Real option valuation in renewable energy literature: research focus, trends and design

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Abstract

In light of intensive development of the renewable energy (RE) sector, a growing number of academic papers address the complexity of RE investment planning and valuation. To take account of the high-risk profile and irreversibility of RE investments, researchers have resorted to sophisticated real options (RO) approaches that enable flexibility to be incorporated into project design in the face of an uncertain environment. The variety of different frameworks and models adopted as well as a lack of aggregated analysis of the field suggest a need for a critical review of RO methodology and design in RE assessment. This study describes the research focus, trends and design found in contemporary academic literature devoted to RE valuation with a RO approach. Particular attention is given to RO in project and policy design. The results give a comprehensive picture of existing research on the topic, thus providing researchers with a solid foundation for further study and indications of directions for future development. Furthermore, the findings provide policymakers and project planners with valuable insights into key aspects of RE project and policy design.

Keywords: real options, renewable energy, dynamic programming, Monte Carlo simulation, binomial tree, literature review.

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1. Introduction

Climate change issues are receiving urgent attention from the global community, and mitigation of and adaptation to climate change is an essential part of national agendas. Among other measures, renewable energy (RE) development has considerable potential to reduce greenhouse gas emissions by replacing conventional fossil fuel based energy.

Global annual investment in renewable energy reached $286 billion in 2015, starting from four times less a decade earlier [1]. Such rapid growth owes a great deal to the widespread introduction of policies supporting renewable energy, which have been implemented in 146 countries around the world [2]. Nevertheless, investors in RE projects encounter many risks and uncertainties that have to be adequately evaluated and addressed to ensure investment profitability. RE projects in the power generation sector are characterized by relatively high upfront investment costs and lower operation and maintenance expenditures compared to conventional energy projects, which implies a high degree of irreversibility in the investment and has invoked a search for flexibility in project design. Projects in the bioenergy sector, in contrast, possess operational flexibility, seen in an ability to change raw material and fuels used, or an ability to modify output products in response to the volatile price environment. These features of RE projects have prompted decision-makers and researchers to employ real options (RO) approaches, which are able to value both uncertainty and flexibility in investment valuation and planning.

Abbreviations

B&S	Black and Scholes model
CCGT	Combined cycle gas turbine
CCS	Carbon capture and storage
DCF	Discounted cash flows
DP	Dynamic programming
FIT	Feed-in tariff
GBM	Geometric Brownian motion
EIA	Energy Information Administration
IEEE	Institute of Electrical and Electronics Engineers
MRP	Mean reverting process
NPV	Net present value
NRE	Non-renewable energy
O&M	Operation and maintenance
PDE	Partial differential equations
RD^3	Research, development, demonstration and deployment
RE	Renewable energy
REN21	Renewable Energy Policy Network for the 21st Century
RO	Real option

Several published reviews explicitly demonstrate a number of models and approaches to RO valuation design for renewable energy investments [3-6]. These papers, however, provide only a fragmentary overview, limiting their samples to a few selected studies and focusing on specific aspects of RE valuation. Moreover, a substantial number of papers published in recent years are absent from these reviews.

Therefore, in order to provide a more comprehensive picture of current research focuses, trends and designs, the current work aims to present a more thorough review of academic papers that apply RO approaches to renewable energy projects or policy valuation. The objectives of the paper are to review the body of scientific literature that considers real options approaches to renewable energy projects or policies, to describe the general research focus and trends in the field, to provide a comprehensive overview of the design methodology and models employed, to characterize cutting-edge research directions and to present implications for project planners and policymakers. The paper combines a state-of-the-art procedure for literature review, the strengths of existing reviews in the field and an exhaustive data sample. The work provides a cogent summary of the literature reviewed and results in a number of insights that may be of value in design of RO valuation of RE and of benefit to researchers and the interested public.

The paper is structured as follows. A brief description of the theoretical background follows this introduction part, after which the methodology of the study is described. The presentation and discussion of the results is divided into three subsections covering the topics of research focus and research trends, research design, and use of RO to enable operational flexibility in RE power generation projects. The paper ends by summarizing the key findings. An appendix is included that gives a tabulated summary of the key characteristics of the papers reviewed.

2. Theoretical background

Real options theory acknowledges managerial flexibility to adjust investment projects in the light of a future uncertain and changing environment. This flexibility refers to finding and incorporating real options into investment projects, or in other words, possible managerial actions that can reshape a project to adapt to changing conditions to maintain or enhance its profitability. By analogy with financial options, RO is a right but not an obligation. Hence, an investment project with RO is more valuable than one without, because it includes a capability of change to account for changing factors in order to maximize gains.

Traditional literature differentiates the following types of real options [7]:

- The option to defer investment in order to get more information or to await technological development. This option is synonymous with an option to delay or postpone, or in broader sense, a timing option.

- The option to stage investment to minimize risks. This option refers to breaking down the investment phase into several stages, thus enabling termination of later stages in the case of unfavorable circumstances.
- The option to abandon. This option implies an option to stop or sell the project.
- The option to change scale. This option allows managers to scale back or expand the project.
- The option to stop/restart operations. This option provides flexibility to adapt to changing demand or other conditions.
- The option to grow. This option enables managers to gain more if market conditions or other factors are more favorable than expected.
- The option to change inputs/outputs. This option refers to an ability to change input materials or fuels or output products. A common example is flex-fuel vehicles.

Nowadays, the whole investment project is often treated as one real option [8-11], in which case it is usually termed an option to invest or, analogous to financial options, a call option.

A considerable body of literature is devoted to approaches to modeling and valuing real options, including reputable textbooks [7,12] as well as concise overviews in recent review papers [3,4,6,13]. Therefore, this paper does not present general discussion of development of the methodology from financial to real option valuation, instead, attention is drawn to commonly used techniques found in the reviewed literature. Here five main approaches are identified:

- Partial differential equations (PDE). Initially used for valuing financial options, the Black-Scholes formula [14] has been adopted for RO valuation. PDE, in general, are applied to formulate specific assumptions or different types of RO [12].
- Binomial trees (or lattices) were initially presented by Cox et al. [15] as a binomial options pricing model. The approach represents a discrete-time model of asset price evolution with two (or more in advanced methods) alternative future outcomes in each step.
- Simulation, in particular Monte Carlo simulation, creates a distribution of project values taking into account all given sources of uncertainty [16]. Monte Carlo simulation could be considered as the easiest way to value RO of complex projects, since it does not require formulation of cash flow through differential equations or trees. However, it appears to be the most computationally expensive approach.
- Fuzzy sets based approaches. In recent years, some modern techniques to value real options have exploited fuzzy set theory, e.g. the pay-off method [17]. Modeling value distribution as fuzzy numbers allows advantages of simulation-based methods to be retained while reducing computational requirements. These methods have, however, not been widely adopted.
- Dynamic programming. In addition to the above listed methods, some researchers use recursive optimization methods such as dynamic programming (DP) [18-20]. The approach allows the optimal

timing of the investment to be found and enables different types of RO to be combined with various possible scenarios. The underlying idea behind the method is to compare the value of different investment realization scenarios with a so-called continuation value (the value of waiting and realizing the optimal scenario in future periods) moving backwards from the last period to the initial one. In each step, the value of the scenario is evaluated using one of the above-mentioned methods, e.g. PDE or simulation. As a result, the optimal solution and timing for the investment in an uncertain environment can be defined.

Since flexibility is only valuable in the presence of an uncertain environment, an important part of RO valuation is definition of the sources of uncertainty and modeling of their possible development. Again, a variety of methods can be applied. However, researchers most often utilize stochastic modeling, including geometric Brownian motion (GBM), mean reverting processes (MRP) or binomial trees that are discreet-time approximations of GBM. Some specific types of uncertainty require specific models, for example, uncertainty in technology cost and efficiency is usually modeled with learning curves. The interested reader is encouraged to visit [21] for a study on the fit of the aforementioned types of valuation models with different types of uncertainty.

As can be seen from the discussion above, many different types of RO exist and there are many different approaches to RO valuation, which explains the significant research design variability in the literature.

3. Methodology

This literature review follows the state-of-the-art practice proposed by the Webster and Watson [22] as well as incorporating the strengths of previously-published literature reviews in the field [3,4]. The reviewed papers are analyzed using several parameters, and the results are then presented in a quantitative form.

A three-part paper selection process was used to gather the relevant literature (Figure 1).

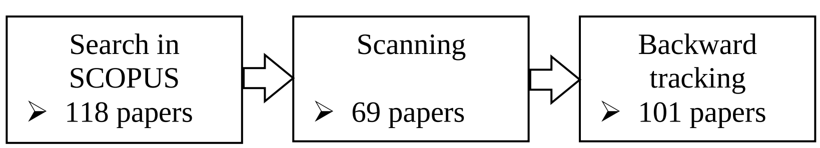

Figure 1. Literature selection process

The initial search in the SCOPUS database was limited by the following criteria:

- A real option approach is used;
- At least one type of renewable energy technology is evaluated;
- The language of the article is English.

The following combination of key words was used as a search criterion: “renewable energy” and “real option”. With the language limitation, the query returned one hundred eighteen results. Forty-nine papers were excluded based on abstract scanning, resulting in sixty-nine candidates for the review. The backward tracking included analysis of references from the selected papers and thematic reviews, a separate search in the proceedings of the major conference in the field, International Conference on Real Options, and a repeat of the same search in the Web of Science database. In total, one hundred and one papers were selected for further study.

The review omits studies that apply RO valuation in the presence of renewable energy but not for its evaluation, see e.g. [23-27]. In addition, smart-grid related studies are excluded; readers are referred to an existing review on RO valuation of smart-grids [28].

Following the best practices of existing reviews in the field [3,4] and expanding them, the selected papers were screened for the following features:

- Year of publication.
- Country – the country for which the research is conducted.
- Focus – the research focus, i.e. project valuation, supporting policy assessment or R&D.
- Technology type – the kind of renewable energy technology evaluated.
- Uncertainty sources – the sources of uncertainty that are taken into consideration.
- Uncertainty modeling – the stochastic process chosen for uncertainty modelling.
- Real option type – the kind of real options identified in the project.
- Valuation approach – the approach used for real option valuation.

Detailed results of this analysis are presented in tabular form in Appendix 1.

The reliability of the research was assured by only considering academic articles from indexed scientific journals and conference materials. Research validity was achieved by strict adherence to the above criteria.

The next section summarizes and discusses the key results obtained.

4. Real option valuation in renewable energy

With growing interest in recent years in the economics of renewable energy [29], several reviews of academic papers addressing renewable energy appraisal have been published. Therefore, before considering the results of the current research, a brief critical summary of these works is presented and their observations discussed.

One of the earliest reviews of renewable energy valuation, conducted by Angeliki Menegaki in 2008 [30], covers a broad scope of cost-benefit analysis techniques. The research focused on the ability of different approaches to capture the non-monetary environmental value delivered by renewable energy projects. With respect to real option valuation, the review treats only three papers that used the approach, from a sample size of 35 articles. The conclusions outline the attractiveness of RO for policymakers, but warn about the complexity of the method for general public understanding.

Later, in 2011, Fernandez et al. [3] performed a more extensive review of the use of the RO approach in the energy sector. The research provides a historical perspective of valuation approaches, highlighting the advantages of RO theory for energy investment appraisal. Emphasizing the growing prevalence of renewable energy technologies and the uncertainty associated with RE investments, the review incorporated analysis of eleven selected studies that applied RO valuation to renewable energy projects. One of the contributions of this paper is a classification of renewable energy valuation literature into three types: project appraisal, policy assessment, and R&D valuation. These classes affect the real option types identified and methodology applied, making such differentiation valuable for analysis and generalization of the applicability of RO theory to renewable energy investments. In addition, it is the only review so far to note and highlight the use of DP in addition to other more conventional valuation methods.

Recent reviews present more narrowly-focused studies emphasizing and discussing a particular aspect of real option valuation. In this vein, Chen-Yu Chang [5] draws attention to the importance of incorporating behavioral uncertainty and the limit of risk transfer into the valuation. This claim is supported by reference to published work, although the number of papers is rather limited, less than a dozen in total. The author proposes a new framework for RE investment modeling. Martinez Cesena et al. [4] conduct a broader review (but still of less than two dozen RE papers) that accentuates the relevance of the field but notes the scarcity of research addressing real options embedded into the design of RE projects. RO in project design encompasses flexibility in technical and technological characteristics and, thus, is specific to the particular project. The complexity inherent in distinguishing such real options and the necessity to involve technical engineers in the RO analysis are the main reasons given for the lack of such research. In the design of their review, Martinez Cesena et al. supplement screening of the sample papers with parameters such as the real option type identified and the uncertainty source addressed by the valuation. Including these features into the literature analysis in addition to the focus on RO in project design provides greater insight into the topic for both researchers and project developers, and is therefore adapted for the current review.

Case studies are often supported with a modest literature review. In this respect, Kim et al. [6] inspect twenty-two studies on RO in RE, classifying papers by year, country, technology type, and uncertainty sources. Less attention is drawn to the methodology employed or RO identified. Nevertheless, this work purports to present a framework analysis for developing countries highlighting such intrinsic risks as changeable policies and volatile market conditions, including loan rates, inflation and exchange rates.

More recently, a bibliographic analysis on the research trends in low-carbon energy technology investment has been presented by Yu et al. [31]. Although real option analysis is not a primary focus of the review, the authors claim that RO theory is the most comprehensive and the most suitable tool for investment appraisal of low-carbon energy projects. The work delivers observations on general topic trends, as well as authors, institutions and journals involved, familiarizing research newcomers with key works in this academic field.

As can be noticed, existing reviews, although providing valuable insights into the topic, give only a fragmentary picture of real option valuation approaches in renewable energy assessment and their scope is limited to a modest number of studies that focus on particular aspects of valuation design. To advance study in the field, the current review attempts to build on the strengths of these predecessors, expand the sample size, and present the results numerically in order to develop a more comprehensive picture of the topic and equip researchers, project developers and policymakers with a solid basis for RE investment planning and assessment.

4.1 Research focus and trends

4.1.1. Trend and country focus

The growing body of research devoted to real option valuation of renewable energy investment is illustrated in Figure 2. The whole sample of 101 papers is distributed along a timescale based on the publication year. Overall, the figure reveals a strong positive trend with more than ten papers per annum in recent years. The current review covers only the first months of 2017, which is the cause of the low number of papers in 2017.

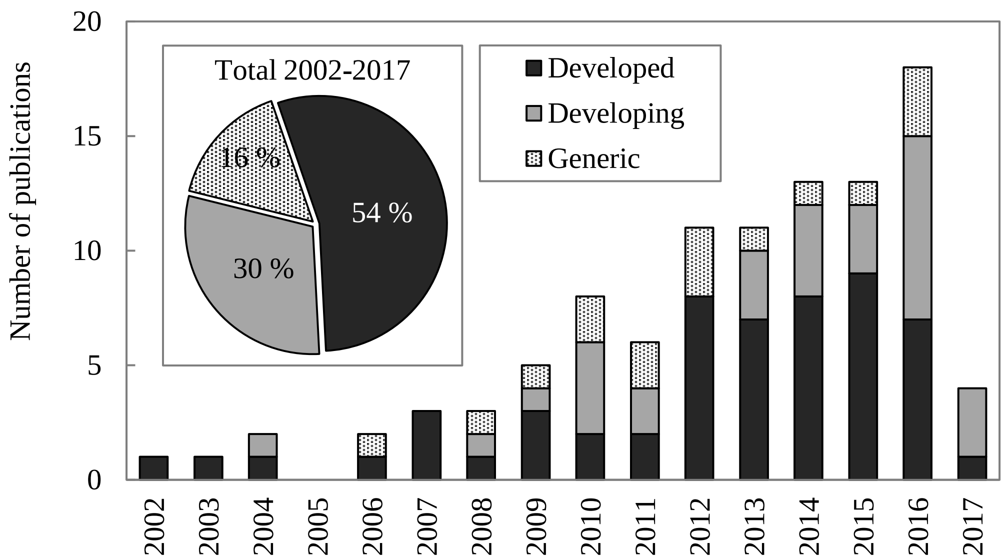

Figure 2. Research trend and country focus

When the data is divided into papers having developed and emerging economies as a research focus, it can be noted that since 2008 increasing attention has been given to RE valuation in developing countries. This research trend reflects real-world dynamics, where implementation of renewable energy policy has become a driving force not only for industry investments, but for academic research as well. For instance, a Renewable Energy Law was introduced in Turkey in 2005 and the first paper on RO and Turkish renewable energy was published in 2008 [32]. In Brazil, the mandatory portion of ethanol in fuel, in operation since 1976, has increased, the latest amendment was in 2007, and a study of ethanol production assessment was published in 2009 [33], and work on valuing flex-fuel cars in 2010 [34]. A paper by Yang et al. [35], published in 2010, investigates promulgation effects of the Chinese Renewable Energy Law in 2006.

The number and scope of national and regional RE support policies is increasing [2], and thus even more research devoted to RO in RE can be expected in the future. Research focusing on developing countries is likely to continue the strong positive trend of the last decade, particularly in view of the substantial RE investments being made in the developing world [1]. It should, however, be noted that although developing countries have become an attractive focus for RO research, in absolute number of papers published, attention to developed economies prevails (Figure 2). Nevertheless, publications with a developing country as a case study already account for thirty publications in total and cover countries such as China, Brazil, Taiwan, Russia, Turkey, Liberia, Mongolia, Indonesia, and Egypt.

In total, only thirteen developed and nine developing countries are represented in the sample. By the end of 2015, renewable energy support policies were identified in 146 countries [2], which reveals the considerable potential for further research in the field.

4.1.2. Research focus and technology

The key application area of the real option approach is investment project valuation, and the greatest part of the research utilizes RO for project (62%) and R&D (6%) appraisal (Figure 3, left). In the remaining cases, the RO approach is used as a method for analyzing the effects of policy support for RE investment. As the main aim of RE policy is to trigger investment, appraisal of investments under such policy can provide insights into policy efficiency and enables comparison of different support mechanisms.

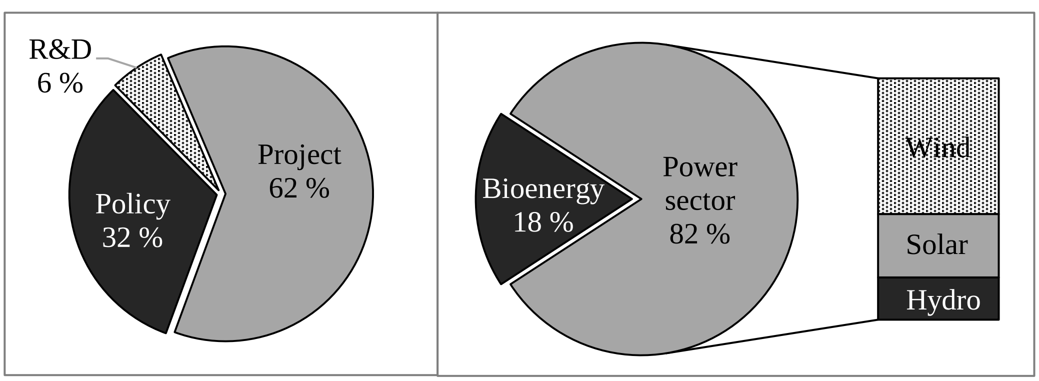

Figure 3. Valuation focus (left) and technology type assessed (right)

For example, Kim and Lee [36] compare different feed-in-tariffs (FIT) and make proposals for their optimization. The authors conclude that there is no optimal policy design, rather policy design depends on the policy objectives and the tradeoff between policy efficiency in RE project promotion and its cost-effectiveness with respect to the burden on taxpayers. Furthermore, the authors note a general tendency that the higher the volatility of electricity prices on the market, the more successful FIT programs become in terms of attracting new investments.

Scatasta and Mennel [11] compare FIT and Renewable Obligation Certificates and study their effect on propensity to innovate. Their results demonstrate that neglecting risk-aversion, the certificate trading scheme favors investment in renewing RE power generation plant to a greater extent than FIT. Their explanation suggests that the higher uncertainty and risks under certificate trading also create more opportunities. Similarly, Boomsma et al. [37] explore investors' behavior under FIT and RE certificate trading and study the effects of market and policy risks under different schemes [38]. This research highlights that the certainty provided by FIT encourages earlier investment, whereas uncertain revenues under the certificate trading scheme, while tending to delay investment, give greater incentives to larger projects once a positive investment decision has been taken. Nevertheless, the authors underline their finding that the difference in market risks between these schemes is less than has previously been assumed. Finally, their model demonstrates an adverse slowing down effect of retroactive policy changes. Similar conclusions of the negative impact of policy uncertainty on RE investments has been reached in other works as well [39-41].

Yu et al. [42] compare a previous Spanish scheme with a new switchable tariff, investigate the impact of the latter on RE investments and define optimal switching strategies. Running a RO valuation model for different policy design, they find that a switchable tariff approach balances the policy efficiency inherent to fixed FIT and the cost-effectiveness commonly induced by market-based RE support mechanisms. The authors argue that the flexibility embedded in switchable tariffs allows risk reduction and provide adequate support to compensate for risks involved in investment in RE projects. The issue of integrating flexibility into RE policy design is elaborated further in section 4.3 of this paper. Research focused on RE policy assessment can provide impulses not only for improving existing policies, but also for designing support mechanisms for emerging policies.

In terms of the focus on technology type (Figure 3, right), most researchers investigate wind power generation projects, followed by solar and small hydro. A few studies depart from these already common RE technologies and consider project valuation of non-mainstream RE technology, e.g., tidal power [43], or unorthodox energy generation such as the 'Powership' concept [44]. Less than a fifth of the reviewed papers focus on bioenergy projects, including biofuel production and flex-fuel cars.

4.2 Research design

In spite of the variety of RO analysis approaches, design of real option valuation contains several common attributes: (i) identification of the sources of uncertainty, (ii) recognition of the available real options, (iii) modeling of the development of uncertain variables, and (iv) valuation of the real options. This review examines all these components of RO valuation and presents the results, first with respect to the uncertainty source and its modeling, second as regards the RO type, and finally the valuation technique used.

4.2.1. Uncertainty sources and modeling

Table 1 summarizes the sources of uncertainty identified in the different papers. The percentage values indicate the share of studies out of the whole sample that identify a particular source of uncertainty; the values do not sum up to 100% because many papers study multiple sources.

Table 1. Uncertainty sources in renewable energy valuation

Uncertainty	Number of publications	Share of sample
Electricity price	48	48 %
Technology	23	23 %
Production	21	21 %
Fuel price	18	18 %
Project value	14	15 %
CO2 price	14	14 %
Subsidy payments	12	12 %
Biomass price	9	9 %
NRE cost	9	9 %
Biofuel price	6	6 %
Demand	5	5 %
Inflation	5	5 %
Regulation	4	4 %
Exchange rate	2	2 %
O&M costs	2	2 %
Cost of capital	1	1 %

Almost half of the studied papers incorporate electricity price uncertainty into the valuation design, and this issue is clearly crucial for the power generation sector. Several other sources of uncertainty are often identified along with electricity price uncertainty, for example: technological uncertainty or, in other words, the assumption that future initial costs are expected to drop (or efficiency to rise) for immature but actively developing technologies; production uncertainty, which appertains to the variability in electricity output of renewable energy sources; and CO_2 price uncertainty, if the environmental benefits of RE projects in terms of CO_2 reduction and associated economic activity are considered. For bioenergy projects, obvious sources of uncertainty are fuel prices and biomass prices. Sometimes the whole project value is considered as an uncertainty, for example, when the Black-Scholes model is used for RO valuation, as in [9,10,45,46]. Studies that investigate switching from conventional energy to RE, especially those focusing on R&D valuation, consider the cost of non-renewable energy (NRE) technology as a source of uncertainty. Market-related uncertainty sources other than electricity prices, e.g., demand, inflation and exchange rates, are examined less often. Regulation uncertainty signifies an expectation of retroactive changes in RE policy. In the literature reviewed, 40% of studies focus on a single uncertainty source in their valuation model, most commonly electricity prices or project value. A maximum of five and an average of two sources of uncertainty are identified in the individual studies.

With respect to uncertainty modeling, most researchers opt for stochastic processes such as geometric Brownian motion or mean reversion. Ongoing debate regarding which process better reflects commodity price evolution has motivated some researchers to implement both models and compare the results. The roots of this debate lie in the origins of RO theory. Use of GBM in RO analysis has been inherited from financial option theory, where it is commonly used to address stock price evolution [47]; commodity prices, including electricity and fuel, have however been shown to have a mean reverting nature [48]. Nevertheless, Pindyck [49] argues that using GBM instead of MRP should not jeopardize the results, if the mean reversion coefficient is low.

Opinions diverge among the reviewed papers. Jang et al. [50] state that resorting to GBM may lead to overestimation of option value due to greater long-term uncertainty in comparison with mean reversion. Similarly, Brandao et al. [51] conclude that MRP provides better approximation of the actual data. However, for instance, Bastian-Pinto et al. [34] report relative independence of the results from the type of process chosen. Nevertheless, the majority of reviewed papers exploit GBM for uncertainty modeling (58%), whereas MRP is a much less popular choice (15%).

Stochastic processes are not applicable for all sources of uncertainty. Thus, for example, technological uncertainty is usually modeled with learning curves as in [52-54]. Once an appropriate model has been chosen, its parameters must be estimated, which is usually done based on historical data.

4.2.2 Real option types and valuation techniques

Moving to the remaining attributes of the RO approach, Table 2 illustrates RO types identified in the reviewed papers. It is a common practice to distinguish RO at different stages of an investment project. However, as opposed to complex projects such as those, e.g., in the mining industry, where one can identify RO at four different stages, namely exploration, development, extraction and reclamation [55], RE projects are known to possess limited flexibility. Cesena et al. [4] identify only two stages of RE investment where flexibility can be found: the planning stage, when the investment has not yet been undertaken, and the operational stage, when the project is already built. Figure 4 shows the number of RO identified within one case and the valuation techniques used in the reviewed papers.

Table 2. Real option types in renewable energy valuation

RO type	Project stage	Number of publications	Share of sample
timing	plan	61	60 %
to invest	plan	22	23 %
to abandon	op	18	18 %
technology choice	plan	9	9 %
to deploy	op	6	6 %
to switch inputs/outputs	op	6	6 %
to continue	op	5	5 %
to expand	op	4	4 %
capacity choice	plan	4	4 %
regulatory	op	4	4 %
to grow	op	3	3 %
to stop	op	3	3 %
to stage	plan	2	2 %
to stop/restart	op	2	2 %
to switch regimes	op	1	1 %
demand response	op	1	1 %

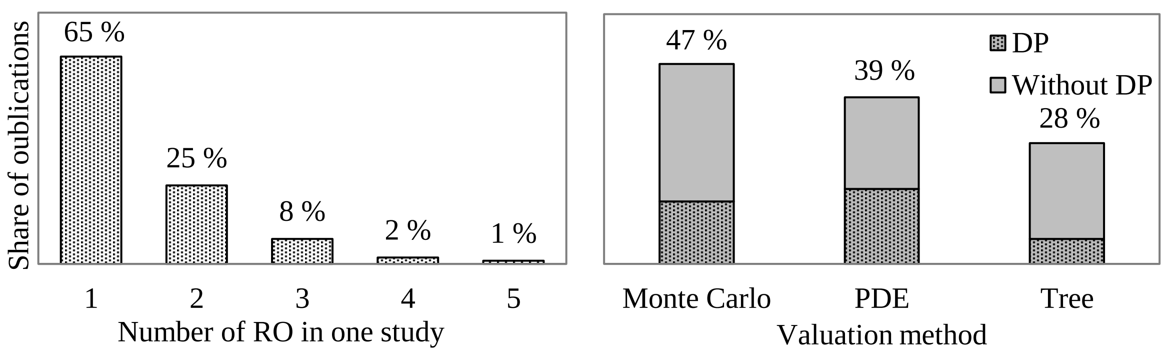

Figure 4. Number of RO identified (left) and their valuation methods (right)

As can be seen from Table 2, the majority of RE valuation studies identify generic RO at the planning stage of a project. The most commonly identified real option is the option to defer an investment or the timing option. In many cases, in the face of various uncertainties, it is often reasonable to wait until some of this uncertainty has been resolved. The option to defer is modeled by techniques that enable comparison of different timing alternatives, in most cases either by use of binomial trees [56,57] or by incorporating DP on top of simulation models [40,52,58,59] or models formulated by PDE [38,60-64]. In 20% of the reviewed papers, timing RO is a single identified option. In addition to the question of timing, the combination of DP with other methods is also used to incorporate options in technology choice [32,65,66] or capacity choice [67,68] into optimal design of the investment.

The second most common option examined, the option to invest, reflects the notion of the whole investment project as a real option. In the majority of cases, it is modeled as a single option. Identification of this option usually coexists with valuation by the Black-Scholes formula [9,10,45,46,69], which constitutes a part of PDE without DP in Figure 4.

Real options to abandon, deploy and continue reside in assessment studies of R&D projects or programs and are generally addressed with binomial, scenario or decision trees as the most convenient methodology to model different scenarios of R&D development [44,50,70-72]. Decision tree approaches intrinsically allow modeling of this combination of options as a compound RO.

The option to switch inputs or outputs is peculiar to bioenergy projects whose operations can be tuned to changing prices of fuels, raw materials or output products. Studies of such facilities often utilize Monte Carlo simulation [33,34,51,73,74].

An emerging trend is incorporation of fuzzy set theory into RO valuation, which allows not only uncertainty to be captured, but imprecision as well. Sheen [75] merges the Black-Scholes method with fuzzy formulated inputs, and Kozlova et al. [76] demonstrate the use of a standalone fuzzy pay-off method for RO valuation of a RE project.

From the above discussion, it can be seen that the choice of valuation approach is linked to the types of real option identified. However, the latter is often dictated by the study domain and research purpose.

Considering RO research design from a broader perspective, we would like to draw attention to the rare attempts to support RO valuation with empirical evidence. Heggedal et al. [77], for instance, perform regression analysis on construction license data and show that investors owning a portfolio of licenses act in accordance with RO theory, while the behavior of single plant owner reflects investment rules dictated by traditional NPV analysis. More evidence confirming investors' behavior in accordance with RO theory is provided from the same dataset in later works [78,79]. Another example, Bartolini and Viaggi [80], assesses RO valuation results by conducting a survey on intentions to adopt bioenergy technologies in the farming sector.

4.3 Operational flexibility in RE power generation projects

Renewable energy investments, which are characterized by long life span and high upfront capital costs, are exposed to market, political and project-internal risks during their operational stage. While bioenergy projects benefit from the operational real option to switch inputs/outputs and R&D projects possess a compound RO with respect to whether to continue, abandon or deploy the project, most RE power generation investments have limited operational flexibility and basically appear to be sunk costs as soon as an investment decision has been made. The commonly examined RO of RE generation project, the timing RO and the RO to invest are generic, and are only available at the planning stage, and thus, they do not contribute to operational flexibility.

Nevertheless, operational flexibility is of crucial importance for such RE investments, as it makes the project able to respond to changing conditions. One way to incorporate operational flexibility is by creating customized real options in the project design. However, as noted in [4], developing RO in project design requires adequate technological knowledge of the project together with understanding of RO theory, which is a rarely found skillset among either project managers or engineers. The shortage of operational RO in RE power generation projects draws attention to the need for consideration of insurance and other hedging instruments. Additionally, it may be possible to enable operational flexibility by RE support policy design.

4.3.1 Real options in project design

Electricity output of run-of-river hydropower plants depends entirely on the water flow conditions. Cesena et al. [67] propose combining this technology with hydro storage facilities. Design parameters of the power plant, including location, generation capacity and storage capacity, are optimized together with investment timing in response to forecasted development of market electricity prices. Inclusion of storage allows control of electricity production volumes and, hence, flexibility in the sale of electricity to the market. The authors demonstrate that such RO design of the project increases expected profits.

Combining pumped storage with a wind farm is examined by Reuter et al. [65]. By the same logic, the storage facility enables electricity to be sold at times of high prices and stored when prices are low. This flexibility increases average profit per unit of electricity produced. However, the presented computations show that this premium does not overweigh the initial costs of storage, leading the authors to conclude that such combined power plants are not profitable without public support.

Operational flexibility is generally embedded in hybrid RE power plants. A combination of RE power generation with back-up energy systems like batteries or conventional energy generation actuate the real option to switch from the RE source to alternative production or storage when the RE resource is scarce or unavailable. Such hybrid systems are often a solution for off-grid power supply [81] and may become economically attractive as a substitute for expensive diesel generation [82]. However, addressing such hybrid RE power systems with RO valuation is not presented in the reviewed literature and represents a potential research direction.

Another approach to operational flexibility is proposed in [83]. The authors shift their focus from supply side flexibility to the demand side, suggesting investment in demand response programs. Electricity consumers under such program are offered incentives to reduce or shift their electricity consumption. In turn, this measure reduces capacity requirements for the energy system and enables flexibility within the project operation phase. The results of the study show that demand response programs are beneficial for off-grid solar PV investments.

There are rare attempts in the reviewed literature to embed operational flexibility into RE power generation projects. The general idea is to combine RE power with storage or alternative generation. Flexibility can be also integrated from the demand side by introducing demand response programs. Revealing real options at the operation stage of RE power generation projects is an emerging research direction and offers opportunities for added value for long-lasting capital-intensive RE investments.

4.3.2 Insurance and hedging in RE generation projects

Taking into account the limited operational flexibility of RE generation projects, it is unsurprising that project developers consider various insurance and hedging mechanisms to secure their revenues in the presence of uncertain resource availability and volatile markets. Indeed, if it is problematic or impossible to build flexibility into a project to make it able to response to uncertainty, hedging against this uncertainty is another alternative. This question has received some limited consideration in the research.

Hedman and Sheble [69] present real option valuation of a wind energy investment to compare hedging uncertain electricity output with either pumped storage hydro facilities or the purchasing of financial call/put options. Their analysis suggests that hedging with financial options is preferable to joint operation of wind and hydro storage plant, since in the former scenario expected profits are higher and more stable.

Bruno et al. [84] analyze hedging RE project revenues against uncertain market electricity prices with forward contracts. Their work corroborates the notion that hedging reduces cash flow uncertainty and they show that coverage of future cash flows with forward contracts depends on the risk aversion level of a particular investor. The authors emphasize that the threshold risk premium of forward contracts should be evaluated on a case-by-case basis accounting for owner's risk attitude and market perception.

Zeng et al. [85] investigate an arrangement of third party financing for distributed solar power with an option to buy back solar panels by the host. The host party allows the third party to finance, install and operate solar panels on its property. The third party benefits from electricity sales and pays charges to the host in return. The host keeps the option to buy the solar panels from the third-party at a specified time in the future. Such schemes enable delayed upfront payment and a lower price. The authors calculate the optimal timing of the buyback year and claim that such arrangements can benefit both the host and the third party.

A range of risk mitigation strategies are available for renewable energy projects, such as opting to invest in various insurance and guarantee instruments [86]. However, the effects of these strategies have not received much attention in RO literature. Nevertheless, comparing and combining available real options with financial contracts and insurance instruments can bring additional value to RE projects and represents another emerging research niche.

4.3.3 Real options in policy design

In a few cases RE support policy itself provides operational flexibility to RE power generation projects. There are four papers in the literature reviewed that identify such regulatory real options.

Yu et al. [42] examine the switchable tariff scheme introduced in Spain in 2004. Under this regulation wind power generators can choose on a yearly basis whether to receive a fixed tariff or a percentage premium over the market electricity price. The authors analyze these alternatives as a single policy and compare the scheme to a combined switchable tariff policy. The results demonstrate that a single fixed tariff incentivizes higher RE deployment levels in terms of capacity installed. On the other hand, the premium as a single policy secures the cost-effectiveness of new projects, creating higher market value of the new electricity produced. The authors claim that the combined switchable tariff scheme balances these often conflicting features of RE policy. Their results demonstrate that operational flexibility provided by the switchable policy reduces risk exposure of wind generators. To further optimize this support mechanism Yu et al. propose a monthly switching tariff that would provide even higher additional value to RE investments.

The same Spanish support mechanism is studied by Iniesta et al. [87]. The authors arrive at a similar conclusion that such regulatory options increase RE project value. Moreover, they argue that these regulatory options are beneficial for policymakers, because the administration has greater control as the policy details can be adjusted in response to shifting policy targets.

In Germany, the Renewable Energy Sources Act was amended in 2012 to introduce a premium scheme on top of fixed feed-in tariffs. Based on this amendment, Barroso and Iniesta [88] identify a regulatory real option to wind generators to switch between the fixed tariff and the premium over electricity price. They treat this RO as an American put option held by the investor and show an increase in RE project value in the presence of this option. They also characterize the provision of the support as a European call option held by the policymaker. Deducting the call option value from the put option value, they obtain an overall negative figure and claim that the policy depreciates the value of RE power generation projects. A similar conclusion is reached by the same authors in analysis of offshore wind energy support in Denmark [89]. These findings are counterintuitive and contradict other research results for both Germany [65,90] and Denmark [8], as well as feed-in tariff scheme analysis for other countries [36,91,92].

Another policy mechanism studied by Kozlova et al. [93] resembles provision of an insurance scheme rather than a regulatory real option. Introduced in Russia in 2013, the RE support aims to guarantee a certain return on investment, thus shielding project cash flows from market risks, including electricity prices, interest rates, inflation, and exchange rates. The remuneration amount is adjusted annually based on changes in listed market factors, which secures the return on investment of RE projects and reduces fluctuation in expected profits. Monte Carlo simulation results indicate substantial risk reduction for RE producers.

Regulatory real options in public policy design can be a powerful tool for promoting RE investment. Limited operational flexibility in RE power generation projects can be compensated with exogenous real options provided by the policy. Thus far, the literature reviewed identifies and analyzes regulatory real options in policy design only for switchable tariffs. All studies report increased project value under such a policy and some show that the policy enables more control over policy efficiency. Clearly, further research effort is required to enable policy design that introduces further regulatory real options.

5. Conclusion

This research presents an academic literature review on use of RO approaches in renewable energy investment valuation. Apart from providing many valuable insights for investors and policymakers, the reviewed studies illustrate the relevance of the RO approach and demonstrate its superiority over traditional capital budgeting techniques, highlighting its ability to capture uncertainty and flexibility.

Overall, a strong positive historical trend in terms of number of papers published is seen. Simultaneously, the increasing policy support for renewable energy being enacted worldwide leads us expect even greater research attention to this topic in the future.

The geographical coverage of the reviewed studies illustrates the dominance of developed countries as a focus of research. However, increasing research interest in developing countries is noted. The fact that the studies cover a mere twenty countries out of 145 having policy support for RE reveals the great potential for further research in geographic terms.

Most of the reviewed articles focus on project valuation. Policy assessment studies can however provide insights that are of value to policymakers. One general conclusion common to many studies is the negative impact of policy uncertainty on RE deployment. Expectation of retroactive policy changes slows down new RE investments.

Wind power technology is the most common energy source analyzed, with almost half of the studies addressing projects involving wind power, followed by bioenergy projects, which account for a fifth of the studies. There is a notable lack of studies considering emerging RE technologies.

When considering the design of the RO approach, a connection was found between the methodology chosen and the real options identified for valuation, reflecting the domain and purposes of the research. The use of DP on top of other valuation techniques is shown to enable comprehensive analysis of compound real options. Emerging interest in the use of fuzzy-based approaches in RO valuation was also noted, as was the importance of selection of appropriate uncertainty modeling techniques.

The review draws attention to the limited operational flexibility of RE power generation projects. The most common real options recognized in analysis of such projects are the timing RO and the RO to invest, which are both found in the planning stage of the RE project and no longer available once the investment decision has been made. To address this issue, some researchers propose integrating real options in the technological design of the project, e.g., by backing up intermittent resource wind farms with hydro storage facilities, or enabling operational flexibility from the demand side, e.g. by introducing demand response programs, or resorting to financial hedging instruments. Additionally, operating flexibility can be provided by RE support policy, if it allows investors to choose between different remuneration approaches. However, only few papers analyze such a setting. Real options in project or policy design, as well as combining real options with financial hedging, is an emerging and crucially important research area that will benefit both investors and policymakers.

This review contributes to existing literature by providing a more comprehensive picture of research applying RO reasoning to RE investments and by revealing hitherto hidden aspects such as the role of research design and the value of introducing customized real options in project design or regulatory real options in policy design.

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Appendix 1. Tabulated summary of reviewed papers

#	Authors	Year	Country	Focus	Project Type	Option	Valuation approach	Uncertainty	Uncertainty Modeling	Reference
1	Iniesta, J.B. and Barroso, M.M.	2015	Denmark	policy	wind (offshore)	regulatory	Monte Carlo	investment cost electricity price inflation production	MRP with trends and jumps	[89]
2	Rohlfs, W. and Madlener, R.	2014	Germany	project	wind coal gas CCS	timing	Monte Carlo tree	electricity price fuel price CO2 price technology	GBM	[94]
3	Adkins, R. and Paxson, D.A.	2016	-	policy	generic RE	timing	PDE DP	electricity price production	GBM	[95]
4	Martín-Barrera, G., Zamora-Ramírez, C. and González-González, J.M.	2016	EU	R&D policy	solar (CSP)	timing to abandon	tree Monte Carlo	project value	tree	[96]
5	Dai, C.Y., Wang, Y.X., Li, D. and Zhou, Y.L.	2015	China	project	wind	to invest	PDE (B&S)	project value	normal distribution	[46]
6	Eissa, M.A. and Tian, B.	2017	Egypt	project	solar	timing	PDE (B&S) Monte Carlo Lobatto3C-Milstein (L3CM) finite difference	electricity price production subsidy payments	GBM	[97]
7	Eryilmaz, D. and Homans, F.R.	2016	US	policy	wind	timing	DP	regulation subsidy payments	Markov process	[41]
8	Fleten, S.E., Molnár, P., Nygård, M.T. and Linnerud, K.	2016	Norway	project	hydro	timing	DP PDE	electricity price subsidy payments	GBM	[78]
9	Fleten, S.E., Linnerud, K., Molnár, P. and Nygaard, M.T.	2016	Norway	project	hydro	timing	DP PDE	electricity price subsidy payments	GBM	[79]
10	Gong, P. and Li, X.	2016	China	project	solar wind biomass	timing	tree (trinomial tree model)	CO2 price	GBM	[98]
11	Kim, K., Park, H. and Kim, H.	2016	Indonesi a	project	hydro	timing to abandon	tree (binomial lattice model)	subsidy payments production CO2 price O&M costs	three-point estimation (best/moderate/wo rst cases)	[6]
12	Kitzing, L., Juul, N., Drud, M. and Boomsma, T.K.	2017	EU (Baltic sea)	policy	wind (offshore)	timing capacity choice	DP PDE	profits	GBM	[99]
13	Mancini, M., Sala, R., Tedesco, D. and Travaglini, A.	2016	-	project	wind solar	to abandon	tree (binomial tree)	production subsidy payments	GBM	[100]
14	De Mare, G., Manganelli, B. and Nesticò, A.	2013	Italy	project	wind	timing to abandon to expand	Monte Carlo	project value	GBM	[101]

#	Authors	Year	Country	Focus	Project Type	Option	Valuation approach	Uncertainty	Uncertainty Modeling	Reference
15	Sisodia, G.S., Soares, I., Ferreira, P., Banerji, S. and Prasad, R.	2015	Spain	policy	wind	timing to expand	Monte Carlo PDE (B&S)	project value	normal distribution	[102]
16	Sisodia, G.S., Soares, I. and Ferreira, P.	2016	Spain Portugal	policy	wind	timing	Monte Carlo PDE (B&S)	project value	normal distribution	[103]
17	Zhang, M.M., Zhou, P. and Zhou, D.Q.	2016	China	project	solar	timing	DP Monte Carlo (least squares)	CO2 price NRE cost investment cost electricity price	GBM	[104]
18	Zhang, M.M., Zhou, D.Q., Zhou, P. and Liu, G.Q.	2016	China	policy	solar	timing	DP Monte Carlo (least squares)	CO2 price investment cost	GBM	[105]
19	Zhang, M.M., Zhou, D.Q., Zhou, P. and Chen, H.T.	2017	China	policy	solar	timing	DP Monte Carlo (least squares)	CO2 price investment cost electricity price	GBM	[92]
20	Kozlova, M., Collan, M. and Luukka, P.	In Press	Russia	policy	wind	to invest	Monte Carlo	investment cost production electricity price inflation	uniform distribution	[93]
21	Adkins, R., Paxson, D.	2016	-	policy	generic RE	timing	PDE	electricity price production subsidy payments	GBM Poisson (jump) process	[95]
22	Gahrooei, M.R., Zhang, Y., Ashuri, B., Augenbroe, G.	2016	US	project	solar residential	timing to stage	Monte Carlo DP	demand technology electricity price	GBM	[106]
23	Ritzenhofen, I., Spinler, S	2016	generic	policy	wind	timing	tree DP	regulation technology electricity price	GBM	[39]
24	Torani, K., Rausser, G., Zilberman, D.	2016	US	project	solar residential	to invest	PDE DP	electricity price technology cost	GBM	[18]
25	Wesseh, P.K., Lin, B.	2016	China	policy	wind	to invest	tree DP	NRE cost	tree	[107]
26	Balibrea-Iniesta, J., Sánchez-Soliño, A., Lara-Galera, A.	2015	Spain	policy	wind	regulatory	Monte Carlo	electricity price production	MRP Weibull distribution	[87]
27	Boomsma, T.K., Linnerud, K.	2015	-	policy	wind	timing	PDE DP	electricity price subsidy payments regulation	GBM Markov process	[38]
28	Bruno, S., Ahmed, S., Shapiro, A., Street, A.	2015	Brazil	project	hydro wind	timing hedging with forward contracts	DP	electricity price forward price production	Markov processes Vector Autoregressive (VAR) processes	[84]
29	Jeon, C., Lee, J., Shin, J.	2015	Korea	policy	solar	to invest	Monte Carlo System dynamics PDE (B&S)	production electricity price interest rate exchange rate	uniform and normal distribution	[108]
30	Kozlova, M., Collan, M. and Luukka, P.	2015	Russia	project	solar	to invest	Monte Carlo Fuzzy pay-off	electricity price inflation	uniform distribution	[76]

#	Authors	Year	Country	Focus	Project Type	Option	Valuation approach	Uncertainty	Uncertainty Modeling	Reference
								technology production localization		
31	Li, Y., Tseng, C.-L., Hu, G.	2015	US	project	bioenergy	timing	PDE DP	fuel price biomass price	Wiener process with drift	[61]
32	MacDougall, S. L.	2015	Canada	project	tidal	timing	PDE (B&S)	project value	normal distribution	[43]
33	Onar, S.Ç., Kılavuz, T.N.	2015	Turkey	project	wind	to invest	Monte Carlo	production electricity price investment cost	Weibull distribution GBM uniform distribution	[109]
34	Schmitz, M., Madlener, R.	2015	Germany	R&D	powership	to abandon	tree (binomial lattice)	investment cost fuel price storage cost	log-normal distribution	[44]
35	Wesseh, P.K., Lin, B.	2015	Liberia	R&D	generic RE	to abandon to expand to deploy	tree (binomial lattice) DP	NRE cost technology	tree	[70]
36	Xian, H., Colson, G., Mei, B., Wetzstein, M.E.	2015	US	project	bioenergy coal & wood pellets	timing	PDE DP	fuel price biofuel price	GBM	[60]
37	Zeng, Y., Klabjan, D., Arinez, J.	2015	US	project	solar residential	timing	Monte Carlo DP	subsidy payments demand maintenance cost	Jacobi diffusion process normal distribution	[85]
38	Anderson, R.C., Weersink, A.	2014	US	project	bioenergy	timing	PDE DP	project value	GBM	[62]
39	Barroso, M.M., Iniesta, J.B.	2014	Germany	project	wind	regulatory	Monte Carlo	technology production electricity price inflation	MRP with trends and jumps	[88]
40	De Oliveira, D.L., Brandao, L.E., Igrejas, R., Gomes, L.L.	2014	Brazil	project	bioenergy	to switch inputs/outputs	Monte Carlo	electricity price	MRP	[73]
41	Kim, K.-T., Lee, D.-J., Park, S.-J.	2014	Korea	R&D	wind	to abandon to deploy to continue	DP tree (decision tree)	NRE cost	GBM	[71]
42	Kokkaew, N., Sampim, T.	2014	-	project	bioenergy	timing	tree	electricity price CO2 price biomass price	GBM	[57]
43	Linnerud, K., Andersson, A.M., Fleten, S.-E.	2014	Norway	project	hydro	timing	least squares Monte Carlo	electricity price subsidy payments	GBM MRP	[110]
44	Maxwell, Christian; Davison, Matt.	2014	US	policy	bioenergy ethanol	to stop/restart timing	DP PDE Monte Carlo	biofuel price biomass price	GBM	[20]
45	Passos, A.C., Street, A., Fanzeres, B., Bruno, S.	2014	Brazil	project	wind hydro	to invest	least squares Monte Carlo	electricity price	MRP	[111]

#	Authors	Year	Country	Focus	Project Type	Option	Valuation approach	Uncertainty	Uncertainty Modeling	Reference
46	Santos, L., Soares, I., Mendes, C., Ferreira, P.	2014	Portugal	project	hydro	timing	tree (binomial tree)	electricity price	GBM	[56]
47	Sheen, J.-N.	2014	-	project	wind	to invest	PDE (B&S) fuzzy	project value	triangular fuzzy number	[75]
48	Siegert, G.	2014	Germany	policy	biogas bioenergy	to invest to stop	PDE (B&S) Monte Carlo	project value	normal distribution	[112]
49	Zhang, M., Zhou, D., Zhou, P.	2014	China	policy	solar	to continue to abandon to invest timing	tree (binomial lattice)	NRE cost CO2 price technology subsidy payments	tree	[113]
50	Adkins, R., Paxson, D.	2013	-	policy	generic RE	timing	PDE	electricity price production	GBM	[114]
51	Brandao, L. E. T., Penedo, G. M., Bastian-Pinto, C.	2013	Brazil	project	biodiesel bioenergy	to switch inputs/outputs	PDE Monte Carlo	biofuel price biomass price	GBM MRP	[51]
52	Detert, N., Kotani, K.	2013	Mongoli a	project	coal wind solar thermal	timing technology choice	Monte Carlo DP	fuel price	GBM MRP	[115]
53	Di Corato, L., Gazheli, A., Lagerkvist, C.-J.	2013	Sweden	project	bioenergy	timing	DP PDE	project value	GBM	[63]
54	Gazheli, A., Di Corato, L.	2013	Italy	project	solar	timing	PDE	foregone profits	GBM	[116]
55	Jang, Y-S, Lee, D-J., Oh, H.-S.	2013	Korea	R&D	generic RE	to continue to defer to deploy to abandon	tree (binomial tree, decision tree)	NRE cost R&D success	MRP BRM	[50]
56	Lin, B., Wesseh, P. K. Jr.	2013	China	policy	solar	to continue to abandon to deploy	DP tree (binomial tree)	NRE cost technology	GBM	[91]
57	Martinez-Cesena, E. A., Azzopardi, B., Mutale, J.	2013	UK	project	solar residential	timing	indifference curves	technology	-	[54]
58	Monjas-Barroso, M., Balibrea-Iniesta, J.	2013	Denmark , Finland, Portugal	policy	wind	to invest	Monte Carlo tree	technology electricity price inflation production	MRP	[8]
59	Rohlfs, W., Madlener, R.	2013	Germany	project	wind gas	timing	Monte Carlo tree	electricity price fuel price CO2 price technology	GBM	[90]
60	Bartolini, F., Viaggi, D.	2012	Italy	policy	bioenergy	timing	DP Monte Carlo	project value biomass price electricity price labor cost	GBM	[80]
61	Boomsma, T. K., Meade, N., Fleten, S.-E.	2012	Norway	policy	wind	timing to grow	PDE Monte Carlo (least squares)	technology electricity price subsidy payment	GBM	[37]
62	Fuss, S., Szolgayova, J., Khabarov, N., et al.	2012	-	project	gas coal	timing to stop /restart	DP Monte Carlo	CO2 price	GBM	[58]

#	Authors	Year	Country	Focus	Project Type	Option	Valuation approach	Uncertainty	Uncertainty Modeling	Reference
					biomass CCS bioenergy					
63	Gonzalez, A. O., Karali, B., Wetzstein, M. E.	2012	US	policy	ethanol bioenergy	timing	DP PDE	biofuel price biomass price	GBM	[64]
64	Heggedal, A. M., Linnerud K., and Fleten S.-E.	2012	Norway	project	hydro	timing	least squares Monte Carlo DP	regulation electricity price	GBM MRP	[77]
65	Kim, B., Lim, H., Kim, H., Hong, T.	2012	Korea	policy	solar	to invest	PDE (B&S)	project value	normal distribution	[9]
66	Kim, K.-K., Lee, C.-G.	2012	-	policy	solar	to switch regimes	tree	electricity price demand technology	complex formulation	[36]
67	Martinez-Cesena, E.A., Mutale, J.	2012	-	project	wind	timing to abandon	tree (scenario trees and decision trees) Monte Carlo	production	Weibull distribution	[117]
68	Min, K.J., Lou, C., Wang, C.H.	2012	US	project	wind	to abandon to invest	PDE	O&M costs	GBM	[118]
69	Reuter, W. H., Fuss, S., Szolgayova, J., Obersteiner, M.	2012	Germany Norway	project	wind pumped storage	timing technology choice	DP Monte Carlo	electricity price	complex formulation	[65]
70	Reuter, W. H., Szolgayova, J., Fuss, S. et al.	2012	Germany	project	coal wind	timing technology choice	DP Monte Carlo	subsidy payment electricity price production regulation	complex formulation	[66]
71	Di Corato, L., Moretto, M.	2011	-	project	biogas bioenergy	to switch inputs/outputs	DP PDE	biomass price	GBM	[119]
72	Lee, S.-C.	2011	Taiwan	project	wind	to invest	PDE (B&S)	project value	GBM	[45]
73	Lee, S.-C., Shih, L.-H.	2011	Taiwan	policy	wind	to grow to abandon to contract to expand to switch	tree (binomial tree)	NRE cost	tree	[120]
74	Martinez-Cesena, E.A., Mutale, J.	2011	UK	project	solar	design of solar system with demand response	tree (binomial scenario tree)	consumer demand	tree	[83]
75	Martinez-Cesena, E.A., Mutale, J.	2011	-	project	hydro	timing capacity choice	tree (binomial path-dependent scenario tree) Monte Carlo	electricity price	GBM	[67]
76	Munoz, J. I., Contreras, J., Caamaño, J., Correia, P. F.	2011	Spain	project	wind	timing to invest to abandon	tree (trinomial decision tree) Monte Carlo	production electricity price	Weibull distribution MRP	[121]
77	Bastian-Pinto, C., Brandao, L., Alves, M. L.	2010	Brazil	project	bioenergy flex-fuel cars	to switch inputs/outputs	Monte Carlo	biofuel price fuel price	GBM MRP	[34]

#	Authors	Year	Country	Focus	Project Type	Option	Valuation approach	Uncertainty	Uncertainty Modeling	Reference
78	Camargo Jr., A.S., Yu, A.S.O., De S. Nascimento, P.T., Marques, J.J., Morilhas, L.J.	2010	Brazil	project	bioenergy flex-fuel cars	to switch inputs/outputs	Monte Carlo	fuel price	GBM	[74]
79	Fuss, S., Szolgayova, J.	2010	-	project	coal wind	timing technology choice	DP Monte Carlo	technology fuel price	GBM	[52]
80	Lee, Shun-Chung; Shih, Li-Hsing.	2010	Taiwan	policy	wind	technology choice	tree (binomial decision tree)	fuel price technology	tree	[122]
81	Siddiqui, A., Fleten, S.-E.	2010	-	project	general numerical example	to stage technology choice timing	PDE DP	electricity price demand technology	GBM	[123]
82	Tolis, A. I., Rentizelas, A. A., Tatsiopoulos, I. P.	2010	Greece	project	gas biomass bioenergy	timing technology choice	Euler–Maruyama method Monte Carlo	electricity price fuel price CO2 price technology	GBM	[124]
83	Vogstad, K., Kristoffersen, T. K.	2010	Norway	project	wind	timing to grow	DP Monte Carlo	electricity price subsidy payments technology	GBM	[59]
84	Yang, M., Nguyen, F., De T'Serclaes, P., Buchner, B.	2010	China	project	wind	risk premium	Monte Carlo	CO2 price technology	GBM	[35]
85	Bastian-Pinto, C., Brandao, L., Hahn, W. J.	2009	Brazil	project	ethanol bioenergy	to switch inputs/outputs	tree (binomial tree) Monte Carlo	biofuel price biomass price	tree MRP	[33]
86	Fuss, S., Johansson, D. J.A., Szolgayova, J., Obersteiner, M.	2009	-	policy	coal CCS wind	timing technology choice	DP Monte Carlo	CO2 price	GBM vs jumps	[40]
87	Mendez, M., Goyanes, A., Lamothe, P.	2009	Eastern Europea n countries	project	wind	to abandon sequential call option	Monte Carlo tree (binomial tree)	exchange rate production electricity price	GBM	[125]
88	Scatasta, S., Mennel, T.	2009	Germany	policy	wind	to invest	DP PDE	electricity price cost of capital	Markov process	[11]
89	Schmit, T. M., Luo, J., Tauer, L. W.	2009	US	project	bioenergy ethanol	timing to invest	PDE	fuel price biomass price	GBM	[126]
90	Bockman, T., Fleten, S.-E., Juliussen, E., Langhammer, H. J., Revdal, I.	2008	Norway	project	hydro	timing	PDE DP	electricity price	GBM	[127]
91	Kumbaroglu, G., Madlener, R., Demirel, M.	2008	Turkey	policy	CCGT coal nuclear hydro wind	timing technology choice	DP PDE	electricity price fuel price technology	GBM	[32]
92	Sarkis, J. and Tamarkin, M.	2008	-	project	solar	to invest	tree (quadranomial lattice)	technology CO2 price	tree	[53]
93	Fleten, S.-E., Maribu, , K.M., Wangensteen, I.	2007	Norway	project	wind	timing capacity choice	PDE	electricity price	GBM	[128]
94	Kjaerland, F.	2007	Norway	project	hydro	timing	PDE	Electricity price	GBM	[129]

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95	Siddiqui, A. S., Marnay, C., Wiser, R. H.	2007	US	R&D	generic RE	to continue to deploy to abandon	tree (binomial lattice) DP	NRE cost	tree	[72]
96	Kory, W. H., Gerald B. S.	2006	-	project	wind pumped hydro	to invest	PDE (B&S) Monte Carlo	production	GBM	[69]
97	Yu, W., Sheble, G. B., Lopes, J. A. P., Matos, M. A.	2006	Spain	policy	wind	to switch tariff	Monte Carlo	production electricity price	MRP	[42]
98	Fleten S-E; Maribu K.M.	2004	Nordic power market	project	wind	timing capacity choice	DP PDE	electricity price	GBM	[68]
99	Wang, T., and De Neufville, R.	2004	China	project	hydro	timing	Monte Carlo tree (binomial tree)	electricity price	tree	[130]
100	Davis, G. A., Owens, B.	2003	US	R&D	generic RE	timing to deploy to abandon	PDE	electricity price fuel price technology	GBM	[131]
101	Venetsanos, K., Angelopoulou, P., Tsoutsos, T.	2002	Greece	project	wind	to invest	PDE (B&S)	project value	normal distribution	[10]