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Valuing investments in the Global Carbon Market Mechanism as compound real options: Lessons from the Clean Development Mechanism

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Abstract
The Global Carbon Market Mechanism (GCMM) aims to incentivize national or sub-national actors to invest in climate mitigation projects at the same time as limiting the global costs of tackling global warming. Using the worked example of the Clean Development Mechanism (CDM), this article shows that the exact valuation of a mitigation project requires the application of compound real options techniques, as it is able to account for the multi-staged nature of a project cycle, as well as the two basic sources of uncertainty (the probability of not moving successfully to the next stage of the cycle, technical risk, and the uncertainty related to future emission reduction credit prices, market risk). Using parameters from the global database of registered CDM projects, this article illustrates that longer than projected lead times, higher than projected transaction costs, and higher than projected rates of failure lowered the value of investing in CDM projects considerably, alongside offset prices and their variability. Regulators of and participants within the patchwork of existing emission trading schemes and market mechanisms, including the GCMM (Article 6.4 of the Paris Agreement), could benefit through wider appreciation of the benefits of this valuation method.

KEYWORDS
(compound) real options, certified emission reductions (CERs), Clean Development Mechanism, Global Carbon Market Mechanism, Paris Agreement

1 | INTRODUCTION

The United Nations Framework Convention on Climate Change (UNFCCC), created at the Earth Summit in Rio de Janeiro in 1992, is the main international institution that coordinates the global response to climate change. Almost all of the countries in the world are represented in the UNFCCC which aims to stabilize greenhouse gas concentrations in the atmosphere and thus avoid dangerous climate change. The convention itself does not stipulate emission reductions, instead, it allows space for binding emission reductions in subsequent protocols or agreements.

The Paris Agreement, signed in December 2015, set five-year cycles for Parties to commit to increasingly ambitious voluntary mitigation goals to prevent 2°C and ideally 1.5°C, temperature increases alongside financing for mitigation and adaptation, in the context of sustainable development. These nationally determined contributions are communicated to the UNFCCC by more than 190 signatories (Stua, 2017). The agreement allows for a range of flexible channels through which commitments can be achieved, including bilateral and multilateral cooperative approaches between countries (so-called "International Transferred Mitigation Outcomes" described in Article 6.2), non-market approaches (as described in Articles 6.8 and 6.9 of the Agreement) as well as through the Global Carbon Market Mechanism (GCMM) (as described in Article 6.4), a mechanism which allows a firm in one nation to sell emission reduction credits to a firm in a different country (Steinebach & Limberg, 2022).[1] Within pre-existing

[1]Article 6.4 includes a 5% levy for the Adaptation Fund, a requirement to retire 2% of credits, and adjustments to ensure no double counting.

market mechanisms, both regulated (compliance) markets and voluntary markets exist. Regulated markets take the form of cap-and-trade schemes (where caps on emissions decline through time), epitomized by the Kyoto Protocol (which we turn to shortly) and the European Emissions Trading scheme. Here, the scarcity of emission rights and trading opportunities in emission rights and offset credits incentivize actors to invest in mitigation activities. Some regulated markets include binding requirements to achieve net zero emissions by 2050, which ratchets up commitment by market participants.[2] As of 2019, there were over 50 emission training schemes globally at a range of scales with around a 5th of global emissions covered, and over 44 billion USD raised in carbon pricing revenues (World Bank, 2019). As of late 2022, 21 emission-trading schemes offered offset mechanisms within their cap-and-trade regulatory framework (see Table 7 later in this article). Importantly, the 26th Conference of Parties in Glasgow in 2021 completed the rulebook for the Paris Agreement including common timeframes, methodologies, and modalities for emission reduction targets, paving the way for implementation of the GCMM.[3]

This article adds to debates on how Article 6.4 of the Paris Agreement will be operationalized.[4] It utilizes the Clean Development Mechanism (CDM), a mechanism that allowed the sale of offset credits in Non-Annex I countries to Annex I parties under the Kyoto Protocol, as an illustrative example to examine the challenges associated with project-level mitigation activities. We show that financing mitigation projects is complicated and involves many specific risks, mainly related to the multi-staged and uncertain success rate of project registration (*technical risk*) and unpredictable offset credit prices (*market risk*).[5] These factors influence decision-making leading investors to treat such opportunities with caution (Cormier & Bellassen, 2013; Shishlov & Bellassen, 2012).

Although the UNFCCC established methodological tools and guidelines for CDM investment and barriers analysis (CDM Rulebook, 2014), a key weakness of most existing calculation models for assessing estimated return to investors in mitigation projects is that they failed to account for the time projects take to come to fruition (Yang et al., 2010). For market mechanisms to work efficiently, a proper assessment of investment decision-making should take the project's life cycle, the preparation of the project, the predictability of risks, and the anticipated market challenges explicitly into account (Karani & Gantsho, 2007). Indeed, in the past many CDM project developers underestimated the risks and uncertainties related to the generation of certified emission reductions (CERs) from CDM projects, which could influence investors' cash flows (Castro & Michaelowa, 2008; Yang et al., 2010). For example, delivered CERs were considerably lower than expected with only 30% of expected credits being delivered in the period 2004–2011 (Cormier & Bellassen, 2013). Furthermore, the market prices of CERs were extremely volatile (Ecofys and World Bank, 2014).

This article introduces a novel valuation approach to assess mitigation projects in a more realistic manner. It argues that compound real options approaches are better able to incorporate both market and technical risks when valuing projects compared to net present value (NPV) or cost–benefit valuation approaches. Compound real options are an asset investment valuation technique for uncertain staged investment decisions that explicitly incorporate diverse sources of uncertainty, such as uncertainty related to the costs and revenues of the project, as well as uncertainty about the successful completion of the multiple stages, through the application of probabilities. We demonstrate that multi-staged, highly-uncertain investment projects, such as climate mitigation projects, are best valued using this approach (Cassimon, De Backer, et al., 2011).

In Section 2, we detail how the CDM project cycle clearly illustrates a highly-uncertain investment context. In Section 3, we show that CDM project cycle valuation can benefit substantially from using a compound option approach, as it is able to treat both the multi-staged nature of the CDM project cycle, as well as the two basic sources of uncertainty (the technical risk of not moving successfully to the next stage of the cycle, and the market risk related to uncertain future CER prices) in an appropriate way. In Section 4, we apply this compound option model to the multi-staged CDM project development cycle using probabilities and risk assessments derived from using the current database of CDM project developments. As such, our article proposes a novel valuation methodology crucial for climate project developers in supporting market mechanism schemes, to more accurately compute the value of a particular CDM project. In this respect, we show how valuation results differ compared to traditional ways of valuing projects, that is, an NPV-based, or cost–benefit based logic. Moreover, the model allows for a broader range of determinants ("value drivers") entering the valuation of a CDM project, which allows a focus on the relative importance of these additional value drivers. This insight offers regulators and market mechanism participants suggestions as to where in the specific stages of the project cycle reforms are needed to increase investments. In addition, it highlights additional intervention tools that are illustrated by this broader set of value drivers. In Section 5, we show that the relevance of using this compound option valuation approach is not limited to the CDM, but applies to a range of existing and pipeline market mechanisms, because of their multi-staged and risky nature. Section 6 concludes.

2 | THE CDM PROJECT CYCLE AND ASSOCIATED RISKS

Prior to the signing of the Paris Agreement in 2015, the Kyoto Protocol was the global agreement which guided global efforts for climate

[2]COP26 in Glasgow reached an agreement that some voluntary offsets credits will be treated as quasi-compliant credits under Article 6 of the Paris Agreement (whilst unadjusted voluntary credits will be excluded and will lose value).

[3]COP26 continued efforts to stabilize temperature increases to 1.5 degrees through the establishment of a work program in mitigation to increase scale and implementation, as well as the creation of an annual high-level ministerial roundtable on ambitious mitigation commitments by 2030. COP26 also called on Parties to accelerate technological advancement and policy frameworks for mitigation, a phase-down of unabated coal power, and a phase-out of inefficient fossil fuel subsidies, alongside support for a just transition for the poorest and most vulnerable. The achievement of these aims is contingent on a clear and assured set of financial commitments.

[4]Decision 3/CMA.3 outlines the rules, modalities, and procedures for the GCCM established by Article 6.4.

[5]Offset credits within the CDM are termed Certified Emission Reduction (CER) credits.

mitigation. This was signed in 1997 and committed (most) industrialized countries to a 5.2% reduction of 1990 emission levels by 2008–2012. In other words, it established national emissions reduction targets, for a single 5-year averaging period, 2008–2012, for nations listed in an annex of the Protocol. The Kyoto Protocol became binding in 2005 (with 55 signatories accounting for at least 55% of 1990 emissions).

Kyoto was a "cap and trade" system that imposes national caps on the emissions of industrialized Annex I countries. The CDM, which entered into force in 2005, was one of the flexibility mechanisms through which developing countries participated in mitigation actions under the Kyoto Protocol (Havukainen et al., 2022).[6] This flexible market-based offset mechanism allowed developing countries to earn CER credits, each equivalent to one ton of CO_2, by investing in emission reduction projects (Lee & Jang, 2022). These CERs could be traded with industrialized countries to offset their emission reduction targets under the Kyoto Protocol (Solomon, 2023). Trading was and continues to be regulated by an "Executive Board" to ensure environmental integrity.[7]

While the second commitment period of the Kyoto Protocol was superseded by the Paris Agreement in 2015, the carbon offset credits or CERs generated from the CDM continue to be issued, and up to December 2020 were transferable into the European Emissions Trading Scheme, the world's largest "cap and trade" system (Ecofys and World Bank, 2014; Newell et al., 2013).[8] Following the Paris Rulebook, ongoing CDM projects can transfer into the GCMM provided they comply with GCMM rules, and that CERs can be used within NDCs subject to certain conditions.

The international governance structure for the CDM involves several steps, actors, and checks, and includes detailed guidelines and tools on specific methodologies, and proving additionality (OECD, 2012). The CDM Executive Board approves and registers methodologies, projects, and accredits third-party verifiers (known as "Designated Operational Entities,") and issues and tracks the movement of CERs (Boyd & Goodman, 2011). It is the responsibility of each host developing country to define whether a project promotes local and national sustainable development. In practice, this means that most host countries have a "Designated National Authority" that approves projects against national pre-defined criteria, usually encompassing social, economic, and environmental aspects of sustainable development. Finally, project developers must submit a project design document (PDD) that uses an approved methodology to calculate the project's predicted emissions reductions (OECD, 2012). As the CDM in principle awards credits only for projects that would not have been implemented in the absence of CDM-related funding, an important component of this PDD is the demonstration of the activities' additionality. Once completed, the PDD then enters a process of gaining approval. The sequence of the involved tasks from project design to CER issuance is generally referred to as the CDM "project cycle."

The majority of CER issuance comes from large-scale projects,[9] which face a project cycle that can be broken down into five main steps:

1. *PDD*. Project participants must prepare a PDD, making use of approved emissions baseline and monitoring methodology. The PDD includes demonstrated additionality and calculates potential emissions reduction (CERs) over the proposed crediting period (CDM Rulebook, 2014).[10]
2. *Validation*. The proposed project is validated by an independent and accredited private Designated Operational Entity (DOE). The DOE evaluates the project against the requirements of the CDM as set out in CDM modalities and procedures and relevant decisions of the Kyoto Protocol Parties and the CDM Executive Board, on the basis of the PDD. The DOE may ask for clarifications or modifications, and eventually issues a positive or negative opinion (Cormier & Bellassen, 2013). As part of the validation process, the DOE obtains a written approval from the Designated National Authority involved in the project (Kim et al., 2013).
3. *Registration*. Once the PDD is validated by the DOE, the proposed project is submitted to the CDM Executive Board for registration. If three or more members of the Board have doubts over a project's credibility, the project undergoes a review which leads to a delay in registration, and possibly rejection. Otherwise, the project obtains registration status.
4. *Issuance*. Once the project is registered, the CDM project can be implemented and start generating credits. In order to calculate the amount of CERs, project participants monitor emissions following the monitoring plan outlined in the PDD. This leads to the submission of a monitoring report to the DOE for verification (Kim et al., 2013). The DOE verifies the authenticity of emissions reduction and provides a written certification report, which constitutes a request for issuance of CERs to the CDM Executive Board. Finally, upon approval by the Board, CERs are issued. The crediting period for a CDM project activity may be 7 years, renewable twice, or a single 10-year crediting period (CDM Rulebook, 2014). At each issuance, the revenue received for selling the CERs will depend on the market price for CERs at that moment, which is uncertain.

[6]Annex I countries grandfathered emissions rights to individual industrial entities, such as a power plants or heavy industries. Individual firms which expected emissions to exceed their allowances were able to purchase either additional emission rights or carbon credits. Kyoto provided three flexibility mechanisms to reduce the overall cost of compliance through: (i) the purchase of emission rights from within industrialized countries; (ii) the purchase of carbon credits from offset projects in other industrialized countries (termed the Joint Implementation channel); and (iii), the creation of Certified Emission Reductions (CERs) from offset projects in Non-Annex I countries through the Clean Development Mechanism.

[7]This has 10 members including one from each of the main UN regions, one member for a SIDS, and two representatives from Annex I and non-Annex I countries.

[8]As the second commitment period (2013–2020) has concluded, the ETS no longer accepts Certified Emission Reduction units from the CDM.

[9]According to the CDM rules, there are four types of CDM projects: large-scale, small-scale, afforestation and reforestation (A/R), and small-scale afforestation and reforestation. The analysis in this article is mainly based on large-scale projects, but the proposed methodology can also be applied to the other types of CDM projects. For example, small-scale CDM projects have a simplified procedure in order to reduce transaction costs and make them more attractive to investors. The different components of the project cycle are, however, the same as for large-scale projects (Wetzelaer et al., 2007).

[10]Though not obligatory, projects may also start with the formulation of a Project Idea Note (PIN), prior to a PDD. In the remainder of the article, the starting point is a PDD.

5. *Sale of the CERs*. The project developer generates revenues from being able to sell CERs rewarded by the CDM project to buyers of carbon credits on international carbon markets. Buyers might include firms, banks, carbon funds (e.g., the Prototype Carbon Fund of the International Bank for Reconstruction and Development), or governments. Buyers' motives include rights to pollute or the purchase of low-cost emission reductions as investments, among others.

The CDM project cycle is a sequential, multi-staged project, in which, at each stage, a cost is paid to enter the stage, and the successful completion of one stage (which is not guaranteed) provides the investor with the opportunity to move to the next stage, again at a particular cost. Only upon successful completion of the final stage, this will provide the investor with an uncertain stream of future revenues, depending on the CER market price at that moment. This multi-staged process can be characterized as a chain of options on options. In the real option literature, this is known as a compound option (Engelen & Cassimon, 2015). Starting a CDM project provides a compound option for generating CER revenues. More specifically, applying it to the stages described above, deciding to write a PDD provides an option on the validation stage, which upon successful implementation, provides the option to move to the registration phase, and so forth. Put differently, the PDD provides a four-fold compound option on CER revenues, the value of which can be derived using compound option models. The value of this compound option can then be compared to the cost of starting this process, that is, the cost of this first project design and formulation phase: if this compound option value (COV) is higher than its cost, it is worthwhile to start the process. Figure 1 provides an overview of the conceptualization of the staged CDM project cycle from this perspective.

Moreover, the compound option model needs to take into account two major types of risk that influence the value of this project. The first one is the probability, in each stage, that stage will not be completed successfully, and the investor will not be able to move to the next stage of the process. This is what we call "technical risk," but can also be called "catastrophic" or "termination" risk. The other major risk, called "market risk," is the uncertainty related to the amount of revenues, mainly due to uncertainty about future CER prices. This can include pure commercial risk as well as regulatory risk.

3 | A COMPOUND OPTION APPROACH TO VALUING INVESTMENT IN THE CDM

The traditional toolbox to assess and value an investment project uses an NPV logic. However, it is now widely accepted in the economics literature that multi-staged projects cannot be accurately valued through this NPV lens (Engelen & Cassimon, 2015). The NPV approach only looks at cash inflows and outflows, without taking into account any flexibility to delay, adjust, re-scale, or abandon a project. It assumes an upfront now-or-never decision, assuming a company will follow a rigid path of continuing the project, once the investment

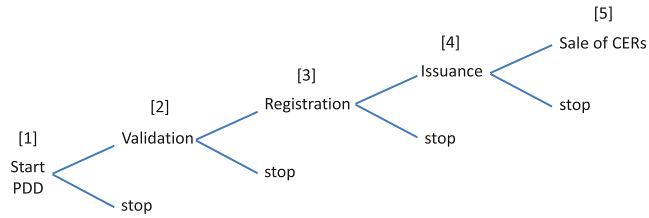


FIGURE 1 Typical phases of a Clean Development Mechanism project as a compound option. CERs, certified emission reductions; PDD, project design document. [Colour figure can be viewed at wileyonlinelibrary.com]

decision is taken. In reality, in a competitive environment with market uncertainty (in this case, uncertainty about future CER prices), it is valuable to companies to adjust their strategy during the execution of the project. More specifically, in staged projects like the CDM, where the project can be abandoned at any stage, this "optional" nature is not accurately incorporated in an NPV approach. Additionally, a simple NPV approach does not take into account the probability of forced intermediate termination, as a result of unsuccessful completion of one of the intermediary stages (*technical risk*). An enhanced NPV approach, using decision tree analysis, adjusting the different scenarios for these stage-specific probabilities tries to accommodate the presence of technical risk, but still has the same basic flaw that it does not accommodate the intrinsic optional nature of the project cycle, allowing the investor to choose at every (successful) stage of the project, to go ahead with the project or not (see e.g., Cassimon, De Backer, et al., 2011; Kellogg & Charnes, 2000).

It is now becoming widely accepted that real options offer the enhancements needed to better value these strategic issues. Real option analysis states that each real investment project (e.g., the investment in CDM) can be seen as exercising a call option to buy the underlying asset at an agreed price (the strike price or exercise price, K) during a specific period ($T-t$). As such, the financial option concept and logic can be applied to a real context. The CDM project can be perceived as an option whereby the firm has the right to obtain all the underlying cash flows that are resulting from the project (here the CER revenues) at a particular price, being the investment cost of the project. When the investor goes ahead with the project, it actually exercises the real option: it pays the investment cost (similar to the exercise price, K) and receives all the future net proceeds of the project (V). Given the above analogy between financial and real options, the valuation models for real options are based on financial option models. The most commonly known option model is Black and Scholes (1973). Its popularity is derived from its closed-form solution, allowing for easy computation of the option value and the sensitivity analysis (partial derivatives). It assumes that the underlying project value V exhibits a geometric Brownian motion, assuming V to be log-normally distributed and returns to be normally distributed. A technical presentation of the Black-Scholes formula to compute the option value is provided in Appendix A. Table 1 shows how the model is built up by comparing the "value drivers" across the classical one-stage option model, and the generalization of this model to allow for

TABLE 1 Formula-specific real-option value determinants ("value drivers").

Value drivers	Black-Scholes (one-period real option)	Generalized B-S *n*-stage (compound) real option	Generalized B-S compound real options with technical risk
Underlying asset	Value of the project, *V* (future revenues from CER sales)	Value of the project, *V* (future revenues from CER sales)	Value of the project, *V* (future revenues from CER sales)
Exercise price	Investment cost, *K*	Stage-specific investment costs (exercise prices to start the particular stage), K_i	Stage-specific investment costs (exercise prices to start the next stage), K_i
Option time	Remaining time to execute the option, or total lead time, $T–t$	Stage-specific lead times, where $T–t$ is subdivided in a number of sub-periods, $t_i–t$	Stage-specific lead times, where $T–t$ is subdivided in a number of sub-periods, $t_i–t$
Risk-free interest rate	(exogenous), *r*	(exogenous), *r*	(exogenous), *r*
Market risk	Project value volatility (standard deviation of revenues from CER sales), σ_m	Project value volatility (standard deviation of revenues from CER sales), σ_m	Project value volatility (standard deviation of revenues from CER sales), σ_m
Technical risk	n.a.	n.a.	Stage-specific success rates, that is, probability of successful finalization of a stage, that opens the option to go to the next stage, p_i

Abbreviations: CER, certified emission reduction; n.a., not applicable.
Source: Authors.

multiple stages. Table 1 illustrates that the consequence of applying a real option approach, and the Black-Scholes valuation approach more particularly, is that three additional parameters enter the valuation formula, and also impact on the option value: next to the value of the project *V* and the investment cost *K*, (which both also enter in and make up the NPV approach), the option value is further influenced by the time window of the option ($T–t$), the risk-free interest rate (*r*) and, most importantly, a measure for the uncertainty surrounding the revenues of the project, typically proxied by the annualized standard deviation of the value of the project *V*, earlier referred to as market risk σ_m.[11]

The occurrence of multi-staged projects, representing options on options, or compound options, however, necessitates the generalization of the one-period Black-Scholes model for *n*-periods. Building on the seminal two-fold Geske (1979) model, Cassimon et al. (2004), provides this closed-form generalization; its exact analytical presentation is detailed in Appendix A, while column 3 of Table 1 presents the list of values-driving parameters. Note that this formula is a mere generalization of the single-phase option model for the case of $(k + 1)$ phases, and the former symbols still apply: *V* remains the value of the project, equal to the (present value) of all the future CER revenues; σ_m remains the measure for market risk, as is the case for the risk-free interest rate, *r*. But instead of one investment cost *K*, we now have a series of stage-specific investment costs, K_i, and the single period ($T–t$) is now distributed in a series of periods (still measured in years), each with timing ($t_i–t$), indicating stage-specific lead times.

However, this still assumes that success to move from one stage to the next is guaranteed, that is, success rates are 100% and there is no "technical risk." To account for the probabilities of failure during project development and implementation, Cassimon, De Backer, et al. (2011) extend the previous framework to allow for technical risk as well, while still keeping its closed-form characteristic. In the empirical analysis of the next Section 4, we apply this technical-risk enhanced compound option model of Cassimon, De Backer, et al. (2011) as it perfectly fits the CDM-set up. Again, Appendix A provides a more technical presentation of the exact valuation equation, while the last column of Table 1 provides an overview of all the value determinants involved. Note again that, compared to the previous Cassimon et al. (2004) model, all the parameters remain the same; it only adds the series of stage-specific success probabilities as additional value drivers. Technical risk is present through the technical risk probabilities; in the formula, p_i is the independent technical success probability of stage *i*.[12] As such, in the next section, we apply this model to show this is feasible, using a baseline case, based on realistic, average, proxies for all the variables of the model, as well as perform sensitivity analysis.

So far, the literature on applying (compound) real option analysis to the CDM is very scarce. One particular exception is Lee et al. (2013) who present a real option model to address issues regarding the effectiveness of CDM. This model is designed for both parties (developed and developing countries) in order to have their fair share of profits and risks by controlling uncertainty associated with the future value of CERs. According to Lee et al. (2013), Monte Carlo simulation was the most appropriate method for the valuation of CDM, because it was regarded as a good fit for this type of real options. This method enables an annual exercise of the option during a 20-year

[11]See also Appendix A for a more detailed explanation of how our model allows to capture both commercial as well as regulatory risk within our market risk parameter.

[12]This model was programmed in MatlabTM which makes it fully operational for exact empirical valuation of any particular real-life project. See for example, Cassimon et al. (2011b, appendix B) for a sample variant of the programming code.

operation period. However, Lee et al. (2013) did not consider the fact that the CDM process consists of multiple stages. This is also the case in Lee and Jang (2022), who apply a real options approach to assess a CDM cook stove project in Myanmar using Korean Offset Credit prices and not CERs. Multi-staged, highly uncertain investment projects are best valued using compound option approaches (Cassimon et al., 2004). As the CDM project cycle clearly fulfills these basic characteristics, we show that CDM project cycle valuation can benefit from using compound option approaches, as it enables to treat both the multi-staged nature of the CDM project cycle, as well as the two basic sources of uncertainty (market and technical risk) in a correct way. As such, we consider our approach to be more suitable.

4 | APPLYING THE COMPOUND OPTION MODEL TO CDM INVESTMENTS

In this section, we apply the compound model determined in the previous section to a typical CDM investment project. First, in Section 4.1, we estimate values for all the relevant parameters of the model. In Section 4.2, we apply these estimated parameters to provide a benchmark valuation for the project, first by applying a conventional NPV technique, followed by the valuation achieved by applying a compound option technique. Finally, in Section 4.3, we provide sensitivity analysis.

4.1 | Determining the parameters of the model

Determining the value of investing in the CDM requires an estimation of all the parameters in a four-fold compound option model. More specifically, it requires determining the (stage-specific) success probability rates, that indicate technical risk (Section 4.1.1), the time needed to terminate a particular stage, that is, the stage-specific lead times (Section 4.1.2), the investment costs per phase (Section 4.1.3), and the mean CER price as well as its volatility, as a proxy for market risk (Section 4.1.4). Obviously, when calculating this value for a particular CDM project, these estimates can be tailor-made and derived from the project documents themselves, in combination with investor-subjective estimates of the uncertain future. In order to make a first baseline application of the model estimation, we derive proxies of the necessary inputs on the basis of "average" costs, "average" success probability rates and "average" lead times, using the full information that is available in the CDM project database, as well as an historic volatility measure. As such, using those inputs, we provide the (compound option) value of investing in CDM for a range of possible mean values of the future CER (Section 4.2).

4.1.1 | CDM stage-specific success probabilities

The average stage-specific success probabilities we use in our model are derived from the database of all CDM registered projects that have started the process of registration. More specifically, it uses the data collected and processed by the Institute for Global Environmental Strategies (IGES), which extracts the data from the official CDM database. In this paper, we use the January 2015 version of this database, including projects up to October 2014. This results in 12,261 projects. Applying a methodology similar to Cormier and Bellassen (2013), including similar data cleaning techniques, to this updated database, provides average success rates for the validation, registration, and issuance stages. Appendix B provides a more detailed analysis of the methodology used, including the data cleaning rules. Table 2 presents the results of our analysis, for all projects, as well as for large and small projects, and also adds the comparable figures of Cormier and Bellassen (2013).

For the baseline valuation, we use the large-scale success rates (in bold in Table 2). Additionally, we need the success rates for the PDD phase, as well as that for the actual sale of CERs; these success rates cannot be calculated from the IGES database. In the baseline case, we assume that these probabilities are equal to 90% and 100%, respectively. In Section 4.3, we provide robustness checks for different values of those probabilities.

4.1.2 | CDM stage-specific lead times

The time it takes for a CDM project to run through the whole administration procedure is often criticized. Indeed, it can easily take up to 3 years from project proposal until CER issuance. The length of the administration process is a result of many factors, but is often related to the much larger volume of projects entering the CDM than originally expected, the insufficient capacity at the UNFCCC to process these projects in a timely manner, and the lack of qualified DOEs (Shishlov & Bellassen, 2012; World Bank, 2010). Table 3 shows the average days a CDM project spent in the pipeline, calculated using the same data from the IGES database.

Again, the lead times for these three stages have been completed with proxies for the lead times of the first PDD and final CER sale stages. In the baseline valuation, we assume the first PDD stage to take half a year on average. In Section 4.3, we will provide robustness checks for different lead times for the PDD stage.

4.1.3 | CDM stage-specific investment costs

Transaction costs in the CDM project cycle vary by technology, but are to a large degree fixed and independent of the size of the project, which means that most investors are particularly interested in larger projects as they have relatively low transaction cost per unit of emission reduction (Wetzelaer et al., 2007). The transaction costs that accrue to project developers in the preparation (and potential) implementation of a CDM project can be related to each stage of the project cycle. However, to our knowledge, to date an all-encompassing study or database that systematically assesses CDM-related transaction costs is not available. Therefore, in Table 4 we summarize estimates for large-scale projects based on different sources (Fenhann

TABLE 2 Average success rates per stage.

Success rate	Total (%)	Large (%)	Small (%)	Cormier and Bellassen (2013) (%)
Validation stage	50	**54**	45	67
Registration stage	92	**91**	93	93
Issuance stage	60	**65**	53	84

Source: Author's analysis of IGES (2014; version January 5, 2015) database.

TABLE 3 Average stage-specific lead time (number of days).

	Average days
Duration validation	357
Duration registration	152
Duration issuance	781

Source: Author's analysis of IGES (2014; version January 5, 2015) database.

TABLE 4 Clean Development Mechanism stage-specific investment costs (in USD).

PDD	50,000
Validation	30,000
Registration	185,000
Issuance	25,000
Sale	24,000

Abbreviation: PDD, project design document.
Source: Author's estimates based on Fenhann and Hinostroza (2011), Michaelowa and Jotzo (2005), World Bank (2010), UNDP (2003), and Wetzelaer et al. (2007).

and Hinostroza (2011), Michaelowa and Jotzo (2005), World Bank (2010), UNDP (2003) and Wetzelaer et al. (2007)). For the baseline valuation, we use these large-scale estimates.

4.1.4 | CDM revenue volatility

In order to estimate the market risk, we calculate historical volatilities using the data presented in Figure 2 on the evolution of CER futures prices over the period January 2009–March 2015. While the 2009–2011 period market prices of CER fluctuated around USD 10, from mid-2012 onwards we can observe a decline in the demand for CERs, resulting in very low market prices (Ecofys & World Bank, 2014). The daily quotes for the total period are used to calculate historic volatilities. We calculated daily and quarterly volatilities using futures prices. In annualized terms, this amounts to about 97% annual volatility. We, therefore, used a volatility measure of 97% as a baseline input. In Section 4.3, we will provide robustness checks for different values of volatility estimates.

4.2 | CDM project valuation

Using the input estimates described above, we provide the (compound option) value of investing in CDM for a range of possible mean values of the future CER. We start with computing the value based on the conventional NPV approach, adjusted to account for technical risk by taking into account the probability distribution of success rates at different stages using so-called decision-tree analysis (Kellogg & Charnes, 2000). We then compute the value using a compound option approach, again with the same implied technical risk.

We take the example of a large-scale project with the following baseline framing: we assume that the CDM project is able to issue 100,000 CER, over a period of 10 years, leading to revenues equal to 100,000 times the CER price. For the baseline calculation, we use a mean CER price of 0.50, in line with the market price information as of February 2015 (see Figure 2), which amounts to a mean annual revenue of 50,000 USD. The estimated investor's weighted average cost of capital (WACC) is set at 8%. The risk-free interest rate is set at 1.67% (representing the US Treasury 10-year bond yield as of February 2015). Appendix C provides a visual presentation of the complete set-up of the CDM project, similar to Figure 1, but with all the stage-specific estimates used in the concrete value calculations.

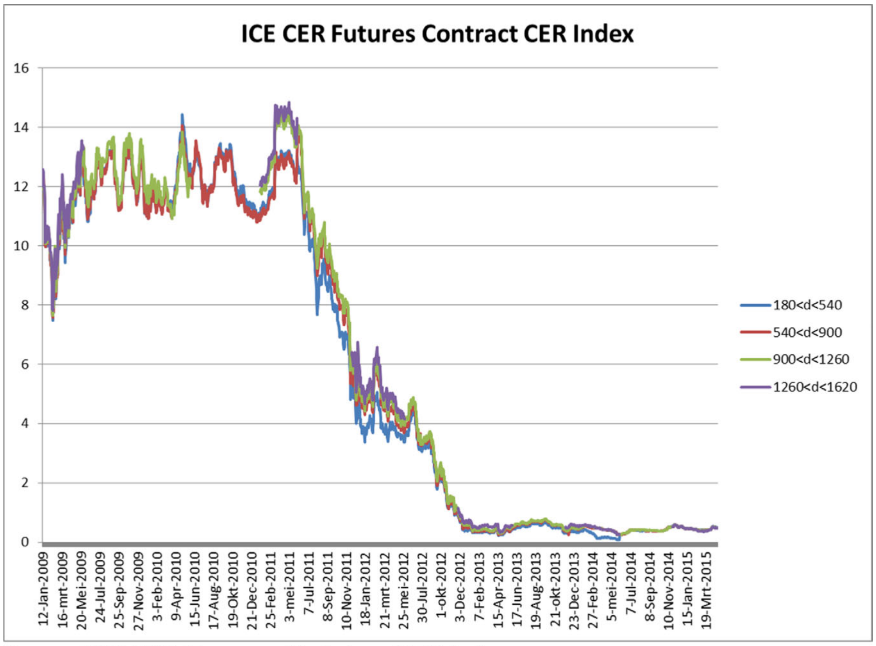
4.2.1 | Baseline NPV-based project valuation

The baseline calculations follow the approach of Kellogg and Charnes (2000), as also applied in Cassimon, De Backer, et al. (2011). The calculations are summarized in Table 5.

The first four columns of Table 5 follow from the analysis in Section 2, recapitulating the different stages (phase), the length of each stage in years (see also Table 3), the costs of each of the stages (see also Table 4) and the net revenue of CER sales for each phase, as calculated in present values at the start of the project (NPV) and the probabilities for success of each phase (p_i) (see also Table 1). These probabilities are then transformed into conditional probabilities ρ_i, being the probability that stage *i* is the end stage for a project that has reached stage *i*−1. These conditional probabilities are presented in column five of Table 5.

At the same time, we compute the NPV of each phase as if it was the end stage (denoted as $CNPV_{i,0}$), that is, the stage-specific present values of the cumulative expected investment stage cash outflows for all the possible outcomes of the project.[13] These CNPV values are then multiplied with the conditional probabilities of each stage, to obtain conditional cumulative stage-specific NPVs (calculated at current day present value), $CCNPV_{i,0}$. As shown in the last column of

[13]Including for the final stage where present value (only) estimates are provided for the expected (net) cash flow for the final stage from CER sales, as in column six of the table.



Source: ICE CER Futures – Emissions CER Index:
https://www.theice.com/marketdata/reports/icefutureseurope/ECXCERIndex.shtml

FIGURE 2 Evolution of certified emission reduction (CER) futures prices. *Source*: ICE CER Futures (n.d.)—Emissions CER Index: https://www.theice.com/marketdata/reports/icefutureseurope/ECXCERIndex.shtml. [Colour figure can be viewed at wileyonlinelibrary.com]

TABLE 5 Valuation of the Clean Development Mechanism (CDM) project according to adjusted NPV (ANPV) using decision tree analysis.

Phase	Year	$NPV_{i,t}$	p_i	ρ_i	$CNPV_{i,0}$	$CCNPV_{i,t}$
PDD	0	−50	1.00	0.0000	−50	0
Validation	0.50	−30	0.54	0.4600	−79	−36
Registration	1.45	−185	0.91	0.0486	−244	−12
Issuance	1.89	−25	0.65	0.1720	−266	−46
Sale	3.83	311	1.00	0.3194	−35	−11
Sum				1.0000		−105

Note: $NPV_{i,t}$ is the present value of the cost or the certified emission reduction sale net cash flows for each project phase *i*, calculated as the present value at the start-of-period *t*, discounted at the firm's weighted average cost of capital of 8%; p_i is the (unconditional) probability of success of stage *i*; ρ_i is the conditional probability that stage *i* is the end stage for a Clean Development Mechanism project that reached stage *i*−1; $CNPV_{i,0}$ is the present value of the total (cumulative) cost given that stage *i* is the end stage, including the expected commercialization cash flow, for the final stage only. $CCNPV_{i,0}$ is $CNPV_{i,0}$ multiplied by its conditional probability of occurring. The sum of all $CCNPV_{i,0}$ provides the ANPV for this project. All present values are in 1000 USD.
Abbreviations: PDD, project design document; NPV, net present value.

Table 5, these stage-specific conditional NPVs then add up to the total adjusted NPV (ANPV). Using decision tree analysis this results in a negative ANPV for the current baseline CDM project of −105,000 USD.

4.2.2 | Baseline compound option project valuation

We now calculate the baseline compound real options value as a four-fold compound option (Validation, Registration, Issuance, and Sale phases). This value should then be compared with the cost of developing the PDD. As shown earlier in Table 4, the cost of the PDD phase varies considerably, but an estimate of around 50,000 USD seems reasonable, so we take this one for the baseline case.

Again, all input parameters to calculate the COV come from the estimates in Section 4.1. The baseline case again takes a mean CER price of 0.50, and a standard deviation of revenues of 97%. Table 6 presents an overview of these input parameters. The first two columns identify the stages and the timing of the different stages (in years) respectively, similar to the NPV calculations of Table 5. Column three provides the values for the exercise prices (*K*) of the different options in the compound chain, that are identical to the stage-specific costs of Table 5. The variable *V* (in column 4) is the value of the project, that is, the NPV of the series of revenues generated by the CER sales. Column five again presents the probabilities for success of each phase (p_i), as from Table 2. The risk-free interest rate is set at 1.67% (representing the US Treasury 10 year bond yield as of February 2015). Based on these inputs, and in application of the

TABLE 6 Baseline value of the Clean Development Mechanism project according to the four-fold compound option model.

Phase	Year (t_i)	K_i	V	p_i	COV
Validation	0.50	30		0.54	
Registration	1.45	185		0.91	
Issuance	1.89	25		0.65	
Sale	3.83	25	336	1.00	
					17

Note: t_i is the maturity date for each of the stages of the compound call option C_i (expressed in years), K_i is the exercise price for each of the stages of the compound call option C_i; V is the current value of the underlying project (net present value of certified emission reduction sale revenues) and p_i is the (unconditional) probability of success of stage i. The success rate of the project design document is 90%. COV is the compound option value based on this four-fold compound option model. K_i, V, and COV are in 1000 USD. The instantaneous standard deviation of the project return (σ) is estimated to be 0.97. The risk-free interest rate amounts to 1.67%.

compound option model detailed in Appendix A (Equation A1), we derive a COV for this baseline CDM project of 17,000 USD.

As indicated earlier, this COV needs to be compared to the cost of starting the process, that is, the exercise price of the PDD stage, set at 50,000 USD. As a consequence, we have to conclude that starting this CDM project under this baseline scenario is not worthwhile as the cost of starting the process is larger than the value derived from it (as represented by its COV).

4.3 | Sensitivity analysis

As the two previous sections calculated the baseline valuation of the CDM project following the NPV approach (Section 4.2.1) and the real option approach (Section 4.2.2.), we can now analyze the impact on project value by changing one or more input parameters by conducting a sensitivity analysis. In each sensitivity calculation, we keep all inputs parameters at the constant value as indicated in Table 5 with the exception of the focal variable which takes different values. For each of the alternative focal variable values, we recalculate the COV and express it as a percentage of the baseline calculation. We perform sensitivity analyses for lead times, stage-specific success probabilities, volatility estimates, and CER prices.

4.3.1 | Lead times

In Section 4.1.1, we assumed the lead time of the PDD stage to be half a year as this information is not available in the IGES database. Although this figure seems reasonable based on feedback from practitioners, we recalculate the COV for different lead times of the PDD stage, varying from one month to one and a half years. Table 7 provides the COVs for changes in the PDD lead time, while keeping the other variables constant as in Table 6.

TABLE 7 Sensitivity analysis for the project design document (PDD) lead time.

PDD lead time	COV	Sensitivity (%)
1 month	8	67
3 months	12	72
6 months	**17**	**100**
9 months	21	123
12 months	24	142
18 months	30	175

Note: All input parameters as indicated in Table 6, except for PDD lead time. The compound option value (COV) are in 1000 USD. Baseline calculation in bold. Sensitivity expressed relative to baseline calculation.

4.3.2 | Stage-specific success probabilities

In our baseline calculations, we assumed the success probabilities of the PDD stage and of the Sale stage to be 90% and 100%, respectively. We recalculate the COV for different PDD and Sale stage success probabilities, as shown in Table 8. For instance, when the PDD stage success probability drops from 90% to 80% the COV decreases by 19%. In a similar way, when we decrease the success probability of the Sale stage from 100% to 90% the COV drops from 17,000 USD to 14,000 USD.

4.3.3 | Volatility estimate

While our baseline calculations used a volatility estimate of 97% based on historical data, we redo the compound option calculations for different volatility input parameters (Table 9). Other studies used different volatility estimates, for example, Abadie and Chamorro (2008) use a volatility of 46% in a real option study on carbon prices. For instance, if volatility would go up to 120% the COV increases to 24,000 USD. On the other hand, if volatility would go down to 40% the COV drops to only 2000 USD.

4.3.4 | CER prices

Table 10 shows COV calculations for different CER prices. We let CER prices vary from 1 to 20 USD and recalculate the present value of the expected future cash flows from selling CER at different prices (technically, we vary the parameter V). It is quite obvious that at the higher (historical) CER price, the CDM was very profitable. Although the baseline case of a large-scale project shows a loss, marginal CER price increases are sufficient to make the project again valuable: the break-even value is around 50,000 USD. This explains the success of CDM projects at higher historical prices.

5 | BEYOND THE CDM: THE GCMM AND EMISSION TRADING SCHEMES

This article has used the CDM as an illustrative example to examine the challenges associated with project-level offset activities. The

TABLE 8 Sensitivity analysis for different stage-specific success probabilities (project design document [PDD] Stage and Sale stage).

PDD stage success probability (%)	COV	Sensitivity (%)	Sale stage success probability (%)	COV	Sensitivity (%)
100	19	111	**100**	**17**	**100**
95	18	106	95	15	89
90	**17**	**100**	90	14	79
85	15	90	85	12	68
80	14	81	80	10	58
75	12	73	75	8	47
70	11	66	70	7	42

Note: All input parameters as indicated in Table 6, except for PDD stage and Sale stage success probabilities. The compound option value (COV) are in 1000 USD. Baseline calculation in bold. Sensitivity expressed relative to baseline calculation.

TABLE 9 Sensitivity analysis for different volatility estimates.

Volatility (%)	COV	Sensitivity (%)
150	33	194
140	30	177
130	27	160
120	24	142
110	21	124
100	18	106
97	**17**	**100**
90	15	88
80	12	69
70	9	51
60	6	35
50	3	20
40	2	9

Note: All input parameters as indicated in Table 6, except for volatility estimates. The compound option value (COV) are in 1000 USD. Baseline calculation in bold. Sensitivity expressed relative to baseline calculation.

TABLE 10 Sensitivity analysis for different certified emission reduction (CER) prices.

CER price	COV	Sensitivity (%)
0.50	**17**	**100**
1.00	68	398
2.00	195	1146
3.00	333	1951
4.00	473	2775
5.00	615	3607
7.50	972	5701
10.00	1332	7807
15.00	2049	12,012
20.00	2767	16,224

Note: All input parameters as indicated in Table 6, except for *V*. The compound option value (COV) are in 1000 USD. Baseline calculation in bold. Sensitivity expressed relative to baseline calculation.

article has shown how this process of starting offset projects is complicated by the multi-staged and uncertain success rates of project registration (technical risks) and unpredictable CER prices (market risks). It also highlighted that such a multi-staged process can be characterized as a chain of options on options, for which a compound real options approach, appropriately accounting for the multiple stages as well as the two basic sources of uncertainty, is well-suited.

The article does, however, have a wider relevance than the CDM as the real compound option approach to project valuation can be applied to a wider range of mitigation projects. The completion of the Paris Rulebook has laid the foundations of the GCMM where host states approve and authorize carbon emission reduction or removal activities and projects to achieve NDCs or for international trade. Such credits, termed A6.4ERs, will need to meet the requirements of a new supervisory body and are overseen by national supervisory bodies. A real compound option approach will allow project developers, that are required to meet these staged submission processes, greater clarity on their decision process, and the exact valuation of the investment, so as to allow them to select those that are investment grade.

The wider relevance of this compound option approach is witnessed by the fact that such multi-staged uncertain projects will be a feature of the GCMM. For example, the list of current emissions-trading schemes (see Table 11), a context-specific version of this approach can be utilized by project developers within the 21 emission-trading scheme jurisdictions which currently offer offset mechanisms within their cap-and-trade regulatory framework (see Table 11). These 21 jurisdictions account for over 5000 MtCO2e of annual emissions, equivalent to those of the EU, UK, and Canada combined.

Jurisdictions allowing offset credits have procedures and protocols available for the application, verification, approval, and issuance of offset credits following a similar multi-stage process as the CDM (see Section 2). Even though the names, the number, or the order of the different phases can slightly differ, they exhibit largely similar compound option-like stages.

A few more detailed examples provide some more detailed evidence for this general statement. For instance, the State of Quebec (Canada) offers offset credits in its ETS system. The process starts with filing an issuance request (Article 70.2), including a project report and a verification report (Article 70.3), after which the Minister takes a decision to issue offset credits (Article 70.4) and subsequent trading

TABLE 11 Overview of current emission-trading schemes (ETSs).

ETS	Offset mechanism	Year of implementation	GHG emissions in the jurisdiction (MtCO2e)
Alberta TIER	Yes	2022	242
Austria ETS	No	2022	85
BC GGIRCA	Yes	2016	60
Beijing ETS	Yes	2013	133
California CaT	Yes	2012	418
Canada Federal OBPS	Yes	2019	762
China National ETS	To be determined	2021	13,740
Chongqing ETS	Yes	2014	132
EU ETS	No	2005	4001
Fujian ETS	Yes	2016	245
Germany ETS	No	2021	874
Guangdong ETS	Yes	2013	648
Hubei ETS	Yes	2014	236
Kazakhstan ETS	Yes	2013	368
Korea ETS	Yes	2015	758
Massachusetts ETS	No	2018	76
New Brunswick ETS	To be determined	2021	14
New Zealand ETS	No	2008	85
Newfoundland and Labrador PSS	Yes	2019	11
Nova Scotia CaT	Yes	2019	17
Ontaria EPS	No	2022	165
Quebec CaT	Yes	2013	78
RGGI	Yes	2009	612
Saitama ETS	Yes	2011	41
Saskatchewan OBPS	Yes	2019	79
Shanghai ETS	Yes	2013	224
Shenzhen ETS	Yes	2013	45
Switzerland ETS	No	2008	48
Tianjin ETS	Yes	2013	161
Tokyo CaT	Yes	2010	66
UK ETS	No	2021	464
#jurisdictions with offsets	21		5336
#jurisdictions with no offsets	8		5798

Source: https://carbonpricingdashboard.worldbank.org/, data as of October 2022.

is possible.[14] Korea has a procedure to apply for offset credits after a feasibility evaluation of the offset project, consultation with the Ministry of Environment and deliberation of the Certification Committee (Article 39). The application requires a reductions monitoring report prepared by an external project operator and a verification report of a verifying institution (Article 40). After approval and inclusion in the offset register, trading is again possible (Article 41).[15] The State of California (USA) has a Compliance Offset Protocol, which start with listing the offset project with an approved Offset Project Registry (OPR), a review by the OPR and a public listing on its website. Once listed, the project will be monitored, reported, and verified. If the project meets the requirements, offset credits will be issued (Article 95973).[16] California uses six different protocols for various types of offset projects such as livestock projects, mine methane capture projects, or forest projects.[17] These examples show that the creation of

[14]Quebec, Regulation respecting a cap-and-trade system for greenhouse gas emission allowances, available at: https://www.legisquebec.gouv.qc.ca/en/document/cr/Q-2,%20r.%2046.1 (as of June 2022), consulted October 31, 2022.

[15]Korea, Enforcement decree of the act on the allocation and trading of greenhouse gas emission permits, Presidential Decree No. 24180, Nov. 15, 2012, last updated by Presidential Decree No. 28562, December 29, 2017 available at: https://elaw.klri.re.kr/eng_mobile/viewer.do?hseq=46598&type=sogan&key=60, consulted on October 31, 2022.

[16]California, Regulation for the California Cap on Greenhouse Gas Emissions and Market-Based Compliance Mechanisms, available at: https://ww2.arb.ca.gov/sites/default/files/2021-02/ct_reg_unofficial.pdf, consulted on October 1, 2022.

[17]See for further details https://ww2.arb.ca.gov/our-work/programs/compliance-offset-program/about.

offset credits typically involves multiple stages, very similar to the set-up we described under the CDM. Such investments in offset credits can be analyzed from a compound real options lens, especially given the uncertainties related to such processes.

6 | CONCLUSIONS

Current levels of investment in mitigation remain below those needed to limit global warming to 1.5°C with less than 20% of the required annual finance flowing towards mitigation goals. Whilst around half of current climate flows are from public actors (national and multilateral finance institutions), the considerable mitigation finance gap, and limited fiscal space in many Annex I countries, suggests a much greater role for the private sector in coming years. One key route through which the private sector can deploy capital is through investing in emission reduction projects. However, investment decisions need to be based on clear-headed analysis of the potential risks and rewards from investing in mitigation projects.

As described in the introduction, the GCMM as described in Article 6.4 of the Paris Agreement allows a firm in one nation to sell emission reduction credits to a firm in a different country. It is the successor to the CDM, one of the three flexibility mechanism at the heart of the Kyoto Protocol, which facilitated the sale of offset credits from entities in non-Annex I countries to entities in Annex I nations. The CDM suffered from a range of shortcomings including considerable delays in planning, construction, and revenue streams which necessitated bridging finance in the form of equity finance, loans, or grants. This article has focused on the heavy and complex administrative burden and the substantial transaction costs related to the uncertain outcomes in the different stages of project registration, verification, certification, and issuance (e.g., Michaelowa & Jotzo, 2005; Thomas et al., 2009), which discouraged private investors to engage in CDM project development.

This article has shown how the development and implementation of mitigation projects is complicated and involves many specific risks, mainly related to the multi-staged and uncertain success rate of project registration (*technical risk*) and unpredictable CER prices (*market risk*). It has argued that the multi-staged project process can be characterized as a chain of options on options, which can be specified using a real compound option approach. The key practical contribution of the article is that it has demonstrated how a real compound option approach is a more appropriate and accurate valuation technique compared to NPV or cost–benefit approaches as it incorporates the multi-staged and risky nature of these projects.

Moreover, the article has argued that the real compound option approach has a much wider relevance than the CDMs. As key sections of the Paris Rulebook have finally been completed, the scope for offset trading is likely to increase in the coming years including through Article 6.4 (as indicated by recent increase in offset prices). In addition to informing mitigation investments in the incipient GCMM, the article has highlighted the 21 emission-trading scheme jurisdictions currently offering offset mechanisms within their regulatory framework. Current market signals indicate that offset projects will play a considerable role in the climate architecture in the coming years. Such an approach to project development would increase the likelihood of closing the mitigation finance gap, decreasing emissions, and ultimately reducing the likelihood of dangerous climate change.

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APPENDIX A: The *n*-fold compound option model

As highlighted in Section 3, this appendix presents the analytical details of the compound option formula used to calculate the values in Section 4, as derived in Cassimon, De Backer, et al. (2011). In order to increase the intuitive understanding of this formula, and similar to the presentation of Table 1 in Section 3, this appendix starts by presenting the simple and classic one-period option model derived by Black and Scholes (1973). It then shows that the compound option model of Cassimon et al. (2004) is a mere generalization of the one-period Black-Scholes model for multiple periods. Finally it details how technical risk is incorporated to come to the final model of Cassimon, De Backer, et al. (2011) used for the empirical analysis.

A.1 | Valuing a single-stage project with market risk: the Black and Scholes (1973) model

If we take the classic assumption that the underlying project value V_t can be written as a Brownian motion following the stochastic process $dV_t = \mu V_t dt + \sigma_m V_t dW_t^m$, with μ the expected rate of return on the project and σ_m being the volatility estimate (market risk), then Black and Scholes (1973) have shown that the value of a call-option, C_1, on the project with value V, can be expressed as:

$$C_1 = V \cdot N_1(a_1) - K \cdot e^{-r(T-t)} \cdot N_1(b_1), \tag{A1}$$

where

$$a_1 = \frac{ln\left(\frac{V}{K}\right) + \left(r + \frac{\sigma_m^2}{2}\right)(T-t)}{\sigma_m \sqrt{T-t}} = b_1 + \sigma_m \sqrt{T-t}, \tag{A1a}$$

$$b_1 = \frac{ln\left(\frac{V}{K}\right) + \left(r - \frac{\sigma_m^2}{2}\right)(T-t)}{\sigma_m \sqrt{T-t}}, \tag{A1b}$$

with V, value of the project, as the value of all the future CER sales; K, exercise price, or investment cost needed to start the project; $T - t$, time to expiration (in years); σ_m, annualized standard deviation (volatility) of the value of the project V;[18] r, continuous risk-free interest rate; $N(x)$, value of x under the cumulative normal probability density function.

[18]It is also important to highlight that our model allows to capture both commercial as well as regulatory risk within our total volatility estimate (market risk). We assume that the underlying project value V_t can be written as a Brownian motion following the stochastic process $dV_t = \mu V_t dt + \sigma_c V_t dW_t^c + \sigma_r V_t dW_t^r$, with μ the expected rate of return on the project, σ_c the commercial uncertainty, σ_r the regulatory uncertainty, dW_t^c and dW_t^r stochastic variables which follow a standard Wiener process. Following Cortazar et al. (2003) and Engelen et al. (2016) we reduce the complexity of the model by collapsing commercial and regulatory uncertainty into one volatility estimate σ_m (market uncertainty), with $\sigma_m = \sqrt{\sigma_c^2 + 2\rho\sigma_c\sigma_r + \sigma_r^2}$ and ρ the correlation between the two sources of uncertainty. As such, the stochastic process is again represented by $dV_t = \mu V_t dt + \sigma_m V_t dW_t^{ct}$, as is similar to the simple Black-Scholes set-up above. Empirically, in Section 4.1.4, we derive the volatility metric from the evolution of CER market prices which most likely capture both sources of uncertainty. Hence, this approach matches the CDM data well.

Note that symbols a_1 and b_1 in the equation are merely instrumental variables, calculated from the parameters in the model, merely for the purpose of simplifying the notation of Equation (A1).[19]

A.2 | A generalized multi-stage (compound) option model with market risk

Using the same assumption on the stochastic process of the project value as in Section A.1, and building on Geske (1979) that extended the single stage Black-Scholes model for two stages, that is, deriving a closed-form solution for the value of an option on an option, Cassimon et al. (2004) generalized the two-fold Geske model for *n*-stages.

More specifically, Cassimon et al. (2004) have shown that for the time line t (t_1, t_2, …, t_{k+1}), the corresponding strike prices (K_1, K_2, …, K_{k+1}) and the corresponding option values at maturity ($C_1(V, t_1)$, $C_2(V, t_2)$, …, $C_{k+1}(V, t_{k+1})$), the closed-form pricing formula for the $(k + 1)$-fold compound option at moment t is as:

$$C_1 = V \cdot N_{k+1}\left(a_1, a_2, \cdots, a_{k+1}; R_1^{k+1}\right) - \sum_{l=2}^{k+1} K_l \cdot e^{-r(t_l - t)} \cdot N_l\left(b_1, b_2, \cdots, b_l; R_1^l\right) - K_1 e^{-r(t_1 - t)} \cdot N_1(b_1), \tag{A2}$$

where

$$a_\ell = b_\ell + \sigma_m \sqrt{t_\ell - t}, \quad \text{with } \ell = 2, \ldots, k+1, \tag{A2a}$$

$$b_\ell = \frac{ln\left(\frac{V}{\overline{V}_\ell}\right) + \left(r - \frac{\sigma_m^2}{2}\right)(t_\ell - t)}{\sigma_m \sqrt{t_\ell - t}}, \quad \text{with } \ell = 2, \ldots, k+1, \tag{A2b}$$

$$\text{where } \overline{V}_l \text{ is the solution of } \tilde{C}_{\ell+1}(V, t_\ell) = K_\ell, \quad \text{with } \ell = 1, \ldots, k \tag{A2c}$$

$$R_1^\ell = \left(a_{ij}^\ell\right)_{i,j=1,2,\ldots,\ell} \text{ with } \begin{cases} a_{ii} = 1 \\ a_{ij} = a_{ji} = \rho_{ij}; i < j \end{cases} \text{ and } \rho_{ij} = \sqrt{\frac{t_i - t}{t_j - t}}; i < j. \tag{A2d}$$

Note that this formula is a mere generalization of the single-phase option model for the case of $(k + 1)$ phases, and the former symbols still apply: V remains the value of the project, equal to the present value of all the future CER revenues, σ_m is the same market risk and r is the same continuous risk-free interest rate. What changes is that:

- instead of one investment cost K, we now have a series of stage-specific investment costs, K_i.
- The single period $(T–t)$ is now distributed in a series of periods (still measured in years), each with timing $(t_i–t)$.
- $N_i(x)$ denotes the value of x under the i-variate normal distribution function.

[19]Note that we use similar notations in the expression of the Black-Scholes equation as in the *n*-fold compound option model to illustrate the similarities between the models. Readers might be more familiar with the notations of d_1 and d_2, but it does not alter the equation.

Note also that R is again merely an intermediary, instrumental variable, used to make the notation of Equation (A2) more simple.

A.3 | A generalized compound option model with market and technical risk

As highlighted in Section 3, the Cassimon et al. (2004) generalization assumes that, in this multi-stage process, the success to move from one stage to the next is guaranteed, that is, success rates are 100% or put otherwise, that there is no "technical risk." To account for these probabilities of failure along the way, Cassimon, De Backer, et al. (2011) extend the previous framework to allow for technical risk as well, while still keeping its closed-form characteristic. The basic assumption here is that the probabilities of success of the different stages, that is, technical risk, are independent from the market risk σ_m. More specifically, if there is a series of technical success probabilities p_1, p_2,..., p_{k+1} at each stage, then Cassimon, De Backer, et al. (2011) have shown that the model from Section A.2. can be rewritten as:

$$C_1 = h_{k+1} \cdot V \cdot N_{k+1}\left(a_1, a_2, \cdots, a_{k+1}; R_1^{k+1}\right) - \sum_{l=2}^{k+1} h_l K_l \cdot e^{-r(t_l - t)} \cdot N_l\left(b_1, b_2, \cdots, b_l; R_1^l\right) - h_1 \cdot K_1 e^{-r(t_1 - t)} \cdot N_1(b_1), \quad \text{(A3)}$$

where

$$a_\ell = b_\ell + \sigma_m \sqrt{t_\ell - t}, \quad \text{with } \ell = 2, \ldots, k+1, \quad \text{(A3a)}$$

$$b_\ell = \frac{\ln\left(\frac{V}{\overline{V}_\ell}\right) + \left(r - \frac{\sigma_m^2}{2}\right)(t_\ell - t)}{\sigma_m \sqrt{t_\ell - t}}, \quad \text{with } \ell = 2, \ldots, k+1, \quad \text{(A3b)}$$

where $\overline{V}_l$ is the solution of $\tilde{C}_{\ell+1}(V, t_\ell) = K_\ell$, with $\ell = 1, \ldots, k$. (A3c)

$$R_1^\ell = \left(a_{ij}^\ell\right)_{i,j=1,2,\ldots,\ell} \text{ with } \begin{cases} a_{ii} = 1 \\ a_{ij} = a_{ji} = \rho_{ij}; i < j \end{cases} \text{ and } \rho_{ij} = \sqrt{\frac{t_i - t}{t_j - t}}; i < j, \quad \text{(A3d)}$$

and

$$h_{k+1} = p_1 p_2 \ldots p_k p_{k+1}, \quad \text{(A3e)}$$

$$h_k = p_1 \ldots\ldots p_k,$$

$$\ldots$$

$$h_2 = p_1 p_2,$$

$$h_1 = p_1.$$

Technical risk is present through the technical risk probabilities; in the formula, p_i is the independent technical success probability of phase i; as such, h_i equals the probability of success of phase i, given that all previous phases were successful; as such, this conditional probability has to be multiplied with the same-phase investment cost K_i, and also with V in case of the final commercialization phase. Again, the variable h is merely an instrumental variable, allowing a more simplified presentation of Equation (A3).

Equation (A3) is used in the empirical Section 4 to calculate the COVs. An overview of the input parameters is presented in Appendix C.

APPENDIX B: Calculation of average stage-specific success rates and lead times

B.1 | Data cleaning

Data cleaning is performed to ensure obviously incorrect data is filtered out of the sample. Firstly, 207 projects that are "under consideration" have been filtered out. Consecutively, the criteria for data cleaning of Cormier and Bellassen (2013) have been applied. According to Cormier and Bellassen, a record is plausible when it meets the following criteria:

1. The validation duration must be greater than 1 day
2. The registration duration must be greater than 28 days
3. The monitoring period duration must be greater than 1 day
4. The certification duration must be greater than 15 days

Since the IGES CDM Project Database does not contain information about the monitoring period, the last two criteria of Cormier and Bellassen (2013) cannot be included into the analysis. 8443 (69%) out of 12,261 projects will remain into the sample after the data cleaning. On the basis of the available information (data IGES database + definition success rates Cormier and Bellassen), the following derivations for the success rates have been selected:

$$SR_{\text{validation}} = \frac{N_{\text{entered\_registration}}}{N_{\text{entered\_validation}}},$$

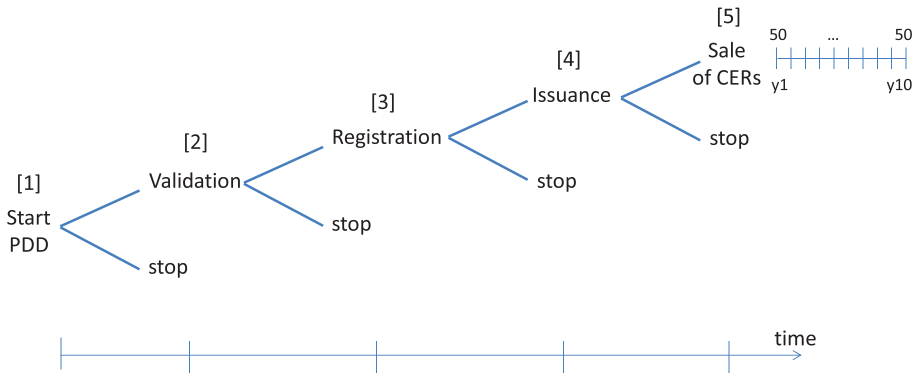
$$SR_{\text{registration}} = \frac{N_{\text{registration\_successful}}}{N_{\text{entered\_registration}}},$$

$$SR_{\text{issuance}} = \frac{N_{\text{issuance\_successful}}}{N_{\text{registration\_successful}}}.$$

B.2 | Lead times

Since the IGES database contains specific dates of several stages in the process, it was possible to determine the average duration per phase. Based on this it is shown that the process from validation to earning the saleable CER credits takes on average 3.5 years. It can be noted that these average durations can only be obtained for projects that have completed a specific phase.

APPENDIX C: Overview of the parameters



Ti	0	0.50	1.45	1.89	3.83
Ki	50	30	185	25	24
Pi	0.90	0.54	0.91	0.65	1.00

V = annuity(10y;8%;50)xDiscountFactor(8%;3.83y)=250 thousand

Vol = 97%, r=1.67%