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Review

Application of real options in carbon capture and storage literature: Valuation techniques and research hotspots

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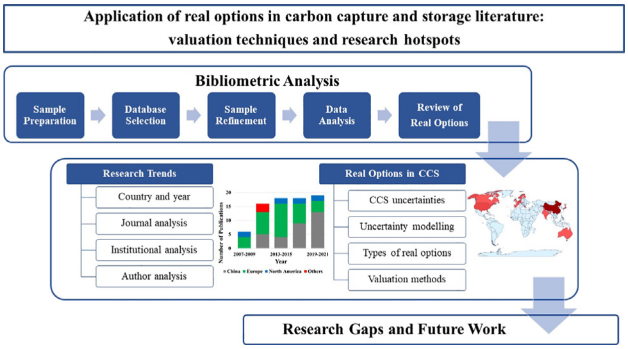
HIGHLIGHTS

- Research trends in the application of real options valuation in CCS are examined.
- CCS papers employed various uncertainties, modeling techniques, types of real options, and option valuation methods.
- Literature review identified research hotspots and gaps.
- Future research and CCS policies are proposed.

GRAPHICAL ABSTRACT



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ABSTRACT

Carbon capture and storage (CCS) is one of the key technologies and measures for the energy transition towards achieving the climate targets. Accounting for the high uncertainty, risks, and irreversibility of CCS projects, a growing number of studies apply the real options (RO) approaches which allow flexibility in the valuation of uncertain investment. Various RO models and valuation techniques are adopted and the critical analysis of the research trends and research hotspots in RO designs in CCS investments has not been made yet. This study employs a bibliometric analysis to examine the features of CCS literature including the research focus and trends as well RO uncertainty and models, types of options, and valuation techniques. The results present a comprehensive overview of the state-of-the-art which provides researchers a concrete basis for future research and directions for further development. This further provides energy and environmental policymakers and CCS project planners with valuable insights on various aspects of CCS policy and project design.

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1. Introduction

Different countries resolved a goal to limit global warming to 1.5 °C to prevent the extreme effects of climate change. To meet this target, the world needs to curb its greenhouse gas (GHG) emissions by at least 49% of the 2017 level by 2030 and then achieve carbon neutrality by 2050 (Tollefson, 2018). According to Intergovernmental Panel on Climate Change (IPCC), this requires "rapid and far-reaching" transitions in managing land, energy, industry, buildings, transport, and cities (Zhenmin and Espinosa, 2019).

Among the climate mitigation technologies available, the carbon capture and storage (CCS) is a "game-changer" with its ability to avoid carbon dioxide (CO2) emissions at source and enable large-scale decreases to CO2 already in the atmosphere making it an essential part of the solutions (Global CCS Institute (GCCSI), 2020). Currently, there are 65 commercial CCS facilities with 26 in operation, 2 suspended their operations due to economic downturn and fire, 3 under construction, 13 in advanced development reaching front end engineering design, and 21 in early development (GCCSI, 2020). The facilities in operation capture around 40Mt of CO2 annually and store it permanently. Despite its potential, large-scale CCS deployment is affected by various barriers including the huge costs, policy incentives, technologies, and public acceptance (Budinis et al., 2018).

In recent years, the increasing number of publications on CCS has brought scholars to review the literature from various perspectives including technical, economic, and social perspectives. One of the earliest reviews was Knoope et al. (2013) which provided a systematic overview of techno-economic models predicting the costs of CO2 pipeline transport. The review compared investment and operations and maintenance (O&M) costs models for pipelines and booster stations. Leeson et al. (2017) carried out another techno-economic analysis on the applicability of CCS technologies in different industries including cement, iron and steel, petroleum refining, and pulp and paper. Applying a systematic review of 250 papers from the academic and grey literature, the study constructed a scenario-based assessment of potentially important parameters driving overall costs at the start of CCS deployment. Budinis et al. (2018) reviewed the barriers to CCS development focusing on the recent cost estimates and assessed the potential of CCS to enable access to fossil fuels without causing dangerous levels of climate change. The study concluded that the worldwide adoption of CCS would be critical with continuous and substantial access to fossil fuel reserves while still meeting the climate targets. In terms of the social aspect, Selma et al. (2014) identified 42 articles discussing the public perception of CCS. The review formed a good basis for the communication of CCS risks and recommended more case studies on CCS acceptance at the project level, as opposed to societal acceptability of CCS. Recently, H. Li et al. (2019) employed a bibliometric analysis of 890 documents to identify the CCS research hotspots and modeling techniques. The results recognized five hot research topics including tackling climate change, CCS technology prospects, cost estimates, sectoral applications, and social attitudes. The study identified three main methodologies including life cycle analysis, optimization methods, and real options (RO) methods to quantify the social, economic, and environmental impacts of CCS. In another bibliometric analysis, J. Li et al. (2019) reviewed 678 documents and identified 4 groups of methods: cost accounting, project planning, investment decision-making, and optimization of low-carbon power generation technology portfolio, and CCS operational decision-making. Among the methods used to evaluate investment decisions of CCS projects, the RO method (20 documents) and net present value (2 documents) were the most common with the former as the better method considering the uncertainty and investment flexibility.

With a variety of uncertainties in CCS investment including technology, policy, social acceptance, and the market (Huang et al., 2020; d'Amore et al., 2020), recent studies employ the RO approach to account for these uncertainties and incorporate the flexibility in decision-making for irreversible CCS investment. Currently, only H. Li et al. (2019) provided a fragmented overview of these studies. The review evaluated 9 documents and identified three characteristics of RO design in the CCS literature. First, the evaluation of the economic feasibility of CCS focused on the replacement of old power plants or retrofitting with CCS. Second, investments in CCS were linked with several uncertainties including CO2 and fuel prices, technical change, and climate policies. Last, the valuation methods for RO models could be grouped into discrete (trees or lattices) and continuous-time (simulation and programming) models. This research, albeit provided an overview of methods in CCS project valuation, had limited samples of selected studies focusing on the application of RO valuation on CCS projects. A substantial number of studies published in recent years were not included, yet, worthy to investigate.

Therefore, this study aims to provide a more comprehensive overview of current research focuses and trends as well as to present a more in-depth review of academic papers utilizing the RO methods to CCS project valuation. The objectives of this study are (1) to review the extant literature that applied RO methods to CCS projects; (2) to present the research trends in the field; (3) to provide a comprehensive overview of RO models and valuation methods; and (4) to identify the knowledge gaps that serve as a basis for research direction. This research employed bibliometric analysis and the strengths of existing reviews in the field. The results summarize the reviewed CCS literature, provide several insights on RO designs that need further research, and present implications that might be useful for project planners and policymakers.

The structure of this article is as follows. Section 2 introduces the basic principles of real options theories which include a comparison with financial options, types of real options, valuation methods, types of uncertainties, and modeling the uncertainties. Section 3 discusses the step-by-step procedure for bibliometric analysis. Sections 4 and summarize research trends, RO valuation research hotspots, and a discussion of the role of CCS in addressing climate change. Section 6 concludes the review, presents the knowledge gaps and provides future research directions.

2. Basic principles of real options

The "real options" was first coined by Myers (1977) as an application of option pricing theory to the valuation of non-financial or "real" assets. An option is a right, but not an obligation, to take some actions at a specified cost. The term "real" refers to tangible assets including products, processes, and services rather than financial assets such as stocks, bonds, and mutual funds. Real options can be seen as opportunities to purchase real assets on possibly favorable terms hinge on adjustment costs, market power, or other imperfections in product or factor markets (Trigeorgis and Reuer, 2017).

Real options valuation is significantly analogous with financial options valuation (Black and Scholes, 1973) as seen in Table 1. However, their differences are not discussed thoroughly as most arguments are rather academic by nature which do not reflect the practical concerns of RO valuation (Haahtela, 2012). Hence, the interpretation of the calculated result and its theoretical correctness may be irrelevant due to the underlying assumptions that contradict reality.

Various reputable textbooks (see Mun, 2002; Copeland and Antikarov, 2001; Trigeorgis, 1996; Dixit and Pindyck, 1994) comprehensively discussed different RO approaches, modeling, and valuation techniques. This review will focus on the RO techniques commonly used in the reviewed literature.

2.1. Types of options

The extension of analogy from financial markets with options traded with specified terms to a real asset resulted in a variety of different types of real options (Trigeorgis and Reuer, 2017). These options describe the management flexibilities in decision-making that relate to project size, project timing, and operation (Agaton, 2019). The traditional types of stand-alone real options include the following.

- The option to wait is flexibility to delay/defer the investment decision to a more favorable period in the future; synonymous with the timing option.
- The option to stop/restart operations provides flexibility to temporarily shut down part or all of the operation when conditions are unfavorable and may restart operations when conditions improve.
- The option to grow is the flexibility to expand business operations, make a new investment, or undertake a new project if conditions are more favorable than expected.
- The option to change scale is the flexibility to scale down or expand the project.
- The option to switch is the flexibility to change the production input materials, fuels, technologies, suppliers, subsidiaries, or output products.
- The option to stage investment refers to the breaking down of the investment project into several stages to flexibly terminate later stages in the case of unfavorable circumstances, hence, minimizing the risks.
- The option to abandon/exit is the option to cease a project or sell technology to realize its salvage value if market conditions deteriorate.

Table 1
The analogy between financial and real options.

Financial option	Symbol	Real option
Value of underlying asset price (stock price)	S	Present value of the project's expected cash flows
Exercise (strike) price	X	Amount of money to be invested or received upon launching (exercising) the action (option)
Volatility of the value of the underlying asset	σ	Uncertainty about the future value
Time until the option expires	T	Time until the decision must be made
Risk-free interest rate	r	Risk-free discount rate
Amount of dividend payments	δ	Dividend of the project over its lifetime

A considerable number of studies use exotic options which are applied to customized project contracts with more complex requirements to meet the risk tolerance and desired profit of the investor (e.g. Di Bari, 2021; Deeney et al., 2021; Kim et al., 2017; Jin and Tian, 2015). These options differ from traditional options in terms of payment structures, expiration dates, and strike prices.

- The barrier options provide a pay-out to the holder depending on whether the underlying asset reach (or does not reach) a predetermined price; can be knock-out when it expires worthless if the underlying exceeds a certain price or knock-in when it has no value until the underlying reaches a certain price.
- The binary options, also called "all-or-nothing" options, are a contract that awards a fixed amount or nothing at all when the option expires; can be cash-or-nothing or asset-or-nothing.
- The compound option is an "option on an option" where the underlying security is another options contract, thus, involves two strike prices and two expiration dates.
- The chooser option allows the owner of the contract to choose whether it's a call "buy" or a put "sell" when a specific date is reached.
- The look-back option allows the owner to exercise at the best price the underlying security reached during the term of the contract.

2.2. Valuing real options

There are various methods to valuing real options as extensively discussed in the books of Dixit and Pindyck (1994) and Trigeorgis (1996) as well as the overviews of Martins et al. (2015) and Regan et al. (2015). Here are the common methods in CCS projects.

- Black–Scholes–Merton (BSM) model is a closed-form method with a continuous-time, analytical, mathematical approach to valuing real options (Dixit and Pindyck, 1994). The main advantage of this model is its simplicity to value the RO which only requires inputting the six variables (see Table 1) into the formula (Martins et al., 2015).
- Lattice-based methods are numerical, time discrete models that use simpler mathematics to value RO with two (or more in advanced methods) alternative future outcomes in each step/node (Kozlova, 2017). The simplest method is the binomial tree (or lattice), initially presented by Cox et al. (1979) as a binomial options pricing model, and later complicated using trinomial (H. Liu et al., 2018) and quadrinomial (Wang and Du, 2016) lattices. The main advantage of this model is its effectiveness with only one uncertainty and flexibility to estimate several options (Martins et al., 2015).
- Simulation methods create a distribution of expected possible values of the project considering different sources of uncertainty (Boyle, 1977). Monte Carlo is the most common simulation method that calculates the RO value by randomly simulating the thousands of possible future scenarios for uncertain variables (Agaton et al., 2020). It is considered the easiest way to value RO for complex projects without formulating the cash flows through PDE or trees, however, the most computationally expensive approach (Regan et al., 2015).

- Dynamic programming is a method that allows the evaluation of the optimal timing of the investment as well as enables the combination of various types of RO with several possible scenarios (Kozlova, 2017). This method divides the investment decision process into two: the immediate or initial decision, and the valuation of the consequences of all subsequent decisions (Machiels et al., 2021). Using backward induction towards the initial investment decision, the option values are evaluated for each scenario, identifying the optimal timing to exercise an option (Kozlova, 2017).
- The differential equation is a numerical solution, introduced by Merton (1977), which be derived by approximating a partial differential equation of the real options model. This can be done with methods such as the finite difference method and finite element method with the underlying idea to discretize the solution domain and calculate an approximative solution of the differential equation in the whole domain (Eissa and Tian, 2017).
- The fuzzy pay-off method for RO valuation, developed by Collan et al. (2009), is based on the use of fuzzy logic and fuzzy numbers to create a distribution of the possible pay-offs of a project. While this method allows the advantages of simulation-based methods to be retained while reducing computational requirements, it has not been widely used in project valuation (Kozlova, 2017).

2.3. Uncertainty modeling

Besides managerial flexibility in a partially or fully irreversible investment, the usage of the RO technique as deemed appropriate only if there is uncertainty (Dixit and Pindyck, 1994). Uncertainties that affect the investment decision-making process include market, policy, technology, social acceptance, or environmental uncertainty (Cardin et al., 2017; Agaton, 2019; Zhao et al., 2004). In RO valuation, various methods are applied to describe the uncertainties. This is done by identifying the stochastic process that better describes the random behavior of the asset prices in time (de Magalhães Ozorio et al., 2012).

A stochastic process on the prices of stock, commodity, and energy is commonly described using Geometric Brownian motion (GBM) and Mean Reversion (MR) (Kozloza, 2017; Agaton, 2019). The GBM is a continuous-time stochastic process in which the variance of a log-normal diffusion of prices grows proportionally with the time interval, while for MR, the variance tends to move to the average price over time (Agaton et al., 2020). Other sources of uncertainties such as technological cost, efficiency, and knowledge capital are usually modeled with the Poisson jump and learning curve (Trigeorgis and Tsekrekos, 2018; Duan et al., 2018). The Poisson jump is a stochastic process with discrete movements, called jumps, of fixed or random size for which the arrival times follow Poisson distribution; while the learning curve describes the cost reductions in more mature technologies due to learning (Agaton et al., 2020).

3. Methodology

Bibliometric analysis is a statistical or mathematical method used to assess and quantify the number and the growing trend of a particular subject (Mao et al., 2018). This method helps researchers to explore, organize, and analyze huge amounts of information such as characteristics, structure, and development of academic literature as well as to grasp the basic information and research trends in the field (Su et al., 2020; H. Li et al., 2019). This study applied bibliographic analysis to identify the research hotspots and RO valuation methodologies used in CCS literature. The sequence of steps includes (1) sample preparation and defining search criteria; (2) database selection; (3) adjustment and refinement of research criteria; (4) analysis of the information; and (5) qualitative review of RO valuation (see Fig. 1).

The initial search was limited by the following criteria: (1) a RO approach is used; and (2) at least one of the processes in CCS is evaluated. The following combination of keywords was used as a search criterion: “real option” and “CCS”, “carbon capture and storage”, “carbon capture and sequestration”, “CO2 capture and sequestration”, “CO2 capture and storage”, “CO2 capture”, “carbon capture”, “carbon capture and utilization”, “CCU”, “carbon capture, utilization, and storage”, “CCUS”, “carbon capture, utilization, and sequestration”, “CO2 capture, utilization, and storage”, “CO2 capture, utilization, and sequestration”, “CO2 storage”, “carbon sequestration”, or “CO2 transport”.

In the database selection, the Web of Science (WoS) was first considered due to its quality, the possibility to search and filter search using several bibliographic parameters, easy access to the full texts of the searched papers, and the most commonly used database, generating useful information for researchers evaluating scientific activity (Ruiz-Real et al., 2018). The SCOPUS, on the other hand, is among the largest curated abstract and citation databases, with a wide global and regional coverage of scientific journals, conference proceedings, and books, while ensuring only the highest quality data are indexed through rigorous content selection and re-evaluation by an independent board (Baas et al., 2020). While Google Scholar is the most comprehensive database as it covers non-journal sources including theses, books, conference papers, and unpublished materials (Martín-Martín et al., 2018), its low data quality raises questions about its suitability for research evaluation (Mongeon and Paul-Hus, 2016). Therefore, this review only covered the literature from WoS and Scopus.

The preliminary search resulted in 116 documents from WoS and 113 from SCOPUS. The two results were combined and the duplicates were removed. The 140 unique documents were then refined to journal articles in the English language applying option valuation in at least one of the CCS processes (capture, transport, storage, utilization). Several papers from conference proceedings were excluded due to the limited discussion of the methodology that was crucial in the critical review of RO valuation techniques (e.g. Nie et al., 2017; Rohlfs and Madlener, 2013). The refinement further omitted studies that apply RO in CCS but not for its evaluation (e.g. Sanders et al., 2013). As a result, there were 67 research articles reviewed for the bibliometric analysis.

The data analysis includes the year of publication; the country and institution for which the research was conducted; the authors; the journal where the paper was published; and the number of citations in SCOPUS and/or WoS to date (22 March 2021). Since the two databases had different citation counts, the analysis took the higher count. Finally, the research hotspots were identified in terms of the type of RO, uncertainty sources and modeling, and the RO valuation method used. The next section summarizes and discusses the key results obtained.

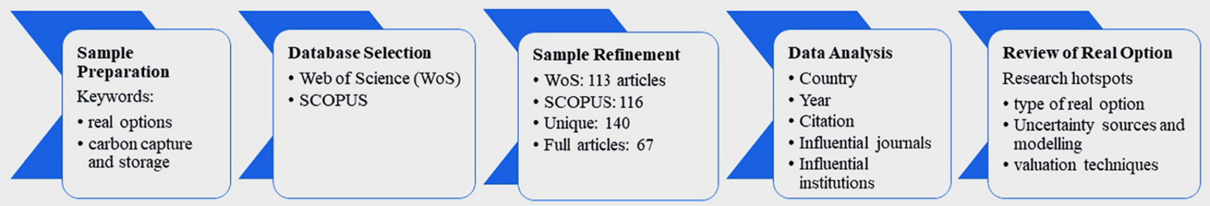


Fig. 1. Bibliometric analysis framework.

4. Research trends

4.1. Country and year trends

A total of 67 research articles were published from 2007 to 2021. All over the world, a total of 19 countries were involved in real options research related to CCS. Among the top countries were China with almost half of all publications (46%), Netherlands (15%), Germany (12%), the United States of America (USA) (10%), and the rest were mostly from European Union with few studies from Japan, Canada, and India (see Fig. 2). The research output suggested that these countries and regions were leading the research on CCS for GHG emissions reduction. This result is expected considering the maturity of CCS technology in the regions with several commercially operating CCS facilities, facilities under development, as well as pilot and demonstration facilities in operation and development (GCCSI, 2020).

The growing body of literature devoted to the application of RO theory in the valuation of CCS investment is illustrated in Fig. 3. It could be noticed that the RO approach was only applied a decade after the first two publications of CCS research in 1997 (Audus, 1997; Audus and Freund, 1997). With a range of three years, the figure shows a positive trend in the number of publications with more than five papers per annum in the past 10 years. This reveals the usefulness of RO in CCS project valuation as more and more researchers are using this approach in the last years.

Comparing the country clusters, European countries and North America began CCS valuation with RO theory. This can be attributed to these regions being consistent forefronts of pushing actions against climate change, and setting subsequent targets to accommodate a shift in the decomposition factors of CO2 emission in these regions (Bekun et al., 2019). China started late but showed a rapid growth rate from the year 2010 onwards. This was the year after China participated in the Copenhagen Climate Change Conference and made important commitments to control CO2 emissions in 2009 (Wang and Zhu, 2020). While European countries have continuous research on CCS with RO, North America and the rest of the world are lagging. This can be explained by the withdrawal of Canada from the Kyoto Protocol after the USA due to the difficulty of meeting the high emission reduction target and the potential economic loss (Lv et al., 2020). Further, the American bait-and-switch between 1997 and 2001 negatively affected the negotiation dynamics which other countries (e.g. Japan, New Zealand, Russia) subsequently decided not to take part in a second commitment to Kyoto Protocol from the period starting in 2012 (Milkoreit, 2019).

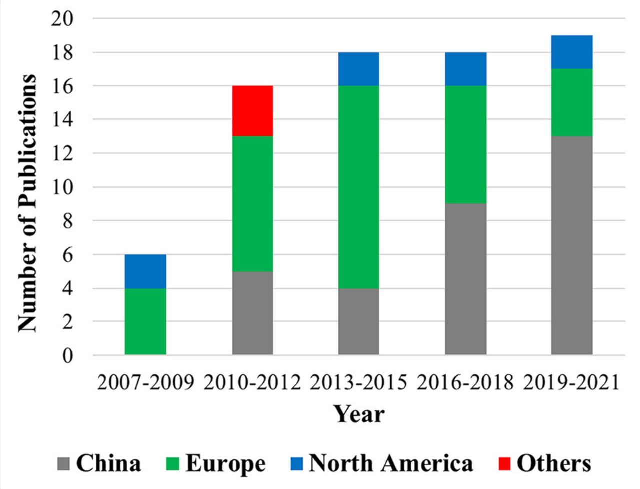
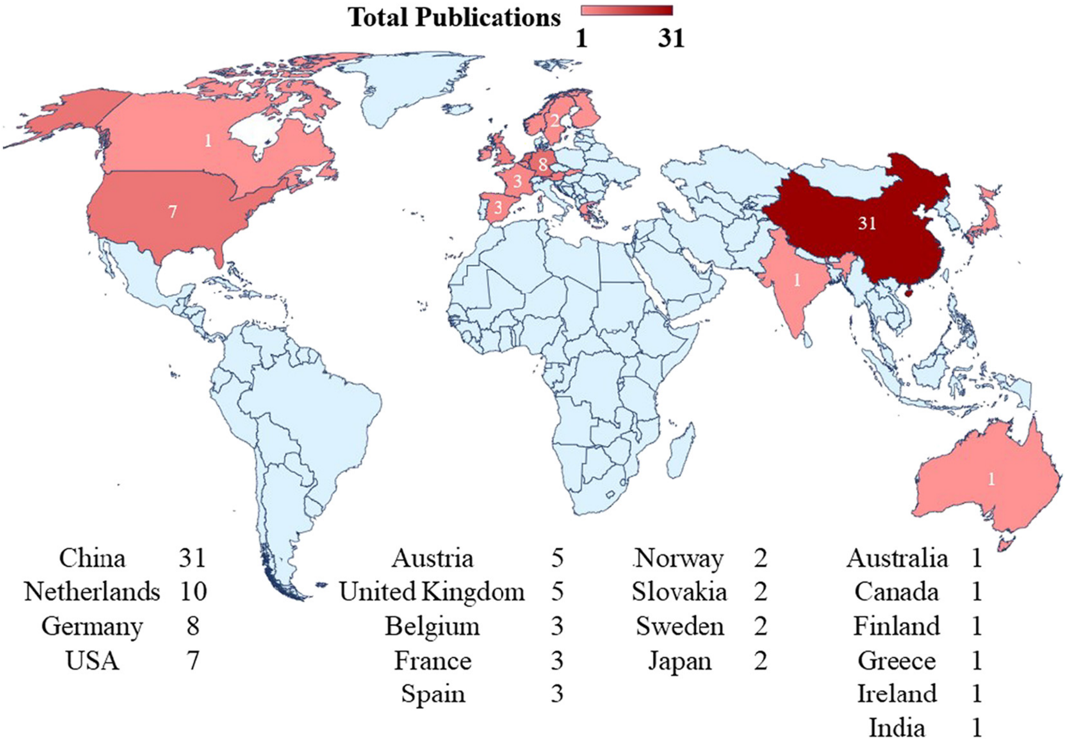


Fig. 3. Time trend and country clusters.

4.2. Journal trends

With the interdisciplinary nature of CCS investment, the project planning and decision-making were positioned in various subjects of energy, policy, economics, and technology. As shown in Table 2, among the top journals include the Energy Policy with 10 publications



China	31	Austria	5	Norway	2	Australia	1
Netherlands	10	United Kingdom	5	Slovakia	2	Canada	1
Germany	8	Belgium	3	Sweden	2	Finland	1
USA	7	France	3	Japan	2	Greece	1
		Spain	3			Ireland	1
						India	1

Fig. 2. Geographical distribution of RO valuation of CCS.

Table 2
Top journals with RO valuation of CCS.

Journal	Total publications	Percentage	Total citations	Percentage
Energy Policy	10	16%	367	24%
Applied Energy	9	15%	432	28%
International Journal of Greenhouse Gas Control	8	13%	56	4%
Energy Economics	6	10%	246	16%
Journal of Cleaner Production	5	8%	123	8%
Energy	3	5%	75	5%
Energy Systems	3	5%	46	3%
Greenhouse Gases: Science and Technology	3	5%	6	0%

Table 4
Most cited institutions.

Institution	Rank	Total citations	Total documents
International Institute for Systems Analysis (IIASA)	1	311	4
Tsinghua University	2	205	4
Comenius University	3	202	2
Chinese Academy of Science	4	188	7
University of the Basque Country	5	182	3
Bilbao Bizkaia Kutxa	6	152	1
International Energy Agency	7	136	1
London Business School	8	136	1
Oxford Energy Associates	9	136	1
US Electric Power Research Institute	10	136	1

(16%), Applied Energy with 9 (15%), Greenhouse Gas Control with 8 (14%), and Energy Economics with 6 (10%). In terms of the total number of citations, Applied Energy took the lead with 432 citations (28%), followed by Energy Policy with 367 (24%), and Energy Economics with 246 (16%). This only showed that CCS papers focused on the development and analysis of CCS processes as well as addressing the policy implications of CCS from economic, social, planning, and environmental aspects.

From these journals, Abadie and Chamorro (2008) from Energy Economics got the highest citations from 152 articles. The study evaluated the option to retrofit a CCS unit in a coal-fired power plant considering the risks of emission allowance and electricity prices. This study is followed by Blyth et al. (2007) from Energy Policy with 136 citations and Zhou et al. (2010) from Applied Energy with 128 citations. Blyth et al. (2007) analyzed how regulatory risks affect the firms' investment decision options for coal- and gas-fired power plants and CCS technologies and illustrated the effectiveness of the RO approach as a policy analysis tool. Meanwhile, Zhou et al. (2010) presented a RO model incorporating climate policy uncertainty and the possibility of a technological change which determined the best strategy for investing in CCS technology in an uncertain environment in China.

4.3. Institutional analysis

A total of 82 institutions were involved with the 67 documents in this study. Among the most productive were Chinese institutions lead by the Ministry of Science and Technology (MOST) with 9 documents (13%) and the Chinese Academy of Science with 7 (10%), followed by Beijing Institute of Technology, China University of Mining and Technology, and North China Electric Power University with 6 documents (9%) each (see Table 3). Among the most recent works affiliated with the MOST include Zhu et al. (2020) which evaluated the cooperated mitigation for CCS and enhanced oil recovery (EOR) projects under oil market and geological uncertainties; Yao et al. (2020) which studied the optimization of dynamic subsidies for carbon dioxide removal (CDR) technology; Fan et al. (2020a) which compared the CCS retrofitting of coal-fired power plants (CFPP) with hypothetical subsidies and renewable power generation projects (RPP) among different provinces in China; and Fan et al. (2020b) which evaluated CCUS retrofitted to the natural gas combined cycle (NGCC), pulverized coal (PC), and integrated gasification combined cycle (IGCC) power plants in China under the same power generation and CO2 emissions levels.

Table 3
Most productive institutions.

Institution	Rank	Total documents	Percentage
Ministry of Science and Technology (China)	1	9	13%
Chinese Academy of Science	2	7	10%
Beijing Institute of Technology	3–5	6	9%
China University of Mining and Technology	3–5	6	9%
North China Electric Power University	3–5	6	9%
China University of Geosciences	6–8	5	7%
Utrecht University	6–8	5	7%
Tsinghua University	6–8	5	7%
Beihang University	6–8	4	6%
International Institute for Systems Analysis (IIASA)	9–11	4	6%
RWTH Aachen University	9–11	4	6%

In contrast with Table 3, the most productive institutions were different from the most cited (see Table 4). For instance, the International Institute for Systems Analysis (IIASA) and Tsinghua University with only 4 documents got the highest citations with 311 and 205 respectively. Comenius University with only 2 documents got 202 citations while Bilbao Bizkaia Kutxa got 152 citations from a sole document.

On the other hand, the MOST was not among the top 10, while the Chinese Academy of Science landed on the fourth spot with 188 citations. As one of the pioneers of the RO approach to CCS, the IIASA, an independent, international research institute based in Austria, has a modeling framework for medium- to long-term energy system planning, energy policy analysis, and scenario development (MESSAGE) that fulfills the International Panel on Climate Change (IPCC) requirement Representative Concentration Pathway (RCP) 2.6 “very stringent” to use a massive deployment of CCS in dealing with tens of billion tons of CO2 (Berger et al., 2017). Moreover, Tsinghua University and the Chinese Academy of Sciences were among the two Chinese academic institutions that entered the research field early and participated in some research and development projects of CCS technology (J. Li et al. 2019).

4.4. Author analysis

A total of 149 scholars all over the world contributed to RO valuation in CCS literature. As seen in Table 5, seven of the eight most productive authors were dominated by Chinese scholars lead by Xian Zhang and Lei Zhu with 9 and 7 documents, followed by Jing-Li Fan, Lin Yang, Xiping Wang, and Ying Fan with 5 documents. Correspondingly, these authors were from the most productive institutions in Table 2. For instance, Xian Zhang from The Administrative Center for China's Agenda 21 of the MOST co-authored 9 articles. One of his works as the first author

Table 5
Most productive authors.

Author	Rank	Total documents	Percentage
Xian Zhang	1	9	13%
Lei Zhu	2	7	10%
Jing-Li Fan	3–6	5	7%
Lin Yang	3–6	5	7%
Xiping Wang	3–6	5	7%
Ying Fan	3–6	5	7%
Mao Xu	7–8	4	6%
Reinhard Madlener	7–8	4	6%

includes Zhang et al. (2014) which considered uncertainties in CO2 price, government incentive, power plant lifetime, and technological improvements to evaluate the power generation enterprises' decision to retrofit CCS and introduce CO2 utilization for enhanced oil recovery (EOR).

The most cited authors were affiliated with IIASA such as Jana Szolgayova, Michael Obersteiner, and Sabine Fuss who co-authored three documents (see Table 6). Their papers including Zhou et al. (2010), Fuss et al. (2009), and Szolgayova et al. (2008) were cited 128, 74, and 72 times for a total of 274 citations. Their first paper assessed the impact of different climate change policy instruments on investment, profits, and cumulative emissions in the electricity sector and found that fluctuations in CO2 prices frequently lead to investment into CCS while the investment is often not triggered in the face of deterministic CO2 prices (Szolgayova et al., 2008).

Among the Chinese scholars, Lei Zhu from the Chinese Academy of Science got on the list with 189 citations from 7 publications. His works as the first author include Zhu and Fan (2011) which evaluated the cost-saving effect and amount of CO2 emission reduction through investing in newly-built thermal power plant with CCS technology to replace existing thermal power as well as Zhu and Fan (2013) which focused on the investment decision to retrofit an existing supercritical pulverized coal (SCPC) unit with CCS technology. Meanwhile, José M. Chamorro's sole paper with Luis M. Abadie got 152 citations making him included in the top 10. This paper was also the most cited among the 67 reviewed articles applying RO valuation of CCS investment.

5. Real options valuation in CCS

With the growing application of the RO approach in various project appraisals, a wide range of modeling and valuation techniques have been employed. However, the research design of RO valuation contains the following common components: (i) recognizing the sources of risks and uncertainties that affect the investment decision, (ii) modeling the stochastic process of the development of uncertain variables, (iii) identifying the type of real options available, and (iv) determining the appropriate technique for valuing the real options. This review analyzed these RO valuation components (see Appendix 1. Summary of Reviewed Papers) and presents here the uncertainty sources and their modeling, type of RO, and the valuation method.

5.1. CCS investment uncertainties

The sources of uncertainties identified in the reviewed CCS literature are summarized in Table 7. The percentage values indicate the share of research articles out of the 67 total samples that recognize a particular source of uncertainty. Note that the sum of the total documents more than the number of articles reviewed, while the sum of percentages is more than 100%. These are due to multiple sources of uncertainties considered in several studies.

Table 6
Most cited authors.

Author	Rank	Total citations	Total documents
Jana Szolgayova	1–3	274	3
Michael Obersteiner	1–3	274	3
Sabine Fuss	1–3	274	3
Lei Zhu	4	189	7
Luis M. Abadie	5	182	3
Ying Fan	6	176	5
Bing Zhu	7–9	165	2
Weiyang Fei	7–9	165	2
Wenji Zhou	7–9	165	2
José M. Chamorro	10	152	1

Table 7
Uncertainty sources for CCS investment.

Uncertainty	Rank	Total documents	Percentage
CO2 price	1	45	67%
Electricity price	2	17	25%
Coal price	3	14	21%
Capital cost	4–5	10	15%
Technology	4–5	10	15%
Oil Price	6–7	9	13%
Natural gas price	6–7	9	13%
Subsidy	8–9	6	9%
OM cost	8–9	6	9%
Geological storage	10–11	4	6%
CER	10–11	4	6%
Policy	12	3	4%
CO2 transport	13–14	2	3%
Spark-spread	13–14	2	3%
CO2 utilization	15–20	1	1%
R&D	15–20	1	1%
CO2 supply	15–20	1	1%
naphtha	15–20	1	1%
CO2 network design	15–20	1	1%

In general, a maximum of six and an average of three uncertainties were present in individual papers. More than half of the reviewed papers recognized CO2 price as the most crucial uncertainty in CCS projects. With high CO2 price volatility, immediate installation of CCS cannot be justified from a financial point of view, thus, it will most likely be postponed until carbon market parameters change dramatically (Abadie and Chamorro, 2008). In several cases, this uncertainty was combined with other sources of uncertainty such as the market uncertainty (electricity, coal, oil, and natural gas prices), for retrofitting CCS in various types of power plants; technological uncertainty, with the expectation of the decrease in investment and O&M cost as the technology matures; policy uncertainty, which either sets reasonable CO2 price levels or compliments with investment subsidy and/or carbon tax; and operational uncertainties including CO2 capture, transport, utilization, and storage. Meanwhile, the spark-spread is uncertain which refers to the variation in the difference between the price of electricity and the cost of fuel used for the generation of electricity (Glensk and Madlener, 2019; Fleten and Näsäkkälä, 2010). For the CO2 transport, CO2 supply uncertainty refers to the reliability of the design strategy of the network in providing the required capacity as and when CO2 supply increases over time (Melese et al., 2017; Melese et al., 2015). For CO2 storage, the geological uncertainty refers to the EOR rate for CCS-EOR projects (Zhu et al., 2020; Welkenhuysen et al., 2018) or CO2 leakage from the storage site (Narita and Klepper, 2016).

5.2. CCS uncertainty modeling

Uncertainties can be modeled with stochastic or deterministic processes. From the reviewed papers, most scholars employed stochastic processes with GBM (see Table 8). Comparing GBM with other uncertainty models, it only needs a small number of parameters to calibrate with the ease of obtaining analytical solutions, which makes a huge advantage to its use (de Magalhães Ozorio et al., 2012). Fifty-four (81%) documents applied GBM to model the market prices of CO2 and fuels including coal, oil, and natural gas. It is also used to model CO2 utilization profits for CCUS as well as the costs of CO2 capture, transport, and storage (Zhang and Liu, 2019; Rohlfs and Madlener, 2011). In one study, Liang and Li (2012) extended this model and assumed that CO2 and coal prices follow a GBM process with mean reversion. Further, Patiño-Echeverri et al. (2007) modeled GBM with jumps which characterized the uncertainty on CO2 prices specifying scenarios in which prices jump from one GBM process to another at a known time.

For electricity price, scholars had a diverse opinion. Mo et al. (2015), Rohlfs and Madlener (2014a), and Rohlfs and Madlener (2014b) applied

Table 8
Uncertainty models.

Uncertainty model	Rank	Total documents	Percentage
Geometric Brownian Motion	1	54	81%
Learning	2	14	21%
Mean Reversion	3	10	15%
Jumps	4	7	10%
Other Brownian motions	5	6	9%
Probability	6	5	7%
Moving average	7–9	1	1%
Controlled diffusion	7–9	1	1%
MR + long term uncertainty	7–9	1	1%

Note: other Brownian motions include inhomogenous GBM, arithmetic BM, and GBM with jumps.

GBM while 10 studies used mean reversion. Electricity price, along with oil and natural gas, follows a mean-reverting process because it may fluctuate over the short term but moves towards a mean value in the long run (Elias et al., 2018). When the price decrease below the mean value, an increasing demand pulls the price up to the mean price, while a decreasing demand causes the price back to the mean value when the prices increase above the long-term mean (Dixit and Pindyck, 1994). On the other hand, Fleten and Näsäkkälä (2010) described electricity and gas prices as short-term mean reversion with long-term uncertainty. Additionally, Glensk and Madlener (2019) proposed the use of an arithmetic Brownian motion process, instead of the standard GBM or mean revision process, due to the observed negative electricity prices on the power exchanges, especially on the European Energy Exchange. Abadie and Chamorro (2008) described electricity price as inhomogeneous GBM. In the area of stochastic volatility models, inhomogeneous GBM is called the GARCH diffusion model (Zhao, 2009), which is the 'mean reverting' extension of the Hull and White (1987) model where the variance follows a GBM and improves such a model under several aspects (Barone-Adesi et al., 2005).

In terms of policy uncertainty, the reviewed studies modeled it using a Poisson process or a jump. For instance, Blyth et al. (2007) quantified the regulatory risks as an exogenous event that created uncertainty in the carbon price which affects the private company's investment behavior for coal- and gas-fired power plants and CCS technologies. A Poisson-type policy jumps consider the probability of implementing a policy if it is not in effect and the probability of withdrawal if it is in effect (S. Liu et al., 2018). For instance, the government may stop the subsidy at some time according to energy technology development, hence, the amount of subsidy and the timing are uncertain. The latter is characterized as the uncertainty of the subsidy and can be modeled using the Poisson jump process (Huang et al., 2020).

With technological uncertainty, scholars agreed to employ a deterministic process. Fourteen studies applied the learning curve model to describe the technological progress in CCS. The learning curve theory reflects the mathematical relationship where the unit cost of a certain technology decreases with accumulated experience which can be quantified by factors such as cumulative output, cumulative knowledge, scale effects, and prices of the input factors (Kang et al., 2020). As an example, Wang and Du (2016) explained the learning effect of CCS retrofitting which decreased the investment cost as well as the O&M cost. This was also pointed out in other studies that the development of CCS technology follows a learning curve model in which the CCS investment cost decreases with the rising of CCS installed capacity and technology improvement (Abadie and Chamorro, 2008; Zhang et al., 2014). Eckhause and Herold (2014) further explained that experience gained in demonstration projects usually increases the performance of innovative technologies and lowers its costs, while successful demonstration plants influence the success of subsequent projects.

Aside from the traditional stochastic and deterministic models in RO valuation, several papers applied nonconventional models. For example, Tayari and Blumsack (2020) described natural gas and CO2 prices with a moving average process which specified that the future prices depend linearly on the current and various past values of stochastic prices. Zhu and Fan (2011) modeled the CCS generating cost with a controlled diffusion process affected by both R&D input and changes in prices of fuel. Welkenhuysen et al. (2018) used a probability density function to describe the probability that geological storage-EOR investment might have positive and negative NPVs.

5.3. Types of real option

Real options in CCS can be identified in three different stages: the planning stage, when the CCS investment has not yet been taken; the operational stage, when the CCS project is already built; and the decommissioning stage when the project will cease to operate. Additionally, the flexibility during the operational years of CCS adds another type of RO including CO2 capture, transport, utilization, and storage (Rohlfs and Madlener, 2011; Zhang and Liu, 2019).

Table 9 summarizes the type of RO identified in the reviewed literature. The most commonly recognized RO was on the planning stage with the timing option, which was also referred to as the option to defer, delay, or wait, with 55 documents (82%). In most studies, the timing option described the flexibility to retrofit CCS with an existing power plant. For instance, Chu et al. (2016) evaluated the timing of retrofitting CCS from the existing thermal power plant by considering the fluctuations of electricity price, carbon price, and thermal coal price. In another study, Elias et al. (2018) evaluated which CCS technology to adopt – by retrofitting CCS either post- or oxyfuel combustion to an existing natural gas-fired power plant and when to adopt under various techno-economic scenarios. Considering the value of waiting in the decision process resulted in an increase in the expected NPV as well as the optimal timing of implementing the CCS project (Rohlfs and Madlener, 2014b). This highlights the advantage of using RO approaches over traditional project valuation techniques as the flexibility in making the investment decision gives additional value to the project (Guno et al., 2021).

Another type of option recognized in CCS literature is the compound option. This option means that the execution and value of a strategic option depend on another strategic option (Mun, 2002). Among the reviewed studies, only four (5%) employed this type of option which included the sequential timing and expansion options. For example, Cui et al. (2018) presented an investment feasibility study on the CCS retrofit project in an existing coal-fired power generation unit in China using a two-stage compound RO model. The first phase included a call option to delay at the demonstration project stage. The second phase applied an option to expand at the commercial operation stage which considered undertaking CO2 transportation, storage, and EOR project, to achieve additional income if the government could provide enough fund incentive. The RO valuation of found that the current carbon price and high construction sunk-cost defer CCS investment at the demonstration phase. This implied the promotion of the development of CCS technology as well as the carbon trading scheme to bring substantial benefits in offsetting the huge investment cost. On the other hand, increasing the government subsidy would diminish the critical carbon price at both stages.

Table 9
Type of real option.

	Rank	Total documents	Percentage
Timing	1	55	82%
Compound	2	5	7%
Abandonment	3	4	6%
Shutdown/restart	4–5	2	3%
Flexible design	4–5	2	3%
Switching	6	1	1%

The abandonment option in the reviewed papers described the management flexibility in various stages of CCS operation: abandonment of a power plant or abandonment of geological storage. For instance, Rohlfs and Madlener (2014a) accounted for the flexibility to abandon the operation of the power plant in cases where the cost of the input quantities exceeds the revenues of the outputs. Fleten and Näsäkkälä (2010) considered how the investment decision changes if there would be an opportunity to abandon the gas plant and realize the salvage value on the second-hand market. In terms of CO2 storage, Zhu et al. (2020) examined the abandon option for CCS-EOR projects under oil market and geological uncertainties. Assuming a profit-motivated oil field project, if the expected revenue from the oil field participating in the CCS-EOR project turned out to be negative, then there would be an incentive to abandon the project (Zhu et al., 2020). Considering this decision flexibility, the option to abandon a project can be exercised if the project is unprofitable, thereby limiting the potential losses and increasing the average value of the project (Knoope et al., 2015a).

The rest of the recognized types of options for CCS were operational flexibility including the shutdown and restart operations, flexible designs, and switching options. In one study, Chen et al. (2010) considered the flexibility to temporarily switch off and restart operations in response to the fluctuations in electricity and carbon prices to maximize their profits. By analyzing the bi-state operation mechanism of a typical PC power plant adopting a carbon capture system in China, the “flexibilities” of the systems were evaluated in a RO approach. The study found that with a high carbon price or low electricity price, it would be profitable to enhance the operation level of the capture system, otherwise, it could be switched off, or operated at a lower load with “capture negative”.

In another study, Melese et al. (2015) proposed a method to evaluate the initial design architectures and provide insights into potential RO and strategies to implement future expansions. The method was applied in the case of the CCS project in Rotterdam, The Netherlands, which aimed at developing a large-scale pipeline network that connects spatially distributed emitters from the port area and storing the CO2 in depleted offshore oil-and-gas fields in the North Sea. Given a range of technical, economic, regulatory, and social uncertainties, the project encourages a demonstration stage with few emitters and gradually progresses to a full-scale CCS network. The findings showed the usefulness of the RO valuation to appraise the flexibility from redundant pipe capacity and length in an uncertain future. It further revealed that incorporating the RO in the expansion of CCS networks could increase the CO2 emission reduction by encouraging other emitters to participate in the project (Melese et al., 2015).

5.4. Real option valuation techniques

Over the decades, various methods for the valuation of RO have been published. Baecker et al. (2003) provided an overview of methods to valuate options which can be categorized into (a) analytic approaches such as closed-form solutions and approximation and (b) numeric approaches including partial differential equation, stochastic process, and other methods. In the reviewed literature, scholars employed five techniques to RO valuation of CCS projects (see Table 10).

Table 10
RO valuation techniques.

Valuation technique	Rank	Total documents	Percentage
Monte Carlo	1	29	43%
Dynamic programming	2	16	24%
Binomial	3–4	8	12%
Trinomial	3–4	8	12%
Differential equation	5	7	10%
Black-Scholes	6	3	4%
Other lattices	7	2	3%

Note: other lattices include bivariate and quadrinomial lattice.

Among the 67 reviewed articles, the most common valuation method applied was stochastic approximation which included Monte Carlo simulation (43%), dynamic programming (24%), and lattices (27%). In one study, Knoope et al. (2015b) estimated the profitability of investing in a point-to-point CO2 pipeline using a Monte Carlo analysis. Monte Carlo is a powerful method to generate probability distributions based on uncertain parameters. As the study assumed uncertainties in the tariff, the probability, and the moment that sources joined the trunkline, Monte Carlo with 5000 simulation runs was calculated. In another study, Melese et al. (2017) used Monte Carlo simulation to compare the value effects of design strategies. This step in the methodology aimed to evaluate, analyze and compare the performance of different combinations of physical and contractual CO2 transport design strategies by simulating them under different uncertain scenarios. Certainly, the Monte Carlo is a useful tool to solve complex RO models which allows for a simulation of several sources of uncertainties that affect the value of RO.

Another stochastic method is dynamic programming, also referred to as dynamic optimization. This method is computationally intense, but simpler and more intuitive than traditional methods, thus allowing for greater flexibility in the modeling of the problem (Brandao and Dyer, 2005). In the reviewed papers, this method was only applied with timing options. For example, Xinhua and Wei (2011) applied a dynamic programming method to evaluate the optimal timing of investment in CCS for a power plant. Eckhause and Herold (2014) formulated a stochastic dynamic program for obtaining the optimal funding solutions to achieve at least one successfully operating full-scale CCS plant by a target year. Several studies combined dynamic programming with Monte Carlo simulation for valuation of timing option (e.g. Yao et al., 2020; Zhang et al., 2019; Fertig, 2018; Compernolle et al., 2017; Hauck and Hof, 2017; Chen et al., 2016; Zhou et al., 2010; Fuss et al., 2009; Szolgayova et al., 2008).

One of the easiest means to value and explain RO is the decision trees or lattices. The simplest lattice is the binomial lattice which value of the option at any node with the probability that the price of the underlying asset will either increase (up) or decrease (down) at any given node. Besides the timing option, the review studies also applied this method to value abandonment (e.g. Rohlfs and Madlener, 2014a) and compound options (e.g. Wang and Zhang, 2018b; Cui et al., 2018). With the complexity of CCS investment, several studies used the trinomial lattice which assumes that prices at each node have three possible paths: up, down, and stable or middle path. In CCS literature, this method was only used to value the timing option (e.g. Fan et al., 2020a; Yang et al., 2019; Fan et al., 2019a). Due to the complexity of CCS investment other studies applied a more complicated type of lattice. For instance, Wang and Du (2016) extended the traditional binomial into a quadrinomial model considering two sources of uncertainties. For each node, carbon and coal prices might simultaneously take four possible paths: up-up, up-down, down-up, and down-down. Considering two correlated GBMs, Elias et al. (2018) described these four paths as joint probabilities in a bivariate lattice model.

The differential equation is another numerical approach to RO valuation. Despite its required mathematical sophistication which cannot readily be used for high-dimensional problems, several studies still applied this method to the valuation of timing options. Among the variations of this method were ordinary differential equation (Wang and Qie, 2018a; Wang and Qie, 2018b; Narita and Klepper, 2016; Walsh et al., 2014; Heydari et al., 2012) and partial differential equation (Huang et al., 2020; Fertig, 2018). Another type of partial differential equation is the closed-form Black-Scholes model. In this review, this model was applied to value timing (Bose et al., 2013), compound (Patiño-Echeverri et al., 2007), and switching options (Chen et al., 2010).

5.5. Climate change and CCS

Climate change is the long-term change in weather patterns caused by GHG emissions. Greenhouse gases, such as CO2, CH4, N2O, and some synthetic chemicals, trap the Earth's outgoing heat in the atmosphere causing the changes in the radiative balance between energy received from the sun and emitted from Earth which alters climate and weather patterns at global and regional scales (Environmental Protection Agency (EPA), 2020). As reported by the United Nations Climate Change Secretariat (UNCCS), the changes in climate indicators include temperature, precipitation, sea-level rise, ocean acidification, and extreme weather conditions (Fawzy et al., 2020).

The two main sources of GHG emissions are natural sources and human activities. Natural sources include emissions from forest fires, oceans, wetlands, permafrost, volcanoes, mud volcanoes, and earthquakes (Yue and Gao, 2018) . On the other hand, the major contributors to GHG emissions are anthropogenic sources which are associated with the burning of fossil products for power plants and industries, agriculture and land-use change, waste management and treatment activities, and various industrial processes (Wilberforce et al., 2020; EPA, 2020).

Both humans and the environment, particularly biodiversity, water resources, coastal and marine resources, agriculture, forestry, energy, and public health, are vulnerable to the adverse impacts of climate change (Tang, 2019). To address the threat of these impacts, the literature provides three main mitigation strategies that reduce and prevent emissions of GHG into the atmosphere. These include (1) employment of decarbonization technologies and techniques such as renewable energy, fuel switching, efficiency gains, nuclear power, and CCUS; (2) utilization of negative emission technologies such as bioenergy and CCS (BECCS) and direct air capture (DAC); and (3) using radiative forcing geoengineering technologies such as stratospheric aerosol injection, marine sky brightening, cirrus cloud thinning, space-based mirrors, surface-based brightening, and various radiation management techniques (Fawzy et al., 2020).

In recent years, the rapid decline in the cost of renewables and storage technologies accelerates the decarbonization of most sectors. However, energy-intensive industries that use carbon as a source of energy and as a feedstock make these sectors difficult to decarbonize. The CCS offers significant potential to reduce emissions on a short to medium timescale, particularly in the cement, steel, and petrochemical industries, in thermal power generation, and waste-to-energy facilities (Akerboom et al., 2021). If fully implemented, large-scale deployment of CCS may contribute to reducing 20% of global GHG emissions from fossil fuels by 2050 and 55% by the end of this century (Ketzer et al., 2015). CCS could serve as an emergent solution to reduce emissions in the near future as we transit towards more efficient energy systems and more sustainable energy sources. In the longer term, we could transform our societal metabolism towards greater resource efficiency, where renewables can play a more important role (Wennersten et al., 2015).

Despite the undeniable potential of having CCS in the climate mitigation technologies portfolio, its deployment is challenged by various criticisms from its technical viability, economic attractiveness, efficacy, and safety. Currently, most CCS technologies available can absorb nearly 85–95% of CO2 produced by a power plant, however, they require additional 10–40% more energy for CO2 capture and compression compared to the existing power plants (Wilberforce et al., 2020). Another challenge is the huge CCS cost being the most significant hurdle in the short to medium term. However, in the long term, CCS is expected to be more cost-effective than other mitigation options (Budinis et al., 2018).

Meanwhile, the presence of multiple uncertainties including market prices energy and CO2; technology and O&M costs; changes in CO2 capture, transport, and storage costs; and utilization revenue fluctuation; as well as policy-related uncertainties further delay the deployment of CCS (Zhang and Liu, 2019; Zhou et al., 2014). In the studies reviewed, modeling these uncertainties were based on abstractions from a complex reality, hence, both stochastic and deterministic models had their strengths and limitations. This raises an issue on the appropriateness of these models for the deep socio-political and techno-economic uncertainties in the decision-making process and long-time commitments for CCS projects. “Deep uncertainty” is a condition where there is a lack of knowledge or agreement between parties on (a) conceptual models describing the relationship between driving forces, (b) the probability distributions of uncertainty across the parameters, and (c) the value or the desirability of various outcomes (Lempert et al., 2003). Under conditions of deep uncertainty, there is no amount of quantitative analysis to likely produce a single solution with clear value judgments and preferences to enable the decision-making process (Li and Pye, 2018). For CCS projects, the deep uncertainty with complex socio-political and techno-economic systems can exert a paralyzing effect on the decisions based on value-laden assumptions that are heavily contested by key stakeholders. Along with the application of quantitative analysis under various uncertainties, effective decision-making, therefore, requires a more inclusive approach with peer engagement that accounts for responsive interdisciplinary perspectives and solutions.

Aside from the concerns on CCS operations and uncertainties, its social acceptance and public support are confronted with the concerns on its safety issues in terms of hazards from its operations and the possibility of CO2 leakage which may endanger communities, commodities, and the environment in the vicinity of an infrastructure (d'Amore et al., 2020). Addressing the issue of fairness, both procedural and distributive, is essential for the public support and acceptance of CCS projects. Procedural fairness relates to the decision processes while distributive fairness refers to the trust in the implementation of the project and the distribution of costs, risks, and benefits (Selma et al., 2014). These can be described in the case of Barendrecht, a canceled CCS project in the Netherlands, where the resistance did not solely arise from risk perceptions and the lack of trust in the project commissioner and the operator, but also the perceived unfairness of the decision-making process from the undue influence of the operator and the lack of citizen involvement (Akerboom et al., 2021). Another issue with distributive fairness is intergenerational justice where future generations incur the risks and costs for sequestering CO2 emissions from which previous generations benefitted. By storing CO2 for a long period, CCS in effect displaces the risk current generations face concerning climate change and imposes that risk on future generations. As CCS is intrinsically linked to climate change, the decisions of current generations affect the distribution of the costs and benefits of climate change across different generations (Medvecky et al., 2014).

The findings from the literature suggest optimal policies leading to the large-scale deployment of CCS. A need for an improved technology that allows a successful integration of the major components of CCS at a lower cost as well as a credible carbon policy that encourages investor confidence to undertake CCS projects, will be crucial in building a global CCS industry that can successfully complement fossil fuel energy in the next decades (Durmaz, 2018).

6. Conclusion and future work

This research presented an academic literature review on the use of real options methods to carbon capture and storage project valuation. Based on a bibliometric analysis of 67 documents, the following can be concluded.

6.1. Research trend

At a country level, China dominated the largest amount of publications with the Ministry of Science and Technology and the Chinese Academy of Science as the top institutions. Comparing the country clusters, European countries and North America were forerunners in applying real options valuation with CCS. China started later but showed a rapid rate along with the growth of CCS research after it made important commitments to control CO2 emissions.

Seven out of the top eight authors with the most number of publications were from China. On the other hand, the top 3 most cited authors came from the International Institute for Systems Analysis (Austria) which also had the most citations from only 4 documents. The CCS topics on policy, energy, technology, and economics were mostly published in Energy Policy, Applied Energy, International Journal of Greenhouse Gas Control, Energy Economics, and Journal of Cleaner Production. The most cited paper was published in Energy Economics in 2008 with 152 citations.

6.2. Research gap and recommendations

In terms of real options design, the majority of papers considered CO2 price as the main uncertainty, and the rest can be categorized into fuel/energy price, investment and OM cost, policy, CCS processes (capture, transport, storage, or utilization), and technology uncertainties. These uncertainties were modeled using GBM, MR, learning, jumps, and other probabilistic methods.

- Social acceptance from both the public and business perspectives can also be quantified and incorporated in the real options modeling. While the main uncertainties were modeled using various stochastic processes, modeling the social acceptance uncertainty would be challenging but would be a good point for further research. With the acceptance in the business perspective, real options may be combined with game theory to illustrate the strategies of emitters and how the Pareto optimal outcome may be achieved to achieve the climate targets.
- In addition to the existing models for stochastic processes, a new model may be developed to capture the interactions among multiple uncertainties from the market, technology, policy, and social aspects. Considering the large deployment of renewable energy technologies and energy storage facilities in the next decades, various uncertainty models may be combined to capture the current uncertain CCS investment environment but evolve to a more deterministic trend in the later periods.

The majority of the reviewed papers employed a timing option and only a few studies used the abandon, compound, shutdown/restart, flexible design, and operational scale options.

- There is a considerable lack of studies exploring other types of options. For instance, a growth option may be applied considering the first-mover advantage of learning-by-doing and the expected growth in the CCS market in the next decades.
- A barrier option can also be utilized to value the option when the CO2 price rises above or the electricity price fall below the pre-specified barrier.
- The option to stage investment can be considered by breaking down the investment project into several stages to flexibly terminate later stages in the case of unfavorable circumstances such as (a) the heavy industries already shifted to cleaner production with energy-efficient technologies resulting in a significant decrease in the CO2 supply for the pipeline, (b) total closures of all fossil-based power plants, (c) development of more sustainable technologies, (d) CO2 leakage resulting to massive social protests, and (e) significant disruption in industrial operations due to a major catastrophe, war, pandemic, or worldwide financial crisis.

Valuation of real options mostly employed continuous-time models with Monte Carlo simulations and dynamic programming while the rest applied discrete-time models with binomial, trinomial, and other lattices/trees as wells as differential equations.

- The applied valuation methods, albeit powerful valuation tools, seem too complicated to apply in a real business setting. On the other hand, the Black-Scholes model offers simple calculations but does not capture the complexities of the risks and uncertainties of CCS investments.
- To increase the relevance and applicability of the options modeling in a real-world setting, a user-friendly app or program may be developed to aid project planners or policymakers in CCS decision-making.
- In terms of comparing various sustainable solutions, a fuzzy real option can be a useful way for valuing competing project investment alternatives.
- Finally, the combination of the real options valuation with other financial and non-financial instruments could be a potentially important research area that would benefit project managers, investors as well as policymakers.

Declaration of competing interest

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

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Appendix 1. Summary of reviewed papers

#	Authors (year)	Uncertainty	Uncertainty model	Type of option	Valuation technique
1	Zhang et al. (2021)	Technology cost, CO2 price	Learning effect, GBM	Timing	Binomial tree
2	Zhu et al. (2020)	Oil price, geological storage	GBM	Abandon	Monte Carlo
3	Li et al. (2020)	CER price	GBM	Timing	Trinomial tree
4	Yao et al. (2020)	Coal price	GBM	Timing	Dynamic programming, Monte Carlo
5	Ding et al. (2020)	Carbon price; electricity price	GBM, MR	Timing	Monte Carlo
6	Fan et al. (2020a)	Technological progress, CO2 price	learning curve, GBM	Timing	Trinomial tree
7	Fan et al. (2020b)	CO2 price	GBM	Timing	Trinomial tree
8	Huang et al. (2020)	Technology, policy, CO2 price	LC, Poisson jump, GBM	Timing	PDE
9	Tayari and Blumsack (2020)	CO2 price, natural gas price	moving average	Timing	Monte Carlo
10	Yang et al. (2019)	Oil price, technology, subsidy	GBM, LC	Timing	Trinomial tree
11	Fan et al. (2019a)	Technology, CO2 price	GBM	Timing	Trinomial tree
12	Zhang et al. (2019)	CO2 price, CO2 utilization, CO2 transport, CO2 storage	GBM, LC	Timing	Dynamic programming, Monte Carlo
13	Yao et al. (2019)	Energy price (CO2, oil, coal), policy	GBM	Compound	Monte Carlo
14	Fan et al. (2019b)	Technology, OM cost	GBM, LC	Timing	Trinomial tree

(continued on next page)

(*continued*)

#	Authors (year)	Uncertainty	Uncertainty model	Type of option	Valuation technique
15	Glensk and Madlener (2019)	Electricity, spark spread (elec-NG)	Arithmetic BM	Timing	optimization
16	Fertig (2018)	R&D, Technology, Cost	LC, GBM	Timing	Dynamic programming, PDE
17	Wang and Zhang (2018b)	Coal price, CO2 price, subsidy, technology	GBM, learning, Poisson	Compound	binomial tree
18	Wang and Zhang (2018a)	CO2, investment, OM	GBM, LC	Timing	Trinomial tree
19	Wang and Qie (2018b)	CO2 price	GBM	Timing	ODE
20	Elias et al. (2018)	Electricity price, natural gas price	MR	Timing	Bivariate lattice
21	Wang and Qie (2018a)	CO2 price, investment cost, subsidy	GBM, LC	Timing	ODE
22	Cui et al. (2018)	Subsidy, CO2 price, investment & OM cost	GBM	Compound	Binomial tree
23	Chen et al. (2018)	Gas market, incentive, technology	GBM, scenario (probability)	Timing	Monte Carlo
24	Welkenhuysen et al. (2018)	Geological storage	probability density function	Timing	Monte Carlo
25	Compernolle et al. (2017)	Market price (CO2, oil)	GBM	Timing	Dynamic programming, Monte Carlo
26	Hauck and Hof (2017)	CO2 price, gas price	GBM	Timing	Dynamic programming, Monte Carlo
27	Melese et al. (2017)	CO2 supply	GBM, probabilistic and simulation methods	Flexible design	Monte Carlo
28	Abadie et al. (2017)	CO2 price and fuel prices	GBM, jumps	Timing	Binomial tree
29	Welkenhuysen et al. (2017)	CO2 and oil price	GBM	Timing	Monte Carlo
30	Chen et al. (2016)	Market price (CO2, electricity, coal)	GBM, MR	Timing	Dynamic programming, Monte Carlo
31	Narita and Klepper (2016)	CO2 leakage, CO2 price, investment cost	GBM	Timing	Differential equation
32	Wang and Du (2016)	Carbon price, fuel price, investment cost and government subsidy	GBM, LC, Poisson	Timing	Quadrinomial
33	Chu et al. (2016)	CO2 price, electricity price, fuel price	GBM, MR	Timing	Monte Carlo
34	Knoope et al. (2015b)	CO2 price	GBM	Timing	Monte Carlo
35	Melese et al. (2015)	CCS network design	GBM	Flexible design	Monte Carlo
36	Mo et al. (2015)	Electricity price, fuel and carbon markets	GBM	Timing	Monte Carlo
37	Knoope et al. (2015a)	Load factor, CO2 price, coal and fuel oil prices, electricity price, utilization rate	GBM, MR	Abandon, shutdown/restart	Monte Carlo
38	Zhou et al. (2014)	Market price (naphtha, diesel, coal and CO2); investment and OM cost	GBM, LC	Timing	Monte Carlo
39	Mo and Zhu (2014)	CO2 price, electricity price	GBM, MR	Timing, operation (shutdown/restart)	Monte Carlo
40	Eckhause and Herold (2014)	Technical uncertainty	Learning	Timing	Dynamic programming
41	Walsh et al. (2014)	CO2 price	GBM	Timing	Differential equation
42	Abadie et al. (2014)	Prices of electricity, oil and carbon allowances	GBM, MR	Timing	Binomial tree
43	Zhang et al. (2014)	CO2 price, technology	GBM, LC	Timing	Trinomial tree
44	Rohlfs and Madlener (2014b)	Coal price, CO2 price, electricity price, gas price	GBM	Timing	Monte Carlo
45	Rohlfs and Madlener (2014a)	Fuel, electricity, and CO2	GBM	Abandon	Binomial tree
46	Laude and Jonen (2013)	CO2 gas price, technical change	GBM, Poisson	Timing	Dynamic programming
47	Zhu and Fan (2013)	Electricity price, carbon price, CCS investment cost and CO2 additional O&M cost	MR	Compound	Monte Carlo
48	Bose et al. (2013)	CO2 price	Probability distribution	Timing	Black-Scholes
49	Liang and Li (2012)	CO2 price, coal price	GBM, MR	Timing	Monte Carlo
50	Heydari et al. (2012)	Electricity price, fuel price, CO2 price	GBM	Timing	Differential equation
51	West (2012)	CO2 price	GBM	Timing	Binomial tree
52	Rohlfs and Madlener (2011)	CO2 price, electricity price, CTS cost	GBM	Timing	Monte Carlo
53	Rammerstorfer and Eisl (2011)	CO2 price	Arithmetic BM	Timing	Dynamic programming
54	Zhu and Fan (2011)	Technology, CCS cost, CO2 price, R&D	Controlled diffusion, GBM	Timing	Monte Carlo
55	Kato and Zhou (2011)	CO2 price	GBM	Timing	Binomial tree
56	Oda and Akimoto (2011)	CO2 price, natural gas price	GBM	Timing	Dynamic programming
57	Xinhua and Wei (2011)	CO2 price, technology	GBM, jumps	Timing	Dynamic programming
58	Chen et al. (2010)	CO2 price	Probability	Switching	Black-Scholes
59	Zhou et al. (2010)	CO2 price	GBM	Timing	Dynamic programming, Monte Carlo
60	Fleten et al. (2010)	Oil and CO2 prices	GBM	Timing	Dynamic programming
61	Tolis et al. (2010)	Electricity, fuel and CO2 prices	GBM	Timing	Monte Carlo
62	Fleten and Näsäkkälä (2010)	Spark spread	MR + long term uncertainty	Abandon	Dynamic programming

(continued)

#	Authors (year)	Uncertainty	Uncertainty model	Type of option	Valuation technique
63	Fuss et al. (2009)	CO2 price	GBM, jumps	Timing	Dynamic programming, Monte Carlo
64	Abadie and Chamorro (2008)	CO2 price, electricity price	GBM, inhomogenous GBM	Timing	Binomial tree
65	Szolgayova et al. (2008)	CO2 price, electricity price	GBM	Timing	Dynamic programming, Monte Carlo
66	Blyth et al. (2007)	Policy	Jumps	Timing	Dynamic programming
67	Patiño-Echeverri et al. (2007)	Emissions allowance prices	GBM with jumps	Compound	Black-Scholes

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