allocation design aspects beyond a brief mention. Only those that discuss at least one of the three practical allocation design aspects defined as relevant for this study (eligibility rules, award procedures or award criteria) are included in the review corpus. Publications that mention allocation without substantive discussion are not considered in the subsequent review of allocation design options.

Table 2 categorizes the most relevant existing literature based on how thoroughly it covers practical CCfD allocation design aspects and the resulting implications in terms of evaluation criteria.

Table 2. Covered aspects in the most relevant publications treating the allocation of CCfDs and the implications of CCfD allocation design choices (2020-2025)[a].

	Practical allocation design aspect			Implication in terms of evaluation criterion			
Reference	Eligibility rules	Award procedure	Award criteria	Effectiveness	Dynamic efficiency	Static efficiency	Feasibility
Chiappinelli et al. [20]	*	*		*		*	*
Gerres and Linares [16]		*			*	*	*
Gerres and Linares [7]	*	***	*	*	**	**	*
Hauser et al. [5]	*	***	***	*		*	
Jeong and Chang [32]		***	*	*	***	***	*
Lösch et al. [14]	***	***	***	*	*	*	**
Lösch et al. [10]	*	**	***	*	*	*	
McWilliams and Zachmann [8]	*	***	**	*	***	***	*
Müller and Lechtenfeld [6]	*	*			*	*	*
Richstein et al. [13]	*	***	**	**	***	***	***
Richstein et al. [2]	*	**	*	*	**	**	*
Rilling et al. [9]	*	**	*	*	**	**	
Sartor and Bataille [15]	*	***	**	*		**	**
Stiebert and Bataille [33]	*	*		*	*	*	
Wambach et al. [21]		**	*			**	*
Vogl et al. [34]	*	**				*	*

Legend: ***: In-depth coverage; **: Medium coverage; *: Low coverage; : No coverage.

[a]References that cover CCfD allocation to some extent and are included in the review corpus. Publications that very briefly mention allocation aspects without discussing them are excluded [e.g., 4, 12, 19, 30, 35].

Proposed allocation design options in the current literature on CCfDs are often discussed in relation to specific policy goals and evaluation criteria. Thereby, the range of policy goals and evaluation criteria utilized complicates comparisons of allocation design options. To organize the allocation aspects covered in the literature, it is therefore necessary to use a predefined policy goal and evaluation criteria.

The overall policy goal defined for this study is to achieve large-scale, non-incremental emission reductions in the industrial sector. This goal is chosen because it can be regarded as the most important and overarching objective among other policy objectives regarding CCfDs,[9] thereby preventing a partial analysis. This aligns with Lösch et al. [10], who consider the avoidance of GHG emissions as the overarching objective of a CCfD scheme.

The policy evaluation criteria used in the literature on CCfDs are grouped into four main criteria that enable to assess the effect of different allocation design options on reaching the defined policy goal: i) effectiveness, ii) static efficiency, iii) dynamic efficiency, and iv) practical and legal feasibility. These criteria are chosen because they allow for a systematic categorization of findings, making it easier to draw compar-

[9]Other stated or implicit objectives in the literature include the commercialization of low-carbon industrial projects [15, 16], the initiation of the industry's transformation to climate neutrality [5], enabling investments in innovative low-carbon technologies [6, 29], and the diffusion of low-carbon technologies [2].

isons across different studies and design options. The policy evaluation criteria and definitions are drawn from [9, 34, 36, 37]. The applied policy evaluation criteria are understood as presented in Table 3.

Table 3. Evaluation criteria and definitions.

Criterion	Definition
Effectiveness	Evaluates the extent to which a given objective is accomplished. For this study, it applies to the realized emission reductions achieved, directly via the CCfD contracts. Effectiveness can be divided into *ex-ante* effectiveness, assessed before project implementation, and *ex-post* effectiveness.[a]
Static efficiency	Refers to the costs incurred to achieve a specific objective, in this case the support costs of a CCfD scheme per unit of emission reduction realized.
Dynamic efficiency	Refers to the costs incurred to achieve a specific objective in the long term, in this case, the long-term costs of emission reductions achieved through a CCfD scheme's impact on innovation, technology diffusion, and other spillover effects.[b]
Practical and legal feasibility	Assesses the risk that a public policy instrument may face implementation challenges due to practical and legal constraints. It includes political acceptance, administrative burden, and compliance with regulations.

[a] *Ex-ante* effectiveness can for instance be reduced through auction undersubscription. *Ex-post* effectiveness is influenced by project delays and realization rates. A more detailed explanation is provided in [37].

[b] The indirect impact of large-scale CCfD programs on emission reductions through their influence on the price of EU ETS allowances is not considered in this analysis.

In the following sections, the CCfD allocation aspects discussed in the literature are systematically presented and categorized according to their relevance for the four policy evaluation criteria. The assessment of allocation design options against the policy evaluation criteria is based on arguments presented by authors in the literature on CCfDs, occasionally supplemented by general economic literature and literature on the allocation of renewable energy support. Each of the four categories is further subdivided into the practical allocation design aspects eligibility, award procedure, and award criteria. This second level of categorization helps linking the implications of allocation design in terms of policy evaluation criteria to tangible design options for practical implementation.

4. CCfD allocation aspects covered in the literature

In the following, the CCfD allocation aspects discussed in the literature are systematically presented, according to the methodology presented in section 3. A visual summary can be found in section 4.5.

4.1. Effectiveness

4.1.1. Eligibility rules

The first relevant aspect regarding the induced effectiveness of a chosen CCfD allocation design is the definition of eligible projects. In this regard, numerous publications emphasize the importance of eligibility criteria related to the level of emission reductions achieved by a project. Such criteria influence which projects participate in a CCfD scheme and, consequently, affect the ultimate emission reductions achieved through a CCfD program. The literature consistently agrees that eligible projects should align with climate neutrality goals [e.g., 6, 20]. This alignment means that emission reductions should be sufficient to meet these goals [20], and projects with

only incremental emission reductions are not eligible [8].

For effectiveness, it is furthermore important that companies have clarity over their eligibility when submitting a final offer. Several publications [e.g., 5, 14] recommend a multi-stage award process starting with a pre-qualification phase. Such a process can allow companies to adapt their projects in case of observed non-eligibility in the pre-qualification phase, thereby enabling more projects to successfully participate in the final awarding phase and increasing *ex-ante* effectiveness.

4.1.2. Award procedure

The impact of award procedures on effectiveness is rarely addressed in the literature despite their potential significance. For instance, an awarding procedure resulting in an increased level of competition affects effectiveness, with potential ambiguous effects. *Ceteris paribus* a higher level of competition results in greater emission reductions within a given budget by selecting more cost-effective projects. In this regard, Wambach et al. [21] state that, from a climate protection perspective, a Europe-wide tender would be more beneficial than a national one. However, it should also be considered that high levels of competition may lead to underbidding, which could potentially affect *ex-post* effectiveness, as discussed regarding renewable energy auctions in [38].

Another aspect relevant for effectiveness, which is indirectly related to the award procedure, is the definition of the reserved budget of a CCfD program. The reserved budget is the maximum budget allocated for CCfD projects and an overall CCfD program and can include risk coverage to fulfill contracts in case of adverse regulatory or market developments [2]. For instance, a less risk-averse definition of the reserved budget would result in more projects being funded with the same overall budget, compared to a bigger risk buffer [2]. However, a reduced risk buffer not only affects the government's but also the projects' risk. Consequently, this could potentially result in a lower number of awarded projects through the addition of risk premiums in bids or a higher rate of project non-realization, negatively impacting effectiveness.

In general, the budget available for a CCfD program naturally has a significant impact on allocation outcomes [10] and overall effectiveness. As an alternative to a fixed budget, the scope of a CCfD program could be based on an emission reduction target [14], which would offer higher certainty regarding the amount of direct GHG emissions reduced.

4.1.3. Award criteria

Whether GHG emission avoidance is used directly as a differentiated award criterion [as suggested by 14] or only indirectly through a cost efficiency criterion – calculated as costs per emission avoided – is relevant for effectiveness. This distinction impacts whether projects that maximize emission reduction or projects with the lowest cost per emission reduction, but lower overall emission reductions, are preferentially selected.[10] The method used to calculate GHG emission avoidance also affects effectiveness by influencing which projects are selected. For instance, relative measurements

[10]However, as pointed out in the literature [10], with a limited budget, the criterion of cost efficiency inherently results in choosing projects that achieve a generally high level of emissions reductions.

may diminish the significance of rankings if all projects achieve complete emission avoidance, in contrast to absolute measurement [10].

Furthermore, award criteria related to project maturity, as suggested by Lösch et al. [14], can have mixed effects on the effectiveness of a CCfD program. On the one hand, such criteria can improve *ex-post* effectiveness, as the likelihood of project delays and non-realization is lower in more mature projects. On the other hand, these award criteria can decrease *ex-ante* effectiveness by disincentivizing applications from less mature projects.

4.2. Static efficiency

Static efficiency, which refers in the case of CCfDs to the support costs per unit of emission reduction realized, is shaped by several economic principles that should be considered when allocating public support.[11] One major challenge in designing CCfD allocation is information asymmetry between contract parties. Companies often have more accurate information about their abatement costs than the state, the CCfD issuer [21]. This can lead to adverse selection, where companies exploit information asymmetry to receive more funding than necessary, for example, by submitting low initial offers and renegotiating the strike price later [13]. Another concern related to information asymmetry is the risk of windfall profits, with companies being subsidized for abatement measures they would have undertaken anyway [39].

Another key economic principle, especially for allocation through auctions, is the level of competition among potential recipients, which is determined by the number of participants and the degree of similarity in their cost structure [40]. An insufficient level of competition can lead to higher auction bids [40]. Lastly, the risk of collusion must be considered [41]. Collusion reduces competition and can decrease static efficiency through potentially higher bids and distorted allocation outcomes.

4.2.1. Eligibility rules

Several publications suggest ensuring static efficiency through stringent eligibility criteria. For instance, McWilliams and Zachmann [8] recommend that eligible projects must be ready for commercialization, which could also address information asymmetry regarding technology costs. Another approach to address asymmetric information is to have a third party verify the cost estimates submitted by companies during the pre-qualification stage [15], which could help identify unrealistic cost estimations early and also potentially enhance *ex-post* effectiveness. Furthermore, setting strict eligibility criteria for emission reductions (as described in section 4.1.1) can contribute to address the risk of windfall profits.

Generally, the definition of eligibility – such as regarding sectors and technologies – impacts the potential number of applicants to a CCfD program. This, in turn, influences the level of competition and static efficiency. For instance, Gerres and Linares [16] point out that high administrative requirements for participation can prevent smaller companies from applying and favor established companies.

[11] Although they are also relevant for the effectiveness and dynamic efficiency of CCfD programs, their relevance is most apparent for static efficiency.

4.2.2. Award procedure

Beyond eligibility criteria, the chosen award procedure is crucial for the static efficiency of a CCfD program and is discussed relatively extensively in the literature. Theoretically, CCfDs could be awarded to all eligible projects [20]. In many publications, auctions or competitive tendering[12] are suggested as means of CCfD awarding. In auctions eligible companies bid on their required strike price for implementing emission-reducing technologies [7]. The strike price can represent the full abatement cost of a low-carbon project, as illustrated in the exemplary project in section 2.1, or cover less than the full cost. The strike price, along with other awarding criteria, can be linked to scoring points and weighted according to program objectives [14].

Auctions are suggested in the CCfD literature due to their economic efficiency and ability to prevent strategic behavior and mitigate the risk of asymmetric information [e.g., 7, 15, 20]. However, Wambach et al. [21] and Richstein et al. [13] caution that in certain industry sectors, such as steel, there are only a handful of companies willing to switch to green alternatives; hence competitive tendering in those sectors is unlikely. Similarly, Jeong and Chang [32] highlight that the industrial concentration of sectors should be taken into account when designing auctions. McWilliams and Zachmann [8] argue that regular auctions can reduce information gaps by continually revealing industry preferences, but warn that in capital-intensive sectors, frequent auctions may result in fewer participants and more unpredictable bids.

While several publications favor auctions, some also advocate for negotiations or combinations of both as a preferred method [5, 7, 13]. This is because the novel low-carbon technologies supported by CCfDs are often immature and innovative, introducing *ex-ante* uncertainty regarding their performance and a high risk of costly *ex-post* renegotiations [7, 13]. Richstein et al. [13] suggest that when uncertainty cannot be resolved in advance, it may be preferable to allow some negotiation – such as by setting price limits through dialogues with stakeholders – before awarding contracts.

In addition to discussing the proposed general means of allocation, the literature addresses how these can be implemented in practice. Several papers examine the options for clustering allocation, according to sectors and technologies. It is highlighted that while supporting diverse sectors aids effective decarbonization, it can increase support costs, by supporting projects from sectors with relatively high abatement costs [13]. Furthermore, the literature points to the risk of inframarginal rents in wide clustering options [13, 32], lowering static efficiency. Fabra and Montero [42] state that when procuring multiple units of a good produced with heterogeneous technologies, the optimal clustering choice depends on several factors, including the degree of information asymmetry, the relative costs of the technologies, and their substitutability.

For less competitive mechanisms, price ceilings are proposed to ensure static efficiency. Richstein et al. [13] argue that price ceilings are essential in markets with few expected participants, such as CCfDs, to maintain price discipline and prevent coordinated bidding. Similarly, McWilliams and Zachmann [8] suggest establishing an *ex-ante* price ceiling to limit the total amount of public funding allocated. However, price ceilings may undermine competitive price discovery in an auction if bidders use them as price

[12]In the literature the terms "auctions" and "competitive tenders" are to some extent used interchangeably.

orientation, as noted by the US Agency for International Development [43] regarding renewable energy auctions.

4.2.3. Award criteria

One of the primary discussed award criteria regarding static efficiency is the support cost efficiency of a project. Lösch et al. [14] suggest using a combination of two criteria: The first criterion is subsidy cost efficiency, measured by the amount of GHG emissions avoided per unit of subsidy. The second criterion considers to what extent a firm is willing to cover risks: Applicants must provide a fixed cost function and a non-negotiable maximum value for CCfD coverage, with price parameters dynamically adjusted using energy price indices [14]. This approach could help address the risk of renegotiation, as raised by [7, 13], see section 4.2.2.

Furthermore, the promotion of green lead markets could be taken into account by considering the extent to which projects commit to selling their products as low-carbon [5]. This approach could reduce the funding need for CCfDs by ensuring a certain amount of low-carbon products sold in the market with a green premium [5], thereby improving the static efficiency.

4.3. Dynamic efficiency

A key economic principle for achieving dynamic efficiency is technological lock-in, which describes the phenomenon where certain technologies become dominant, even if they are potentially less effective or efficient in the long term compared to other, initially more expensive, technologies [44]. Public policies can therefore be evaluated based on their ability to avoid technological lock-in, thereby increasing dynamic efficiency. In the context of CCfDs, this can be achieved by supporting diverse project types, including different sectors and technologies. Supporting a wide range of sectors is important for avoiding lock-in, as specific technologies often relate more closely to certain sectors (e.g., carbon capture is particularly relevant to the cement sector).[13]

4.3.1. Eligibility rules

The literature offers various suggestions for project eligibility by sector and technology, which impacts the diversity of a CCfD scheme's allocation outcome. These suggestions range from limiting eligibility in general to the industrial sector [20] or the energy-intensive industry with process emissions [14] to specific sectors and technologies [5]. Through a more indirect approach, Richstein et al. [13] propose implementing participation constraints based on minimum emission reductions by sector, which could be similarly applied to technologies. In this regard, the authors, drawing on [45], highlight that innovation is fostered when contract requirements and evaluation criteria emphasize functionalities – such as emission reduction potential – rather than specifying particular technologies [13].

[13]It is worth noting that technological lock-in can also be avoided using a combination of different instruments, with one instrument (e.g., CCfDs) focusing on a specific set of technologies, while another instrument covers other sectors or technologies. For the purposes of this analysis, this consideration is excluded for clarity.

4.3.2. Award procedure

Regarding the implications of the award procedure for dynamic efficiency, not the award procedure, but rather the clustering options of award procedures are discussed in the literature. Richstein et al. [13] describe three principal approaches for sector and technology clustering, drawing on earlier categorizations [e.g., 15]. These are broad clustering, which allows competition across all sectors and technologies; intermediate clustering, which restricts competition to within sectors but across technologies; and narrow clustering, which limits competition to the same sector and technology. Technology clustering could also be applied by creating distinct groups for established and emerging technologies [8]. Choosing between clustering options involves trade-offs, as highlighted by Richstein et al. [13] and McWilliams and Zachmann [8]: wider clustering supports competition and static efficiency, while narrower clustering enhances resilience through greater technological and sectoral diversity.

As an alternative to holding auctions for different sector or technology pots, McWilliams and Zachmann [8] propose the use of *ex-post* technology pots, based on [42]. This method incorporates a general auction with minimum quotas for specific technologies, which only become effective if the cross-technology competition fails to support a diverse range of technologies. Richstein et al. [2] see advantages in another approach: conducting a single auction while differentiating sectors and technologies using distinct price ceilings or bid scaling factors[14] to support a balanced competitive environment. This approach would allow different sectors and technologies to participate and potentially win, while creating a high level of competition between projects [2]. However, the authors highlight that this method does not fully address the inherent cost disparities among technologies. Another recommended approach to achieve dynamic efficiency consists in using a joint clearing algorithm to account for project interdependencies, such as by prioritizing projects across sectors [13].

4.3.3. Award criteria

The choice of award criteria can affect dynamic efficiency by influencing the distribution of projects within and between different sectors [10]. For instance, the way in which the criterion for GHG emission avoidance is defined – whether it is measured in absolute or relative terms[15] [14] – can influence the type of selected projects. While absolute measurement of emissions avoidance tends to favor larger projects, several smaller projects can trigger more learning effects [10].

Positive spillover effects are mentioned as an additional criterion affecting the dynamic efficiency of allocation outcomes. This includes evaluating projects for their external benefits in advancing overarching infrastructure or regional production networks [5], their contributions to supporting a decarbonized industry through system-level improvements,[16] and their scalability at the sector level [14]. McWilliams and Zachmann [8] likewise recommend focusing on projects that can be easily replicated and benefit significantly from learning effects.

[14]Different factors per sector or technology, that are multiplied with the bids and thereby scale up or down the bids.

[15]Per ton of product compared to a sector-specific reference process.

[16]Such as contributing to the scale-up of a hydrogen economy or the use of demand side management of electricity consumption.

Furthermore, considering the promotion of green lead markets as an award criterion as suggested by Hauser et al. [5] – see section 4.2.3 – could help growing such markets and thereby drive cost-efficient decarbonization in the long term. Moreover, suggested award criteria regarding the technological, financial, and operational maturity of a project, as suggested by Lösch et al. [14], can negatively influence to what extent a technological lock-in is avoided.

4.4. Practical and legal feasibility

4.4.1. Eligibility rules

In the literature, eligibility is mainly discussed in relation to administrative burden. Setting a minimum project size in terms of investment volume and requiring proof of the applicants' financial capacity, as recommended in [14], can ensure the proportionality of the administrative burden. To further reduce the administrative burden, Sartor and Bataille [15] propose that winners of European or national innovation grants automatically become eligible.

4.4.2. Award procedure

The award procedure is mainly discussed concerning legal and political feasibility. Müller and Lechtenfeld [6] favor competitive tendering due to its alignment with EU state aid guidelines. Conversely, Richstein et al. [13] favor negotiations over auctions and explore how negotiations could be practically implemented within the EU public procurement framework. The authors note that although negotiations in the EU are beneficial and feasible to implement, they tend to prolong the allocation process and are resource-intensive for both parties [13].

Furthermore, even though several publications advocate for European-level tendering due to its ability to enhance competition, this approach is often considered less feasible. According to Wambach et al. [21], it would take more time to implement compared to national initiatives. Additionally, McWilliams and Zachmann [8] highlight that European-level tendering is politically less feasible as national governments tend to be protective of their industrial policies and may oppose the allocation of funding to companies outside their own countries.

Regarding the feasibility of award procedures, the complexity of a scheme is also relevant. Overly complex schemes may be impractical to implement, as they require significant resources from the implementing authorities and can also lead to transparency issues [13]. Furthermore, complex allocation schemes increase the risk of mistakes, such as when allocating budgets in narrow clustering options [32]. Moreover, due to political economy reasons such as the influence of interest groups, technology-specific auctions are likely to deviate from theoretically optimal solutions [42].

4.4.3. Award criteria

Award criteria are also considered from the perspective of political feasibility. Integrating employment impact as an award criterion, as suggested by Gerres and Linares [7], could enhance the political appeal and acceptability of a CCfD scheme. Additionally,

award criteria are discussed in terms of complexity and transparency. For example, including soft criteria, such as technological pathways, in the awarding stage may increase complexity and reduce transparency [13]. Lösch et al. [14] highlight that the evaluation of projects should be institutionalized in a way that ensures a high level of objectivity, such as by experts conducting the evaluation according to clear guidelines.

4.5. Visual summary

In the following, a visual summary of the elements discussed in sections 4.1 to 4.4 is presented.

Table 4. Synthesis of the discussed relevance of CCfD design options for policy evaluation criteria.

Design option	Effectiveness	Static efficiency	Dynamic efficiency	Feasibility
Eligibility rules				
Sectors			•	
Technologies			•	
Project size				•
GHG emission reduction	•	•	•	
Commercialization level		•		•
Financial capacity				•
Innovation grant winners				•
Prequalification stage	•			
Third-party verification	•	•		
Award procedure				
Auctions		•		•
Negotiations		•		•
Combinations of auction and negotiations		•		•
National vs. international allocation	•	•		•
Risk buffer in the reserved budget	•			
Price ceiling		•	•	
Ex-ante sector/technology clustering		•	•	•
Ex-post technology pots		•	•	
Joint clearing algorithm			•	
Bid scaling factors		•	•	
Funding round frequency		•		
Award criteria				
Support cost efficiency		•		
Risk propensity		•		
GHG emission reduction	•	•	•	
Promotion of green lead markets		•	•	
Maturity	•		•	
Positive spillover effects			•	•
Employment impact				•
Verification of criteria fulfillment				•

A • indicates that the corresponding CCfD allocation design option is discussed in this paper as relevant to the specified policy evaluation criterion, according to the underlying literature. This table does not provide any assessment on the direction of effects – only the relevance is indicated. General topics, such as the overall impact of competition on effectiveness, are excluded.

5. Discussion

5.1. State of the literature

This study addresses the lack of a comprehensive review of allocation design options for CCfDs by systematically analyzing and structuring the current literature. The analysis reveals that the existing literature on CCfD allocation primarily relies on grey literature and qualitative analyses, lacking quantitative methods to thoroughly analyse allocation implications. Publications mainly address CCfD allocation as a side topic, proposing several options and discussing their implications, but frequently remaining high-level and non-exhaustive.

For instance, while it is mentioned that well-designed auctions can prevent strategic behavior and exploitation of asymmetric information, detailed guidance on how to design auctions to achieve these outcomes is lacking. Similarly, eligibility and

awarding criteria are proposed without objective assessment methods, and proposals for dynamic and static efficiency lack practical details, such as how to configure technology pots or scaling factors. Furthermore, some statements, such as equating auctions with competition, lack substantial reasoning.

Large parts of the literature suggest auctions as a means of awarding CCfDs [e.g. 15, 20]. However, important aspects regarding auctions, such as pricing and non-compliance rules, as well as lead times and bidding strategies, are only sparsely addressed. Similarly, the literature lacks discussion on the definition of reserved CCfD budgets, which determines the size of risk buffers and is relevant for allocation outcomes and budget implications. It influences the amount of potentially supported emission reductions within a given overall budget and affects static efficiency and effectiveness through the impact on the projects' risk coverage. Furthermore, while the literature does cover the issue of asymmetric information, it typically addresses the topic broadly in relation to abatement costs. However, this issue spans various levers, such as information on technological capabilities, input factor costs, cost of capital, and company abatement efforts, each of which should be addressed distinctly.

Several allocation options discussed in the literature are framed in relation to pertinent awarding objectives or policy evaluation criteria. Thereby, the literature tends to evaluate allocation design options in relation to different evaluation criteria in isolation rather than in combination, leading to inconsistent evaluations across publications and limited consideration of trade-offs. A notable exception involves the trade-off between dynamic and static efficiency, which is especially prevalent in the literature. In contrast, the impact of allocation design on effectiveness as well as the connection between effectiveness and static efficiency are generally less discussed. In particular, the risk of non-realization is almost non-existent in the literature, although it is essential for the achievement of policy objectives and is influenced by the allocation design.

Various authors note that trade-offs between objectives and design options are inevitable and must be resolved politically or by clearly defining intended objectives [e.g., 10, 13]. Indeed, the final outcome of CCfD design depends on a program's specific objectives and constraints. However, it is essential for policymakers to understand the implications of the different design options as well as the trade-offs and synergies involved to make informed decisions.

5.2. Additional findings on the implications of allocation design options

The analysis points to many implications of allocation design options in terms of the four applied policy evaluation criteria. In some cases, the implications of a design option in terms of a criterion are not straight-forward. For example, less stringent eligibility criteria could reduce effectiveness by allowing projects with less ambitious emission reductions to participate or by negatively affecting realization rates. However, they might also enhance effectiveness by increasing competition, lowering costs, and hence funding more projects.

Furthermore, as pointed out in the literature, trade-offs in CCfD allocation design exist. Besides the strongly discussed trade-off between dynamic and static efficiency,

this analysis points to others, such as that award criteria regarding the maturity of a project can increase *ex-post* effectiveness but also negatively impact dynamic efficiency. There can also be a gap between theoretically optimal and politically feasible choices. For instance, a trade-off exists between the speed of implementing a measure and its optimality. This becomes clear when considering whether negotiations or auctions are better suited for CCfDs, or whether allocation should be at European or national level. Moreover, some theoretically ideal suggestions may be complex to implement and challenging for companies to understand (e.g., joint algorithms, scaling factors). If too complex, companies might not participate due to high entry costs and difficulties in assessing winning chances.

The analysis also shows that synergies exist between the various allocation options. For example, addressing asymmetric information and the risk of collusion is beneficial not only for static efficiency but also for overall effectiveness and dynamic efficiency, as the over-funding of projects prevents the support of further projects. Additionally, promoting green lead markets as an award criterion and relaxing entry requirements for smaller companies can increase both static and dynamic efficiency. Furthermore, a third-party verification of companies' cost estimates can be beneficial for both *ex-post* effectiveness and static efficiency.

While not the primary focus of this paper, it is important to note that also general design aspects impact allocation outcomes. Relevant aspects, such as the consideration of green premia for the strike price, the coverage of energy price risks or the payback mode are not adequately addressed in the literature in the context of allocation. These considerations are crucial for allocation as they influence the extent of risk coverage provided by the CCfD, which in turn affects bidder behavior and participation in allocation mechanisms. For example, a one-sided payback mode compared to a two-sided increases projects risks and financing costs as bidders must consider uncertain revenues [2].

5.3. Limitations and need for further research

While this study offers a comprehensive overview of potential CCfD allocation options as well as insights into the associated implications, trade-offs, and synergies, several limitations must be acknowledged. Firstly, the analysis omits certain CCfD design aspects relevant to allocation, such as the governance of awarding, i.e., the actors involved in the award decisions [13]. Additionally, it should be noted that an analysis of CCfD allocation through a literature review enables highlighting various aspects relevant to CCfD allocation, but is only an indication and lacks empirical verifications to draw definitive conclusions. This is underscored by the fact that, due to a lack of peer-reviewed literature on the matter, the analysis is mainly based on grey literature, i.e., working papers and studies. Furthermore, how the institutional and legal context shapes CCfD allocation options and choices is rarely analyzed in depth in the literature. Consequently, this review can only treat these aspects at a high level.

To enhance the understanding of the allocation of CCfDs, various avenues of further research can be explored. One key area of research is investigating the practical implementation of allocation in the first real-world CCfD programs. Such analysis would enable comparisons with theoretical principles and shed light on allocation aspects

not covered yet in the literature. Another promising direction for further research is the quantitative analysis of allocation options. This could include empirical *ex-post* analyses of allocation outcomes from implemented CCfD programs, marginal analyses of design options to quantify trade-offs and identify no-regret options (as suggested by Río and Kiefer [37] regarding renewable energy auctions), as well as agent-based modeling of CCfD auctions to analyze potential bidding strategies. Further research could also delve into currently under-explored aspects of CCfD allocation. Key areas to investigate include: pricing rules, auction types, the impact of the award procedure on dynamic efficiency, risks of underbidding, realization rates and penalties.

6. Conclusions

Allocation is a key element of CCfD programs due to the substantial budgets involved and its impact on CCfD scheme's overall effectiveness. As CCfDs begin to be implemented in practice, understanding allocation design becomes crucial for managing public expenses and effectively supporting industrial decarbonization, especially amidst tight government budgets. Hence, it is concerning that current research on allocation mechanisms remains scarce and relatively high-level. This study aims to address this research gap through a comprehensive literature review and analysis of CCfD allocation aspects. The paper contributes to the limited body of literature on CCfD allocation by offering a detailed overview of relevant allocation aspects, potential options and respective implications, and highlighting previously under-explored topics. While the findings are primarily based on an analysis of CCfD literature focused on Europe, they are also relevant to CCfD implementation globally and offer insights for the allocation of other contract-based industrial decarbonization support instruments.

Beyond providing a comprehensive overview of design options and their implications, this study points to trade-offs and synergies in CCfD allocation design, demonstrating the interconnection between design elements and evaluation criteria. Key insights include the following: There is a strong trade-off between static and dynamic efficiency, which can be addressed by specific measures such as bid scaling factors in auctions. Generally, there exists a gap between theoretically optimal and politically feasible choices. Furthermore, complex allocation design elements can potentially deter company participation or fail to be implemented. Synergies are also identified, such as that adopting less stringent entry requirements for smaller companies and using the promotion of green lead markets as an award criterion can improve dynamic and static efficiency. The study also points to the fact that general CCfD design aspects, such as the accounting of green premia, energy price risk coverage, and payback modes, significantly influence risk coverage and bidder behavior but are inadequately addressed in the literature on CCfD allocation. This research also makes it apparent that the implications of design options in terms of policy evaluation criteria are not always clear, such as the effects of price ceilings on static efficiency.

Policymakers can draw several implications from these findings. Trade-offs, interconnected effects, and synergies must be considered in designing CCfD allocations, alongside their interplay with the overall CCfD design. While the final decision on design options depends on political objectives, it becomes apparent that more information and guidance on the implications and interactions of different design options

is required. For this purpose, robust quantitative analyses are crucial. Making data on allocation results available in anonymized formats would facilitate contributions from the academic community.

While these insights are valuable, further research is needed to better understand the complexity of CCfD allocations and provide guidance for policy decisions. Further policy-relevant research gaps include investigating the allocation design of implemented CCfD schemes and conducting quantitative analyses such as *ex-post*, marginal trade-off, and agent-based modeling analyses. Additionally, it is important to shed light on topics not yet covered in detail, such as pricing methods in auctions, penalties, bidding strategies, the role of institutional and legal constraints in shaping CCfD allocation design, and how allocation choices affect effectiveness and interact with general CCfD design.

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Declaration of generative AI and AI-assisted technologies in the writing process

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