

Systematic Review

The Real Option Approach to Investment Decisions in Hybrid Renewable Energy Systems: A Systematic Literature Review

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Abstract

In recent years, the global energy crisis, concerns about energy security and grid parity, and the pressure to develop policies for reducing the environmental impact of anthropogenic activities have accelerated investments in renewable energy. A growing body of literature applies the real options approach (ROA) to renewable energy projects, recognizing its value in capturing irreversibility and flexibility under uncertainty. The present work provides a detailed state-of-the-art analysis on the adoption of real options to evaluate mixes of energy technologies for power generation, with a special emphasis on investments in hydropower and solar photovoltaics. The objective is to assess current applications, identify knowledge gaps, and outline priorities for advancing decision-making tools in this domain. We performed a systematic literature review following the PRISMA protocol, identifying 38 papers from the Scopus database up to February 2024. Eligible studies were peer-reviewed articles in English applying the ROA to power generation, following a technology selection process; policy evaluation or research and development studies were excluded. The selected papers were analyzed to identify trends over time and space, adopted energy technology, types of real options with valuation methods, and sources of uncertainty. The present paper also discusses the main findings and emerging gaps, providing an overview of hybrid renewable energy systems. Our analysis suggests that, despite the significant advances achieved in this area, further research is needed to exploit the potential of the ROA in investment decisions for combined renewable energy technologies, especially in cases where internal uncertainty and community perspectives need to be explicitly considered. By linking the ROA to the challenges of mixed renewable energy projects, this study enhances understanding of investment decision-making under uncertainty and identifies pathways toward more robust and adaptive project evaluation.



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1. Introduction

The awareness of society and the scientific community of the interconnection between the environment and energy production, delivery, and use is not recent [1,2]. The International Energy Agency estimates that energy is responsible for more than three-quarters of global greenhouse gas (GHG) emissions into the atmosphere. In 2021, electricity and heat generation accounted for about 44% of global CO₂ emissions from fuel combustion, with 73% of this release produced by coal fired power plants [3]. Owing to the impacts of

the energy sector on climate, efforts to address GHG release must foresee changes in production, transmission, distribution, and consumption of energy [4]. The progress to a new generation of energy systems is embedded in the term energy transition, i.e., the change in the composition of primary energy supply, the gradual shift from a specific pattern of energy provision to a new state of an energy system [5]. This broad definition of energy transition highlights that the challenge is not uniform across nations and continents. Rather, it depends on a mix of each country's energy resource endowment and production, which is shaped not only by climatic and geographical conditions but also by policy frameworks, market structures, and economic conditions. In practice, the rhythm and feasibility of the transition are largely determined by the interplay of these drivers, leading to markedly different trajectories across the world's major economies.

In 2022, China, the United States, India, the European Union (EU), Russia, and Brazil were the world's largest GHG emitters [6]. To tackle climate change (CC), in 2015, under the aegis of the United Nations, the Paris Agreement was signed. The Paris Agreement is a legally binding international treaty outlining countries' commitment to cut emissions, formalized in 2015. It represented the most important pact for international cooperation to act on CC after the 1997 Kyoto Protocol. Yet, the effectiveness of the Paris Agreement critically hinges on the participation of the largest emitters. Recent analyses suggested that non-participation by key countries would substantially reduce its impact. For instance, United States's withdrawal would offset more than a third of global emission reductions, while the potential non-participation of China would lower it by about a quarter [7]. In response to international agreements, the European Commission announced the European Green Deal, a set of proposals on climate, energy, transport, and fiscal policies to cut emissions by at least 55% by 2030, compared to 1990 levels [8]. Indeed, energy production and consumption currently account for more than 75% of the EU GHG emissions [9]. Therefore, energy is central to the EU's transition to meet the Paris Agreement goal of net-zero emissions. The Clean Energy Package (CEP), adopted in 2019, proposed an adaptation of the European energy policy framework to facilitate the shift from fossil fuels towards cleaner energy and to achieve the target of carbon neutrality by 2050 [10]. Among the set of directives and regulations contained in the CEP to meet this ambitious objective, the Electricity Directive (EU/2019/944) [11] together with the revised Renewable Energy Directive (EU/2018/2001) [12] led to the promotion of citizen energy communities (CECs) and renewable energy communities (RECs). While CECs are open to all types of entities with less restrictive ownership and control than RECs, they both limit the effective control of the community to their local members or shareholders as primary beneficiaries, providing important social, economic, and environmental advantages [13]. Directive EU/2019/944 established new regulations to allow for active consumer participation in all markets, either individually or through CECs [12]. This goal can be achieved by producing, consuming, sharing, or selling power, or by offering flexibility services through demand response and energy storage. The amended Directive EU/2023/2413 [14]—also known as RED III—raised the share of renewable energy sources (RES) in the EU overall energy consumption to 42.5% by 2030, predicting an enhanced role of renewable self-consumers and RECs [15]. A renewable self-consumer is defined as a final user that consumes, stores, or sells self-generated electricity without this being their primary commercial or professional activity [16]. In the utility context, a widely used term not explicitly defined in the EU legislation is “prosumer”, i.e., “an energy user who generates renewable energy in their domestic environment and either stores the surplus energy for future use or trades to interested energy customers in smart grid” ([17], p. 615). A renewable self-consumer is also an energy prosumer, as both consumers and prosumers generate energy with the possibility of selling and storing power [16,18]. The implementation of these ambitious

directives is still incomplete across different member states, partly due to the fragmented structure of EU energy markets and heterogeneity in effectively transposing the directives into national laws.

Citizens' practice of organizing locally to exploit energy from available RES is not a recent phenomenon. An emblematic example is the bottom-up initiatives that affected the Danish wind power sector in the late 1970s [19–22]. Several distributed electricity and heating networks were built and run by cooperatives and local governments as alternatives to nuclear power plants. Inspired by Denmark, other countries were involved in the community energy movement. Netherlands, Germany, and, to a limited extent, the United Kingdom, Sweden, Belgium, and France saw a growth in citizens' initiatives in various forms and names (community energy groups or renewable energy cooperatives) depending on the local legislation and context [20,23–25]. Southern Europe was less affected by the development of this type of initiatives [19,26,27], despite hydroelectric cooperatives established at the beginning of the 20th century in Italian alpine regions [28,29]. This evolution indicates that institutional settings and cultural factors strongly condition the success of community initiatives, factors often underestimated in techno-economic assessments.

According to Huybrechts and Mertens [23] the success of community energy initiatives depends on barriers to entry (limited access to capital, few locations, consumer inertia and lack of public support) or cognitive barriers, and it relies on the penetration of RE [30]. Physical geographies and socio-economic development, including cultural traits, drive the diversity in energy supply security between EU regions, which are characterized by different energy resource endowments, available energy infrastructure, and market integration levels [31]. In light of this heterogeneity, the diversification of the EU energy supply (i.e., the reduction in its import dependence) and the stimulation of renewable deployment are among the main long-term objectives of EU energy policy [32]. Diversification in the field of economics and finance traditionally refers to a corporate strategy in which financial assets and investments are distributed in favor of promising sectors of business development. The long-term goal of diversification strategies is to ensure competitiveness and sustainable growth [33]. In the context of energy projects, diversification translates into the selection of a variety of project types, locations, contracts, and generation technologies to reduce risks [34]. We propose that diversification can be particularly relevant in the energy domain, since the balance among RES is not just theoretical but has direct implications for grid stability, system reliability, and market value. Diversifying investments in RES allows the exploitation of the spatial and temporal complementarity of variable energy sources. The asynchronicity over time of energy sources can be exploited in terms of different energy production profiles with fewer instances of zero power production. Conversely, their spatial variability could affect the complementarity of renewable profiles, avoiding risk of congestion and lower market values [13,23]. Systems exploiting multiple renewable energy sources, namely hybrid renewable energy systems (HRES), can be coupled to non-renewable energy sources and operate both in stand-alone or grid-connected modes [13,35,36]. This combination can address limitations in power intermittency, reduced or absent electrical-grid connection, as well as limited efficiency and reliability affecting traditional renewable energy (RE) power plants and energy systems [37]. Since variable energy resource production is uncertain, location-specific, modular and with low short-run costs [38], investing in RE projects has two unique characteristics: (i) the irreversibility of RE investments arises from high and unrecoverable initial costs [39], and the non flexibility of the project due to environmental and technical constraints; (ii) the uncertainties pertain to the energy market, regulations, policies, and future energy production and revenues [40]. In the light of the irreversible and uncertain nature of the RE sector, the opportunity to modify the investment or the firm's strategy to incorporate future information or reduce losses represents an intrinsic value.

The term Real Options (ROs) was conceived to define “opportunities to purchase real assets on possibly favorable terms” ([41], p. 22). The correspondent theory was developed for valuing investments under uncertainty via financial tools. The opportunity to invest is similar to a financial call option [42] as it is a right, but not an obligation, to take some future specified action (e.g., invest) at a defined cost [43]. Historically, ROs analysis thus originates from finance, with its roots in option pricing theory developed by Black and Scholes (1973) and Merton (1974) [44]. Myers (1977) [41] introduced the notion of “ROs” by distinguishing between real assets and investment opportunities that resemble options on such assets. This conceptual foundation was expanded by early contributions such as Brennan and Schwartz (1985) [45] and McDonald and Siegel (1986) [46], who demonstrated how uncertainty and irreversibility affect the value and timing of investment. The field was consolidated by an influential volume by Dixit and Pindyck (1994) [42], which provided a comprehensive framework for investment under uncertainty, and further enriched by Trigeorgis (1996) [47]. The first applications of ROs to the energy sector appeared in the late 1970s and 1980s, in the works by Tourinho [48] and Brennan and Schwartz [45] on resource extraction, followed by studies in the oil industry such as Paddock et al. [49] and Ekern [50]. These works highlighted the value of flexibility in investment decisions in highly volatile markets. Since the late 1990s, an expanding body of research has applied ROs to the energy sector, starting with electricity resource planning [51] and electric power markets [52]. Some of the earliest applications to RE include Venetsanos et al. [53] on wind power, Hoff et al. [54] on photovoltaic systems, and Wang and de Neufville [55] on hydropower (HP), to the authors’ best knowledge. The Real Options Approach (ROA) in the field of the energy sector and its applicability to RES projects was the focus of several past studies, which followed a pioneering review by Menegaki [56]. The subsequent reviews [39,57–59] introduced a systematic classification of previous works based on the areas of application, the type of options used, the implied sources of uncertainty, and the related valuation methods (for an overview of these papers and the foundations of the ROA see Kozlova [39] and Lazo and Watts [60]). Fernandes et al. [57] identified three main fields of applications of the ROA to RE, i.e., power generation projects, policy evaluation, and research and development (R&D) programs. In light of the recent expansion of this body of research, Lazo and Watts [60] provided a review on the ROA to evaluate solar photovoltaic (PV) projects. In the same year, Alonso-Travesset et al. [61] analyzed economic and regulatory uncertainties relevant to RE projects.

To date, however, there are no reviews that analyze the ROA applied to multiple technologies in power generation, with a specific investigation on HP and PV projects. Constructing a diversified portfolio of RES assets can help investors achieve profitable returns while accelerating the energy transition. From the perspective of a REC investing in electricity generation facilities, the combination of several assets reduces dependence on a single technology. Hence, the community can become less dependent on a specific technology which in turn relies on the available natural resources and the related climate/weather patterns. HP and PV deserve special attention not only because they represent the most relevant sources of RE in many regions of the world [62–64], but also because they are particularly well suited for integration and complementarity [65–68].

Similarly to Martínez Ceseña et al. [58] and Lazo and Watts [60], the present work investigates the use of ROs in specified RE technologies, with the exception that it regards exclusively the field of power generation as one of the main areas of application identified by Fernandes et al. [57]. Two central research questions guide this review:

1. What is the current state of the art in the ROA applied to multiple RES technologies with a focus on HP and PV in the area of power generation?

2. What are the main findings, novel gaps, and future directions of this research area in the context of the energy transition?

Building on these questions, the study aims to deliver a comprehensive synthesis of the available literature on the ROA to multiple RE technologies to systematize diverse ROs, approaches, and sources of uncertainty, and to outline perspectives for further methodological development and policy relevance in the context of the energy transition.

The Introduction contains contextual references on the energy sector, including its regulatory framework, a definition of HRES, and context on ROs, which were necessary to frame the research problems. The remainder of the paper is structured as follows: Section 2 shows our search strategy, selection process, and data collection; Section 3 presents a quantitative analysis of the reviewed papers which specifically concerns applications of the ROA; Section 4 provides classification and qualitative analysis of the selected papers; in particular, Section 4.4 includes further references on HRES, complementing the analysis with background information beyond the scope of ROs; and Section 5 concludes.

2. Materials and Methods

2.1. Search Strategy and Selection Process

Following the systematic review protocols proposed by Brown (2007) and Moher et al. (2009) [69,70] and the guidelines provided by the PRISMA Statement [71], this review was structured into a three-stage procedure: planning, conducting, and reporting the review. The PRISMA 2020 flow diagram, checklist, and abstract checklist are available in the Supplementary Materials. In the first stage, after testing the originality of the research question via a preliminary literature review, we planned the review using a dynamic protocol to optimize the selection process. This protocol allowed us to introduce in-progress changes to search criteria and parameters as well as to the research setting [72–74]. In the second stage, we first identified relevant keywords and search strings, starting from the most cited and relevant papers on the topic screened during the planning phase. We then defined criteria to refine the research sequentially, and finally, we assessed the quality of selected contributions, excluding those considered non-relevant. In the third stage, we carried out thematic and descriptive analyses and discussed the search findings. The systematic literature review was conducted using the Scopus database, whose comprehensiveness is similar to the Web Of Science database, as confirmed by the results obtained by Lazo and Watts [60]. The overall search strategy adopted in this review is shown in Figure 1.

To capture as many articles as possible and consistent with previous reviews conducted in this field [39,60], the search string (“renewable energ*” OR “hydropower” OR “photovoltaic*” AND “economic*” OR “corporate finance” OR “investment*” AND “real option*”) was entered into the Scopus database in November 2023 (and subsequently updated in February 2024), without introducing any restrictions on the year of publication. This primary search offered a perspective on a broad context, thanks to the keywords related to economics and energy, as well as on the specific context of the ROA, thanks to the keyword “real option*”. This primary search provided an initial set of 293 contributions (see Figure 1a, “BROAD” to “SPECIFIC” context, and Figure 1b, Boolean search in Scopus). Scopus filters (“Filtering” and “Filters” arrows in Figures 1a and 1b, respectively) were used to select articles published in English in peer-reviewed journals and within the following subject areas: Energy (32% of the initial set), Engineering (17% of the initial set), Environmental Science (16% of the initial set), Economics–Econometrics and Finance (9% of the initial set), and Mathematics (9% of the initial set). By contrast, 17% of the initial set of articles, corresponding to 11 minor off-topic subject areas, were excluded based on the relative subject areas’ statistics. This filtering procedure generated a sub-set of 212 papers to be further processed. We applied inclusion and exclusion criteria to both abstract screening

(i.e., G criteria) and full-text reading (i.e., G and S criteria), as detailed in Table 1, which specifies the general inclusion criteria (G1, power generation; G2, technology type: HP, SHP, PV, or mix) and the exclusion criteria (G3, policy evaluation; G4, R&D programs; S1, no RO valuation; S2, utility-scale PV projects; S3, CC adaptation studies). In the abstract-screening and the full-text reading phases, papers on power generation were included and contributions focusing on policy evaluation or R&D programs were excluded, in accordance with Fernandes et al. [57]. Moreover, a filtering criterion based on focused energy production technologies such as HP, small hydropower (SHP)—hydropower plants with a capacity below 10 MW—PV, and a mix of the former (i.e., technology mix). This process retrieved 54 papers. During full-text reading, articles centered on utility-scale PV power plants or CC adaptation strategies and contributions lacking ROs valuation were excluded. Finally, 33 contributions were obtained. We then implemented backward citation tracking, which consists of checking references in published papers and reviews in the field [60]. This process led to the selection of 5 additional studies, which were included in the final dataset consisting of 38 publications (as shown in Figure 1b, existing reviews were extracted during the abstract screening and full-text reading stages and then used to identify additional papers). Although not included in the final set of papers, the contribution by Di Corato and Moretto [75] deserves a mention. They contribute indeed to the body of literature on the ROA in the energy sector, and specifically in the biogas sector, and provide a stochastic dynamic optimization model to investigate the technology choice problem of a biogas plant under the assumption that the input mix is constituted by factors that are substitutes. They model the value of flexibility in the mix, which, to a broad extent, can be extended and applied to the choice of the technology mix when multiple energy sources are involved.

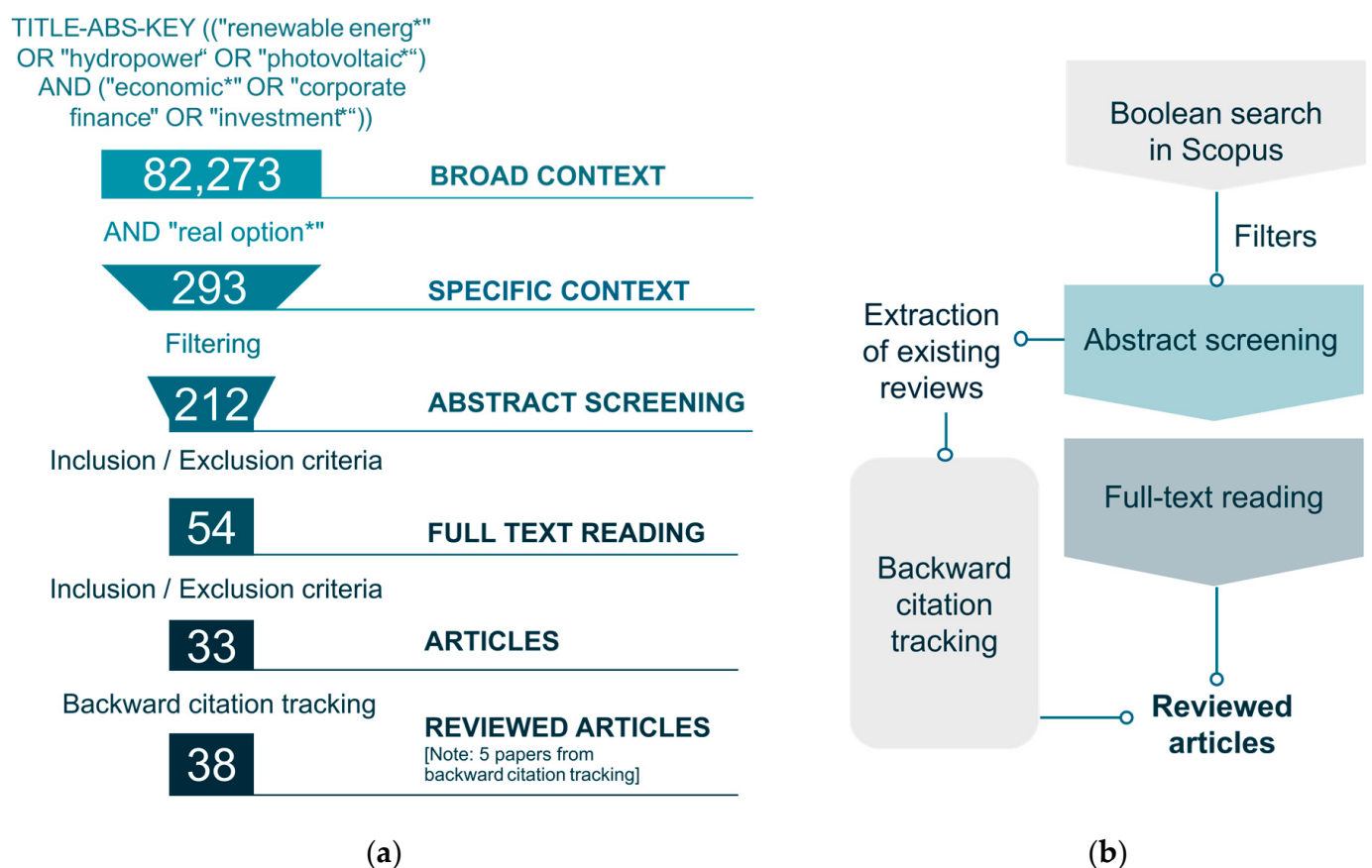


Figure 1. Literature selection process: (a) funnel; (b) procedural summary (our processing).

Table 1. Inclusion and exclusion criteria applied for the paper selection, namely general criteria (ID letter G) and specific criteria (ID letter S) were applied in the full-text reading and backward citation tracking.

Criteria	ID	Description
Inclusion	G1	Power generation
	G2	Technology (HP, SHP, PV, mix)
Exclusion	G3	Policy evaluation
	G4	R&D investments/programs
	S1	No ROs valuation
	S2	Utility-scale PV projects
	S3	CC adaptation strategies

Abbreviations: HP, hydropower; SHP, small hydropower; PVs, photovoltaics; R&D, research and development; CC, climate change.

2.2. Meta-Analysis

Meta-analysis provided basic information and initial insights into the selected articles. It helped identify uncovered issues, areas for future research within a certain body of knowledge, and recurrent findings. Similarly to Kozlova [39], we constructed a synoptic table (Table A1) synthesizing the introductory information that constitutes the basic structure of the reviewed papers, and we stored the corresponding metadata in Microsoft Excel spreadsheets. The qualitative classification of the selected studies was based on predefined categories reflecting technology type, valuation method, and sources of uncertainty, as derived from the research objectives. We developed a manual code to manage the data, following a consistent set of definitions. Given the scope and scale of the review, we did not apply any inter-rater reliability tests; however, the classification scheme is fully reported in Table A1 to ensure reproducibility. We selected Scopus as the only reference database for its comprehensive coverage of multidisciplinary peer-reviewed literature in engineering, economics, and energy, and its frequent adoption in similar systematic reviews. This choice ensured methodological coherence but may have excluded relevant studies indexed elsewhere, which is acknowledged as a limitation of the present work.

3. Results

The body of literature focusing on the application of the ROA to RES and RES power plants grew steadily over the last two decades (January 2002–February 2024), as is proven and shown in Figure 2a, based on the set of 293 articles resulting from the search, before filtering. This trend was indeed less evident when considering the final set of selected articles. Publications were very limited until 2009, then a growing interest in this domain rapidly emerged: the body of literature increased considerably in the period 2016–2023, during which 153 papers were published (on average more than 15 publications per year), and a peak of 30 articles was reached in 2022, likely in response to the global energy crisis [76].

The geographical distribution of publications is shown in Figure 2b. According to the number of publications by country, the implementation of the ROA to investments in RES was investigated in depth in Italy, Norway, the United Kingdom, and Germany, while China is the leading country for the number of publications in Asia, immediately followed by South Korea. There was indeed a flourishing group of researchers interested in the ROA in relation to RES investments in Italy and Norway, as testified by Figure 2b and recent contributions by Andreolli et al. and Dønnestad et al. [77,78]. In addition, the above-discussed findings about publication year and country were largely in line with those by Lazo and Watts [60], although a trivial difference emerged due to the inclusion in our search of both HP, particularly studied in Norway, and technology mixes.

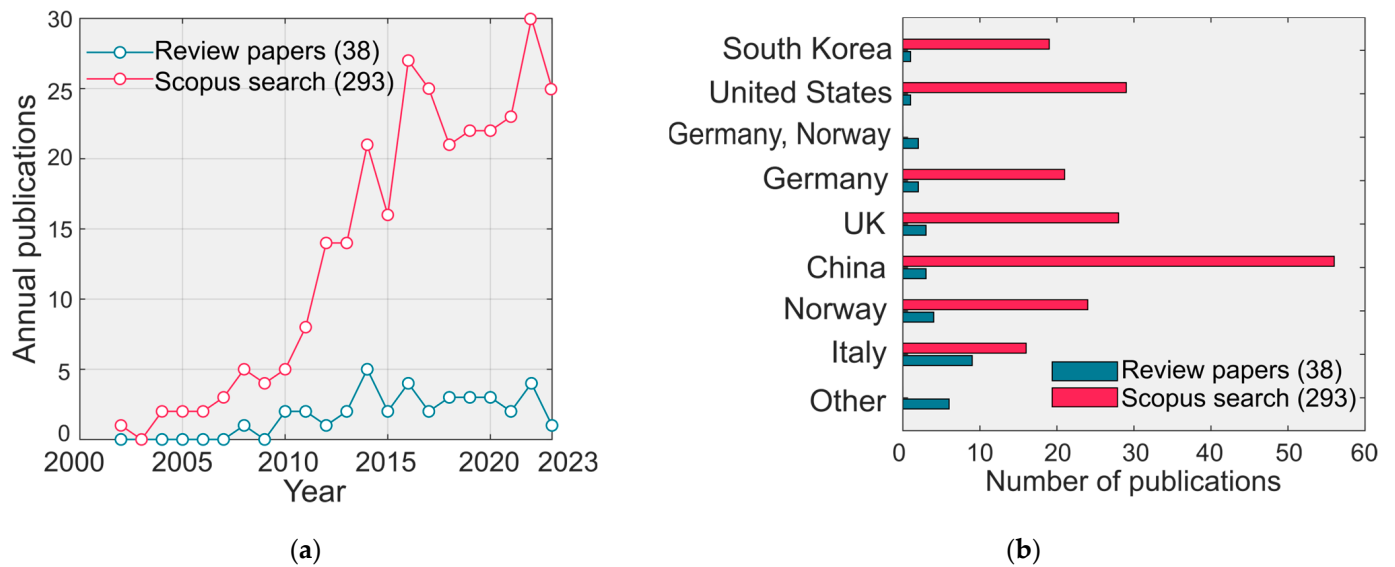


Figure 2. Contributions by year until 2023 (panel (a)) and by country (panel (b)) (our processing). Solely one article was detected in the 2024 search update.

3.1. Technology Adoption

The final set of publications was organized into two groups: the former investigates the adoption of a single power-generation technology, and the latter covers a mix of different power-generation technologies. It is worth recalling, though, that the search focused on investments in HRES, where the primary power generation sources were solar or hydro, eventually combined or coupled with others, to be implemented in mountain areas. Consequently, as an example, wind power as a single power-generation technology was not considered, in contrast to Kozlova [38], whose objective was to broadly investigate the value of investments in RES to inform incentive policy design. Our search findings revealed indeed that most contributions focused on single production technologies (27 out of 38), whereas few contributions (11 out of 38) analyzed technology mixes, of which 4 included non-renewable energy sources (e.g., coal or gas) [79–82] while 7 papers focused exclusively on combinations of RE technologies [40,83–88]. This distribution is illustrated in Figure 3.

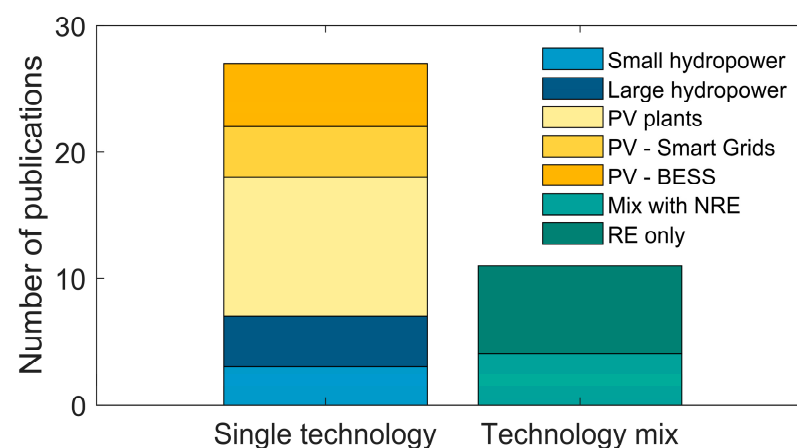


Figure 3. Share of publications focusing on a single power-generation technology or a technology mix (our processing). Abbreviations: PVs, photovoltaics; BESS, battery energy storage systems; NRE, non-renewable energy; RE, renewable energy.

Specifically, as already highlighted by D’Alpaos and Andreolli [73] and Lazo and Watts [47], PV power generation was widely analyzed in the context of the ROA in relation to investment decisions in RES. Within the broader group of solar-based technologies, we

identified three specific subgroups: (i) standalone PV plants in 11 publications [89–99], (ii) PV systems integrated with smart grids in 4 papers [100–103], and (iii) PV combined with battery energy storage systems (BESS), namely PVBs, counted in 5 papers [104–108].

Despite the central role of HP in energy production [49,50], few articles (7 out of 38) covered the application of the ROA to investments in HP plants, where 4 publications dealt with large HP plants [109–112] and 3 papers focused on SHP plants [113–115]. In accordance with Martínez Ceseña et al. [45], our systematic search confirmed the heterogeneity of the applications of the ROA to investment decisions under uncertainty in the energy sector, and specifically in energy power plants, which range from the identification of the optimal investment timing and size to technology choice and diversification aimed at hedging investment risk.

3.2. Source of Uncertainty, Uncertainty Modeling, and Real Options

In line with Kozlova (2017) [39] and Lazo and Watts (2023) [60], we examined three main features of the selected publications: identified ROs, valuation approaches to assess ROs, and recognized sources of uncertainty. All this information is reported in Table A1. Table A1 reports indeed for any contribution: (a) the ROs considered and classified according to the taxonomy provided by Trigeorgis (1996) [47]; (b) the valuation approach adopted and grouped into stochastic dynamic programming (DP), simulations (e.g., Monte Carlo Simulations), decision trees, and others; and (c) the source of uncertainty.

The most common ROs identified were: (i) the option to defer an investment decision to a future date, which is a type of call option; (ii) the time-to-build option (or staged investment), which involves holding the right to withdraw from the project in future stages to limit potential losses; (iii) the option to alter operating scale (e.g., to expand, to contract, to shut down and restart) according to market conditions; (iv) the option to abandon when the situation no longer justifies the project's continuation (this is a kind of put option); (v) the option to switch (e.g., outputs or inputs) in order to capture the flexibility of the project; (vi) the growth option, when an investment opens up future growth opportunities (acting as a call option on another investment); and (vii) the multiple interacting options involved in the same project with a combined option value.

Statistics on the frequency of RO typologies in the reviewed articles are presented in Figure 4a. The option to defer appears in 24 out of 38 papers, accounting for 63% of the dataset [40,81,82,84–86,88,90–97,99,102–105,109,111,113,114]. Other option types were much less frequent: the option to expand and the option to abandon were each identified in 1 paper (3%) [87,110]. The time-to-build option was identified in 2 studies (5%) [89,112], as well as the option to switch (5%) [79,80]. Compound options, typically involving combinations such as defer and expand or defer and abandon, were included in 5 contributions (13%) [98,106–108,115]. Finally, 3 papers (8%) explicitly modeled multiple interacting options within the same investment decision [83,100,101].

For an explanation of commonly used RO valuation techniques found in the literature, we refer to the review by Kozlova [39]. As shown in Figure 4b, DP was the most frequently adopted valuation method, appearing in 18 of the reviewed studies [40,79,80,82–84,88,91–93,95,100,102–104,108,110,113]. DP is an optimization approach that decomposes complex problems into a sequence of simpler ones, and it is particularly suited for decision problems under uncertainty, such as investment timing evaluation. Simulation-based approaches followed, with 11 occurrences [85,96,98,99,101,105–107,111,112,114]; this group includes all forms of Monte Carlo simulations. Decision tree models were implemented in 8 papers [81,86,87,89,94,97,109,115], while only 1 study adopted a different method, which was classified under “Others” [90].

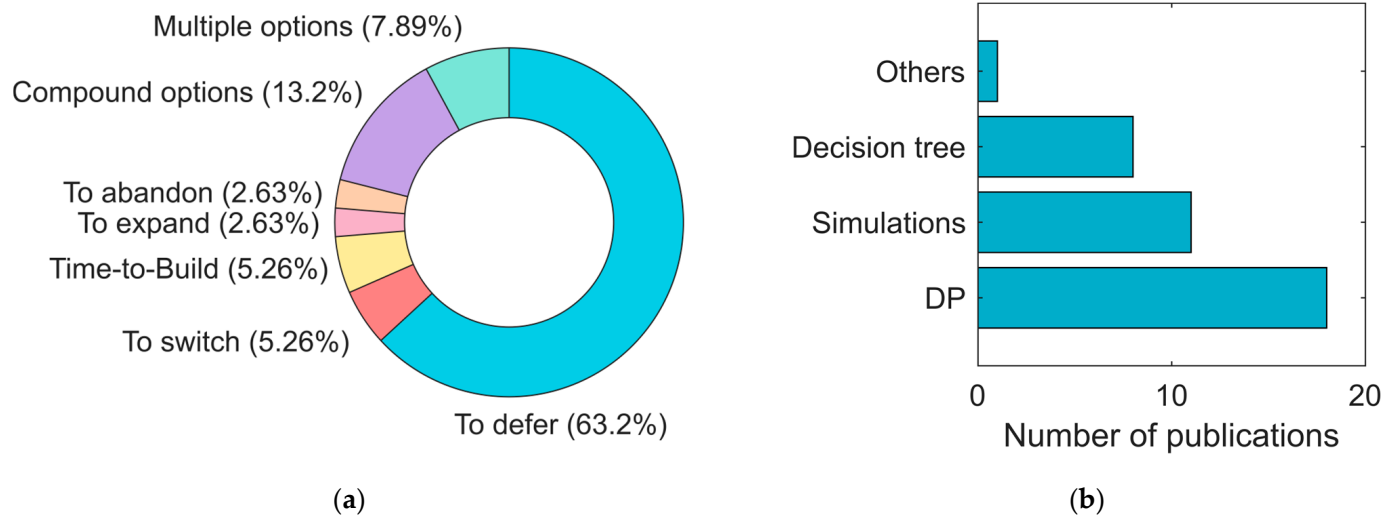


Figure 4. (a) RO types identified in the selected papers; (b) valuation approaches used to evaluate ROs Ro (our processing). Abbreviation: DP, dynamic programming.

Figure 5 shows the sources of uncertainty identified in the selected papers. Most papers included one source of uncertainty (46%), followed by three or more sources (33%), and two sources of uncertainty (21%). Because several studies analyzed multiple sources, the total count in the bar chart exceeds the number of publications. Energy price was the most frequently modeled uncertainty, appearing in 29 studies [40,81–86,88,91–94,96–105,107–111,113,114], and the uncertainty over investment or operation and maintenance (O&M) costs was addressed in 14 studies [40,83,88,90,91,93,95,96,99,105–107,112,115]. Investment and O&M costs represented key drivers of revenues and capital expenditures in energy projects. Other sources of uncertainty included fuel price [80,82,93,106], energy production [84,86,87,115], and demand patterns [89,92,106]. Less common were uncertainties related to carbon prices under emission trading schemes [93,108], reservoir level [79], and policy-related factors such as subsidies [114]. Papers dealing with HP projects almost always considered uncertainty over electricity prices, while technology mix papers also included uncertainty over investment costs and non-renewable energy (NRE) input price as sources of uncertainty. The PV group of papers followed a similar trend, including mainly uncertainty over the energy price, investment costs, and technology adoption.

Most studies modeled uncertainty using stochastic processes, and the geometric Brownian motion (GBM) was the most widely applied approach. Although there was some debate on the most suitable process for representing uncertain variables, other stochastic processes such as the arithmetic Brownian motion, mean-reverting processes, and jump diffusion processes also appear in a few cases. When it was not possible to estimate stochastic processes for the state variables, uncertainty was often addressed through numerical simulations, probabilistic scenarios, or learning curves, especially for emerging technologies. Calibration was typically based on historical data from the target region. For a broader modeling overview, Afzali et al. [116] provided a comprehensive review of uncertainty and risk modeling techniques in power systems. In this work, the authors emphasized how technical, environmental, and financial uncertainties can be addressed through statistical risk models, stochastic modeling, scenario analysis, stress testing, actuarial techniques, qualitative system analysis, and machine learning methods.

To enable comparison between studies and progress towards a more solid estimation of hazards in energy projects, we classified the reviewed papers according to their risk categorization.

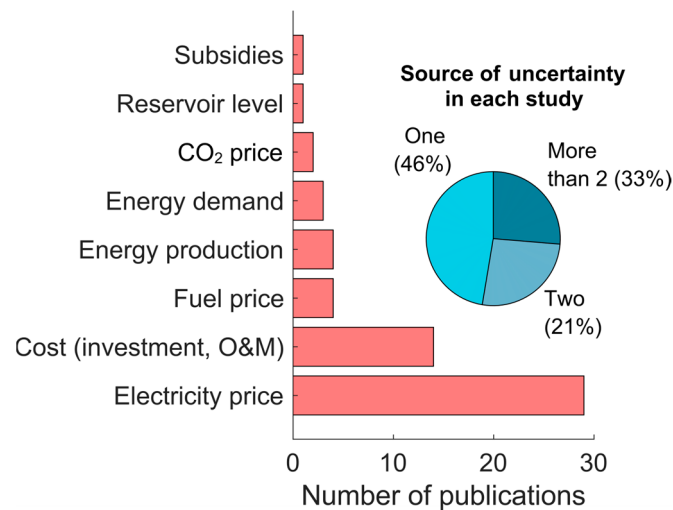


Figure 5. Sources of uncertainty in the selected papers and number identified in each study in the donut chart (the total count in the bar chart exceeds the number of reviewed publications) (our processing). Abbreviations: O&M, operation and maintenance; CO₂, carbon dioxide.

The ISO 31000 is an international standard that provides principles and guidelines for risk management and defines risk as the “effect of uncertainty on objectives”. In the context of RES, we followed the identification of risk types provided by Egli [117], who systematically tested alternative categorizations with investors to define a proper classification. The author identified five main types of risk in RES investments: curtailment risk (e.g., grid bottlenecks), policy risk (e.g., taxation or other policy measures), price risk, resource risk (e.g., wind speed or solar irradiation), and technology risk (e.g., faster degradation). In our review, these categories were adapted to ensure consistency and comparability across the reviewed papers. Specifically, curtailment and technology risks were integrated into a broader technical risk category, policy risk was maintained in line with the reference paper, and price risk was generalized as market risk (covering energy and fuel prices as well as energy demand). Resource risk, which in Egli’s framework was limited to renewable potential, was included in the technical risk dimension together with the technology performance or degradation rate. Finally, the costs (capital expenditure—CAPEX, O&M, and component costs) were grouped under a dedicated financial risk category. This adaptation ensured consistency with Egli’s empirically tested framework while tailoring the classification to the specific focus of our dataset. Table 2 classifies the reviewed papers according to the four broad categories of risk: technical, market, policy, and financial. This mapping highlights the heterogeneity of risk treatment across the literature and enables better comparability among different studies and technologies.

Table 2. Classification of risk sources in the 38 reviewed papers into four categories: technical, market, policy, and financial.

Authors and Ref.	Power Generation Technology	Technical Risk	Market Risk	Policy Risk	Financial Risk
Bockman et al. [113]	SHP plants		Electricity price		
Martínez-Ceseña and Mutale [109]	Storage HP plants		Electricity price		
Andersson et al. [110]	Storage HP plants		Electricity price		

Table 2. Cont.

Authors and Ref.	Power Generation Technology	Technical Risk	Market Risk	Policy Risk	Financial Risk
Fertig et al. [111]	Pumped storage HP plants		Electricity price		
Linnerud and Simonsen [114]	SHP plants		Electricity price	Subsidies	
Locatelli et al. [112]	Pumped storage HP plants				CAPEX
Kim et al. [115]	SHP plants	Energy production		RE tariffs, CER price	O&M cost
Martínez-Ceseña and Mutale [89]	Off-grid PV plants		Consumer energy demand		
Martínez-Ceseña et al. [90]	Domestic PV plants	PV efficiency			PV cost
Biondi and Moretto [91]	Domestic PV plants		Electricity price		PV cost
Gahrooei et al. [92]	Domestic PV plants	Building performance	Electricity price		
Zhang et al. [93]	Domestic PV plants		Electricity price	CO ₂ price	RE investment cost and NRE cost
Kim et al. [94]	Domestic PV plants		Electricity price		
Bertolini et al. [100]	Domestic PV plants		Energy price		
Moon and Baran [95]	Domestic PV plants				PV cost
D'Alpaos and Moretto [101]	Domestic PV plants		Energy price		
Penizzotto et al. [96]	Domestic PV plants		Electricity price		PV cost
Di Bari [97]	Domestic PV plants		Electricity price		
Kelly and Leahy [105]	Not specified	Battery degradation	Electricity price		Future BESS CAPEX
Ma et al. [106]	Domestic PVBs		Peak demand, diesel price		Generator cost, PVB cost
Castellini et al. [102]	Domestic PV plants		Energy price		
Castellini et al. [103]	Domestic PV plants		Energy price		
Andreolli et al. [104]	Domestic PVBs		Energy price		
Hassi et al. [107]	Domestic PVBs		Electricity price		PV cost, battery cost

Table 2. Cont.

Authors and Ref.	Power Generation Technology	Technical Risk	Market Risk	Policy Risk	Financial Risk
Li and Cao [108]	Domestic PVBs		Electricity price	CO ₂ price	
Biancardi et al. [98]	Domestic/utility-scale PV plants		Electricity price		
Or et al. [99]	Domestic PV plants		Electricity tariff, electricity distribution price		PV cost, inverter cost
Siddiqui and Fleten [83]	Unconventional Energy Technology (UET) and RE		Electricity price		UET operating cost
Kjærland and Larsen [79]	Storage HP and thermal power plants	Reservoir level			
Reuter et al. [84]	Wind power and pumped-storage HP plants	Energy production (wind)	Electricity price		
Detert and Kotani [80]	Coal-fired, wind and solar thermal power plants		Fuel price		
Passos et al. [85]	Wind power and SHP plants		Energy price		
Rohlfs and Madlener [81]	Coal-fired, wind, gas-fired power plants		Electricity, coal and natural gas prices		
Weibel and Madlener [86]	Pumped-storage HP plant, wind power and PV plants (ringwall storage hybrid power plant)	Wind intensity, solar irradiation	Electricity price		
Mancini et al. [87]	Wind power and PV power plants	Energy production	Market conditions		
Gazheli and Van Den Bergh [40]	Wind power and PV plants		Electricity price		Wind and PV costs
Li et al. [88]	Storage HP and PV power plants		Electricity price		Wind and HP costs
Zhang et al. [82]	Coal-fired, gas-fired, wind power, PV, and biomass plants		Electricity, fuel prices	Carbon prices (CO ₂), RE certificates	Wind and PV costs

Abbreviations: HP, hydropower; SHP, small hydropower; PVs, photovoltaics; CER, certified emission reductions; CO₂, carbon dioxide; CAPEX, capital expenditure; O&M, operation and maintenance; RE, renewable energy; NRE, non-renewable energy; BESS, battery energy storage system; PVB, photovoltaic with battery storage system; UET, unconventional energy technology.

Figure 6a shows the distribution of risk type mentions, i.e., how many times each risk type was addressed. Figure 6b shows the distribution of risk types in the papers, i.e., how many papers included each risk type at least once. In terms of mentions (73 uncertainties in total), market risks accounted for 52.1%, followed by financial risks (27.4%), technical risks (12.3%), and policy risks (8.2%). Looking at the number of papers, market risks were considered in 86.8% of the studies (33 out of 38), while financial, technical, and policy risks appeared much less frequently (36.8%, 21.1%, and 13.2%, respectively). Because many papers addressed multiple risks, the total number of mentions exceeded the number of publications, and the percentages across papers were more than 100%. The classification showed that market risks clearly dominate among studies and confirmed that, in the ROA literature, market-related uncertainty was the primary driver that affects investment decisions. By contrast, financial risks were moderately modeled in the studies, while technical and policy risks were relatively underexplored. Overall, the imbalance between the market/technical dimensions suggested that future research should adopt a more comprehensive approach to risk modeling in order to improve the robustness and applicability of the ROA for energy investment decisions.

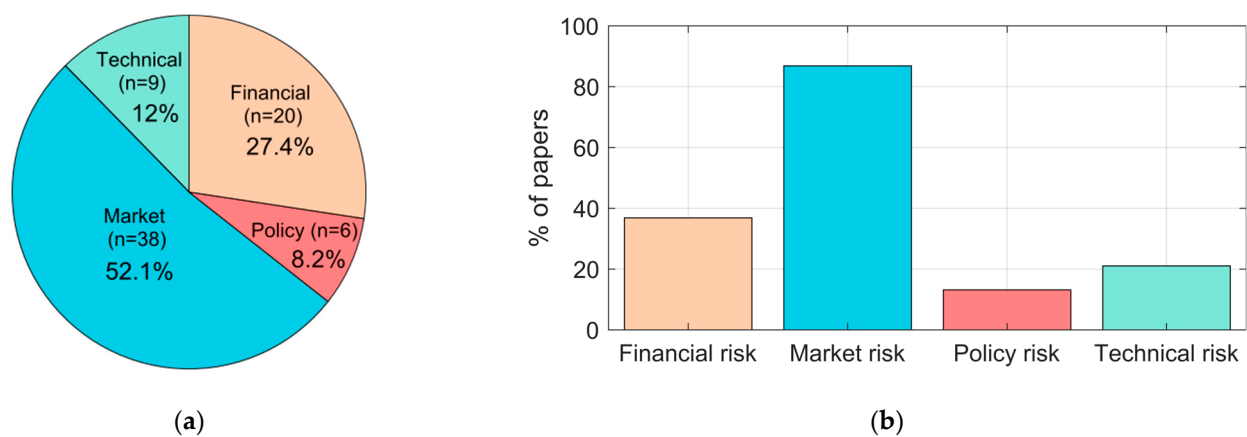


Figure 6. (a) Distribution of risk types across the reviewed papers; (b) share of papers (% of N = 38) that include each risk type at least once (our processing).

4. Discussion

This section provides current findings, identifies literature gaps, and proposes future directions of ROA applications to investments in HP, PV, technology mixes, and HRES. A limitation of this study was the reliance on a single database (Scopus), which may have excluded relevant contributions indexed elsewhere. While Scopus offered broad multidisciplinary coverage and was widely used in systematic reviews of RE topics, future studies can adopt a multi-database search strategy to further enhance coverage and reduce the risk of omissions.

4.1. Hydropower Projects

As highlighted in Section 3.2, publications on the ROA applied to HP projects were limited compared to other technologies despite HP being considered the world's primary RES and an essential dispatchable power source to support other variable RES [62]. HP plants can be broadly classified into categories according to the operation and type of flow (facility type), head (difference between the upstream and downstream water levels), size (i.e., installed capacity measured in MW), and loading type (base load, peak load, and storage for peak load). Egré and Milewski [118] proposed the following HP project classification: reservoir-type projects with significant storage capacity, run-of-river (RoR) projects with little or no storage capacity, pumped-storage, river diversion, and small/mini/micro

projects. Reservoirs involve impounding water behind a dam to enable flow regulation, providing a reserve of energy to prevent fluctuations in power demand. This technology causes changes in river flow patterns [119], production activities, and in environmental impacts (e.g., landscape variation, aquatic and terrestrial ecosystem alterations, land use transformations) [118]. RoR projects use part of the natural streamflow regime without reservoir impoundment, and this causes them to have no control on the timing of water releases and fluctuations in energy production. They are considered attractive due to their low investment costs and short construction time. Even though they are typically linked to less environmental impacts than reservoir systems, researchers demonstrated that RoR plants built in cascades along the same river may alter the flow regime and the fluvial ecosystem [120–122]. An accurate assessment of the hydrology to evaluate resource availability is the main step in a pre-feasibility study. Planning and design stages include the identification of civil works, electrical/mechanical equipment (e.g., turbine types, penstocks, and generators), and transmission and distribution lines [123]. Economic/financial analyses and environmental impact assessments are part of the analyses for projects' viability. These characteristics are essential to properly frame the investment. However, in the authors' view, most of the reviewed ROA studies adopted a simplified representation, focusing on generic categories (reservoir, RoR, pumped storage), rather than site-specific hydrological or design details. This limitation reduced the capacity of current models to reflect the full heterogeneity of HP systems.

Reviewed publications analyzed reservoir-with-storage [109,110], pumped-storage [111], and small RoR HP [113–115] projects. Bøckman et al. [113] presented an ROA for assessing optimal investment decisions in SHP with a fixed design. They applied the approach to three Norwegian projects, finding a unique trigger price that indicates profitability (i.e., the minimum electricity selling price to obtain a positive Net Present Value (NPV)). When the electricity price is above the trigger, it is optimal to invest at the optimal size for the capacity of the plant. They modeled investment costs through a convex function with the constants determined through regressions on an unspecified source dataset [124]. Kim et al. [115] proposed an ROA framework to assess RE investment in developing countries and applied it to an RoR project in Indonesia (Sumatra province). They considered a fixed design (i.e., capacity of the plant) and four variables affecting the project volatility: tariffs, O&M costs, energy production, and the price of certificates of emission reduction (CER). Investment construction costs are a fixed factor. They built a compound option model to enable investors to make various investment decisions (to fund or abandon) at each of the planning, design, construction, and operation stages. The use of a compound option was proven to reduce risks and maximize profit by properly modeling the sources of uncertainty. Linnerud and Simonsen [114] examined whether policy and regulatory uncertainty affected investment decision-making (IDM), based on the panel data of 214 licenses to construct RoR plants in Norway. The license holder has the right, but not the obligation, to construct a power plant within 10 years, which is a RO with characteristics similar to an American option. They found different behaviors between professional and non-professional investors, i.e., non-professional investors behaved as if their investment opportunity was now-or-never and acted according to the NPV rule, ignoring the opportunity to create additional value by waiting. Studies on SHP generally confirm the potential of the ROA to capture the value of flexibility in investment timing and policy effects, but they also share important limitations. Most models relied on simplified technical assumptions (e.g., fixed design or perpetual licenses), which reduced realism and neglected the flexibility inherent in project development. In addition, weak or highly context-specific data foundations limited the robustness and generalizability of results, especially when applied to developing countries. Finally, research on investor's behavior was still limited and context-specific,

reducing its applicability to broader investment settings. These observations reinforced the need for further research on SHP design flexibility, realistic cost functions, and more accurate quantification of uncertainty, particularly in developing countries where data availability is often limited. In line with this, the main emerging gaps and future direction identified in SHP papers are: (i) lack of ROs models for SHP with flexible design; (ii) introduction of proper investment cost function; and (iii) accurate quantification of uncertainty in developing countries, e.g., using climate scenarios or big data analysis approaches. Martínez-Ceseña and Mutale [109] addressed part of the gap concerning model design flexibility in HP projects. Assuming three possible locations along a river basin with the same design limits and storage capacity, the model adjusted the design variable and investment timing to maximize profits. The proposed advanced RO methodologies further enhanced the value of projects by considering flexible designs and investment timing simultaneously or alternately. Andersson et al. [110] addressed future cash flows uncertainty in HP projects with storage in Norway. They combined HP production scheduling (i.e., value of 1 year of power production) and the ROA to decide the optimal investment timing and upgrading capacity choice for existing plants. They found that the optimal investment timing is at year one and various capacity choices depending on long-term electricity price level, discount rate, and investment costs. Fertig et al. [111] considered five capacity alternatives for a new pumped-storage facility in southern Norway that practices arbitrage in the German spot market with the aim to prevent fluctuations from increased wind power penetration. Investors should hold the option to postpone for approximately eight years and then invest, thus avoiding unprofitable investment. Reviewed papers on the ROA applied to HP addressed the following issues: design flexibility, upgrading capacity, and optimal investment strategy given increased short-term price volatility. Studies on large HP illustrated how the ROA can be combined with optimization models to support investment decisions, particularly in relation to arbitrage opportunities and capacity upgrading. These approaches provided valuable insights into timing and capacity choice, yet, in our view, some underlying assumptions may have strongly influenced the results. On the one hand, plants were often treated as isolated assets interacting with a single foreign market, neglecting their role within the national energy system and associated regulatory constraints. On the other hand, simplified operational assumptions and case-specific settings reduced the transferability of results to more complex or heterogeneous contexts. HP project design implies the knowledge of hydrological features and technical/economic characteristics of the plant. This highlights the need for interdisciplinary professionals to accurately assess HP projects. The assessment of energy production mainly depends on the sequence of streamflow workable by the plant during its lifetime, and the calculation of the plant capacity is strictly related to the hydraulic regime at the intake. Martínez Ceseña et al. [58] have already raised this issue, underlining that RES projects are affected by at least one internal uncertainty, i.e., the RE input, which was found to be addressed by only 5% of the reviewed papers. Overall, while the ROA has been applied to a variety of HP contexts, the current body of work remains fragmented and often technically simplified. In our view, stronger integration of hydrological variability (e.g., flow duration curve), realistic design flexibility, and system-level or regulatory considerations are needed to move beyond case-specific applications and provide more robust guidance for both investors and policymakers.

4.2. Solar Photovoltaic Projects

The RO literature dealing with solar PV energy was already reviewed in a paper by Lazo and Watts [60]. Our dataset, which focused on residential PV projects in the context of power generation, was categorized in a similar manner: PVBs, multi-phase PV investment, PV plants in buildings and building integrated PV systems, smart grids (SGs)

and prosumers, and specific factors addressed in PV evaluation (technological progress, energy price volatility, CC initiatives, weather patterns, etc.).

An important topic emerged in the last 15 years regarding the combination between BESS with PVs as they can mitigate the intermittent nature of solar energy by storing the power produced. However, the high-cost variability of BESS makes the investment decision not always straightforward. Consequently, this branch of research developed significantly. Martínez-Ceseña and Mutale [89] presented an ROA applied to an off-grid PV system design under an uncertain demand-response program. Demand-response implementation increased the lifetime of the batteries and, by considering the system's components as ROs, thanks to the approach, it is possible to evaluate the advantages of only installing equipment when and if it was required. Among the applications of the ROA to solely BESS, Locatelli et al. [112] provided a monetary quantification of the investors' risks and flexibility during the IDM process through the implementation of three options: (i) to defer the investment until a reduction in capital costs occurs; (ii) to build immediately; (iii) and to wait to build after a detailed design is provided. They showed that, in the presence of investment uncertainty, the ROA evaluated more positively the profitability of a project compared to what was obtained with a classic discounted cash flow analysis. Therefore, Kelly and Leahy [105] applied the ROA to determine the optimal investment time and BESS capacity size (MWh) from the perspective of private investors by introducing scenarios of BESS CAPEX and battery degradation. Their findings indicated that BESS CAPEX impacted the BESS size and a change in BESS retention limit in year 10 may have a major impact on the project's viability. Ma et al. [106] proposed an ROA to model investments in residential PVBs calculating the values of the compound option to expand and to defer. Delaying the PVB investment/expansion and considering interactions between the ROs increased the project value and mitigated the risk of financial losses. Andreolli et al. [104] investigated households' decision to invest in a PVB system implementing the ROA and an optimization model. In the case of battery adoption, they showed an increased value of the project given by managerial flexibility. They found a positive relationship between the optimal PVB size and investment timing: the investment deferral increases as the plant size increases. Hassi et al. [107] modeled the flexibility of staged investment in a domestic PVB system through a compound RO with the possibility of upscaling the components' capacities. They showed a tendency to invest in maximum PV power capacity and minimum storage capacity, and staged investment was found optimal in 36% of future scenarios. Further, using a compound RO, Li and Cao [108] investigated the optimal investment decisions of PVB projects in China under different incentive mechanisms and multiple sources of uncertainty. They showed that the subsidy on the energy price favored the investment, speeding it up by 2 years compared to the non-incentive situation. Studies on PV-BESS consistently show that flexibility from storage adds value: compound option frameworks have indicated that deferral and staged expansion can boost project value versus static NPV, and households revealed a tendency to invest in large PV size and to postpone when volatility and CAPEX uncertainty are high. In our view, however, these results were highly sensitive to modeling choices. BESS costs, which strongly affected model results, widely varied across studies (e.g., 210 EUR/kWh, 2000 Yuan/kWh, 392.86 USD/kWh, from 2168 USD/kWh to 1369 USD/kWh, etc.). Battery degradation was usually simplified (e.g., 80% energy capacity retention at 10 years) or not included in the models, so life-cycle value may have been mismeasured. Moreover, analyses lacked community use of storage that could have both improved energy production utilization and spread upfront CAPEX among community's members, which remained high for a single household. Policy design might have shifted investment timing (e.g., energy price subsidies accelerate investment). Taken together, these considerations highlighted the emerging gaps from reviewed papers

on the ROA applied to investment in PVBs: (i) lack of assessment models considering multi-users' load profiles with heterogeneous energy demand; (ii) limited research on battery degradation; (iii) need to consider future investment opportunities in battery storage (i.e., growth option) [104]; (iv) need of modelling investment decisions in PVBs at the community level, where energy sharing and grid constraints are endogenous.

Gahrooei et al. [92] analyzed the timing and sizing of residential PV systems with four different design scenarios and found the optimal staged investment strategy. Phasing the investment helps to save energy, reduce solar panel costs, and increase the return of the investment. The value of option to defer was found to depend mainly on the variations in the electricity price and the PV installation cost. In the field of staged investments, Biancardi et al. [98] included in their PV project evaluation the managerial flexibility of changing investment size (i.e., to switch scale) in the operating phase and, through a compound option, investment timing in the planning phase. They found that managerial flexibility makes investment attractive and profitable. In the context of building integrated photovoltaic (BIPV) systems, Kim et al. [94] developed an ROA to value BIPV systems under different scenarios of electricity price uncertainty. They identified the optimal investment timing and size for integrating PV modules into apartment complexes in South Korea considering available south facade, roof, and external wall areas. They found it optimal to waiting to invest in BIPV systems when there is high uncertainty on the future price of electricity. Penizzotto et al. [96] proposed an IDM tool for a rooftop PV system in a government building in Argentina. They compared results between the ROA and a conventional approach, finding that the decision to invest should be postponed but not abandoned, as indeed suggested by the NPV rule. Studies on residential PV and BIPV projects highlighted the importance of managerial flexibility, and showed that a phased adoption or the option to switch scale can significantly increase the project value. Case studies ranged from household systems, where the option to defer depends on the dynamics of the electricity price and the costs of panel installation, to large-scale "smart city" projects. Evidence from BIPV systems in South Korea showed that, regardless a project positive NPV, the optimal choice under price volatility was often to wait and defer investment. Rooftop PV plants in Argentina demonstrated that conventional NPV rules would recommend to abandon projects that, based on the ROA, are profitable under stochastic panels and inverter cost trajectories. In our view, these studies highlight the value of the ROA in capturing investment timing and scale flexibility in PV deployment, but their insights remain constrained by narrow settings and simplified assumptions. Household and rooftop applications were typically modeled for single buildings, smart city scenarios grounded in hypothetical scaling factors, and BIPV valuations often hinged on local guarantees or a single source of uncertainty, such as uncertainty in the electricity price. While these designs demonstrate the methodological richness of the ROA when applied to residential PV investments, the omission of factors such as module degradation, specific regulatory settings, and cross-building interactions limits the robustness and transferability of their conclusions to broader market and policy contexts.

The unidirectional provider–consumer model has been transforming into a bidirectional energy and information model [18], shifting from a centralized to a decentralized and polycentric system. SGs and microgrids have supported this transformation, providing two-way electric communication in both large- and small-scale power supply networks [100,125]. In this context, the role of end-users changes from passive to active, and consumers turn into prosumers, assuming control over electricity production/consumption and acting as energy market players [126]. With the introduction of the concept of RECs in the European directives, users can directly exchange energy quotas via peer-to-peer (P2P) energy trading, increasing investment profitability by generating revenues from excess energy [126]. In this

context, citizens play a larger role than just being energy consumers, determining the type and quantity of energy produced with community participation in energy projects [27]. Bertolini et al. [100] addressed prosumers' investment decisions in an SG-integrated PV plant implementing the ROA. They considered and priced the managerial flexibility arising from the connection to an SG, which provides the option to switch from prosumption to production at any point in time. Their findings showed that flexibility increases the investment value, and there is a positive relationship between the optimal investment size and timing. D'Alpaos and Moretto [101] investigated whether SG-integrated PV plants affected real estate market values in Italy. They showed a 5–10% increase in PV investments value due to the connection to an SG, which increases as both energy savings and flexibility increase. In addition, they proved that the greater the flexibility, the greater the property market value. Castellini et al. [102] modeled prosumers' decisions to invest in an SG-integrated PV plant considering the exchange of energy among prosumers. They found that the flexibility to exchange energy increased the plant's investment value, with a positive relation between the investment optimal size and timing. Exchange-oriented agents (their aim is to reduce energy costs and not to sell energy) invest in larger plants compared to non-exchange-oriented agents. Castellini et al. [103] extended the previous work, introducing four energy trading scenarios with different prosumers' profiles and several combinations of their individual energy demand and supply. They demonstrated that there are situations in which there is no energy exchange between prosumers, and it depends significantly on individuals' energy demand and supply curves. In particular, the maximum benefit existed when there is excess demand between the two prosumers, and their profiles displayed complementary and asymmetric demand and generation curves. A critical review by Schachter and Mancarella [59] on the ROA for valuing the flexibility of investments in SGs and low carbon energy systems highlighted the need to include in the model fundamental features of energy systems (e.g., multiple uncertainty and interacting options, cash-flow volatility, flexibility in design for future growth options). Studies on SGs and prosumers have highlighted how the ROA can capture the additional value generated by managerial flexibility. In our view, these contributions show that flexibility, if optimally exercised generally leads to larger plant size and earlier investments, but they also rely on stylized settings: exchange scenarios were often limited to pairs of prosumers, and results hinged on complementary demand, while broader community frameworks remained underexplored. As noted in the critical review by Schachter and Mancarella [59], modeling multiple uncertainties, interacting options, and realistic participation levels are essential to move beyond illustrative case studies and provide transferable insights for policy design and planning. Therefore, in this field of research, we identified three main gaps: (i) need for considering SG-integrated PV systems in a community framework (realistic number of prosumers participating in the market [60]); (ii) lack of SG studies in other EU or non-EU countries; and (iii) lack of estimated supply and demand curves that consider non-domestic energy profiles and complementarity between different technologies.

In the present review, we created a category of papers addressing specific factors affecting PV investment valuation. Technological improvement is an important factor since it generates reductions in the technology cost based on learning curves. Martínez-Ceseña et al. [90] implemented an ROA for the assessment of domestic PV systems considering the expected evolution of PV technologies. The results showed that the deferral option depends mainly on the time value of money, the type of loan, and forecasts of PV panel costs and efficiency increasing the project's value in most scenarios. Biondi and Moretto [91] investigated the impact of energy prices and the volatility of PV modules' cost on PV investment timing in Italy, by calibrating a standard grid-parity model. They estimated the dynamics of the Levelized Cost of Energy (LCOE) following a learning curve approach.

They predicted that grid parity would be reached in 2015 from the perspective of a private investor. The results of this model were far-sighted, given that grid parity was achieved in 2018 in the entire Italian peninsula, and was achieved in 2014 in the sunniest regions. Volatility of PV costs was also investigated in Moon and Baran [95] for the United States, Germany, Japan, and Korea. Using an ROA, they showed that investors exercise the option to invest at a lower cost in case of increasing volatility. Zhang et al.'s [93] filled the knowledge gap on ROA studies considering different incentives and carbon emission trading schemes. They proposed a model to evaluate investments in PV projects in China in the presence of carbon emission trading schemes and multiple sources of uncertainty, i.e., CO₂ price, NRE cost, RE investment cost, and electricity prices. They showed that these schemes accelerate investments by increasing their value, while volatility of electricity price, CO₂ price, and investment costs induce to postpone investments. Studies that isolate influential factors confirmed that the option value to defer and the optimal timing in PV investments depend strongly on financing and forecast assumptions (e.g., UK feed-in tariff settings, average demand, and insolation profiles). Indeed, the uncertainty on the PV module price and cost delays investments. Cross-country analyses [91,93,95] show that it is worth waiting to invest 5.8–11 years compared to invest immediately according to the NPV rule. Policy and carbon schemes can push investment forward, contrary to high volatility in electricity prices, CO₂ prices, and investment costs. In our view, these insights are valuable but still limited by assumptions such as fixed tariff schemes, simplified demand profiles, stylized cost decline paths, or policy settings limited to one national context, reducing the extent to which results can be transferred to broader market and policy frameworks.

As highlighted in Section 4.1, RE projects are affected by climate/weather patterns, which are an internal source of uncertainty. Di Bari [97] proposed an ROA to model investment decisions in PV projects in different Italian regions using Photovoltaic Geographical Information System tools [127] to address the issue of solar radiation and PV performance in different locations in the country. They also considered in the modeling the estimated system losses due to degradation as well as public incentives. Using data on actual monthly energy production, Or et al. [99] studied investments in rooftop PV systems in Turkey, analyzing differences between results obtained via conventional NPV models and the ROA when multiple sources of uncertainty are present. In our view, these contributions highlight the importance of resource variability, yet they remain isolated efforts; most ROA models still neglect interannual fluctuations of RE inputs, limiting their realism. Since our review showed limited research on ROA models that include the variability of climate/weather patterns (e.g., interannual variability of the RES), the development of this branch of research could represent an interesting future direction. Overall, applying the ROA to PV projects has demonstrated its ability to capture the value of investment timing, sizing, and policy-driven flexibilities across a variety of contexts, from domestic PV-BESS to prosumer-oriented SGs. Yet most contributions rely on fragmented cost assumptions, narrow case studies, or stylized tariff and panel or battery degradation models, which weakens the robustness and comparability of results. Future research should therefore advance towards community-scale modeling, more consistent treatment of technology and cost dynamics, and the explicit inclusion of climate variability and policy interactions to provide more transferable insights for investors and decision-makers.

4.3. Technology Mix

The assessment of energy technology alternatives can be relevant at different spatial scales since it regards energy security at the country/regional level, and locally it avoids demand-supply mismatches. Twelve of the final selected papers considered more than one

technology in the context of the ROA applied to power generation. We divided technology mix studies into two categories: mixes with NRE and mixes with RE only.

The operational flexibility of an HP operator to add NRE thermal power to their production was discussed by Kjærland and Larsen [79]. They analyzed the option to switch from HP production to energy production from separate thermal plants, which can be switched on and off easily. They showed that the option has a positive value when the thermal power plant is managed directly by an HP operator. Detert and Kotani [80] evaluated the attractiveness of switching from coal to RES in Mongolia, applying different scenarios for electricity prices and externalities associated to energy production. Their findings suggested that the use of coal-based infrastructures results in significant welfare losses. Rohlfs and Madlener [81] assessed optimal investment strategies in power generation assets including the probability of investing in a specific technology and its risk related to different commodity price variations (e.g., price of electricity, fuel and CO₂ allowances). Their findings showed that waiting reduces potential losses, and they obtained more robust results via the ROA compared to those obtained according to the traditional NPV rule. They also investigated the market conditions (CO₂ and electricity prices) needed for the deployment of carbon capture and storage technologies in Germany. Similarly, Zhang et al. [82] applied the ROA to find optimal investment portfolio strategies for a single power enterprise in China considering coal, gas, wind, PV, and biomass power plants. They found that boosting the share of wind and PV power, with solar power having a greater impact, produced high expected investment values and reduced risks. Finally, they showed that high risk is associated with large investment values, and this is a relationship that investors should consider in their investment decisions.

Among the selected articles involving multiple energy sources, eight studies considered exclusively RES. Siddiqui and Fleten [83] developed an ROA framework to model a firm's staged commercialization of alternative energy technologies, i.e., a new unconventional energy technology (UET) vs. a smaller-scale existing RE technology. They found that commercialization and deployment of UETs are highly valuable. They concluded that the firm's investment strategy must consider how the UET and the RE technology interact: RE technology increases the value of staged commercialization, nonetheless it delays the start of UET commercialization.

The growth of RE power plants inclusion in the power system will increase volatility and uncertainty of power generation, causing both under-supply and over-production of energy. Solutions that enable energy storage are required for both large-scale RE plants and individual households or communities in the presence of self-consumption systems. Moreover, storage via HP storage plants increases expected profits, because thanks to their adoption, energy can be sold in the market when its price is high [109]. Reuter et al. [84] addressed this issue by combining pumped-storage plants with a wind farm and considering the uncertainty on electricity prices and wind production in Germany and Norway. Based on their results, a tradeoff emerged between an increase in profits obtainable by selling at the peak price, but they found that this hybrid technology was unprofitable due to the high investment costs of the facility, which require substantial public support. A ringwall hydro storage system with wind and PV plants, namely a ringwall storage hybrid power plant (RSHPP) was considered by Weibel and Madlener [86]. They applied the ROA to model the optimal investment timing, sizing, and siting of an RSHPP by varying storage volume and considering the stochasticity of wind and solar power, investment costs, and electricity prices. Their results showed that, given the high investment costs and the relatively low present value of future cash flows, the construction of an RSHPP was extremely unprofitable without a government intervention. In our view, the above mentioned contributions were valuable investigating large-scale HRES investments, from

staged commercialization of new technologies to profit stabilization through wind–hydro storage and innovative technology mixes such as RSHPPs. Yet the results remain highly context-dependent. In the case of wind and HP power generation, profitability would require unrealistically high price premiums or subsidies, covering 35–90% of capital costs. Specifically, for RSHPPs, investment needs were estimated at around EUR 40 billion and even flexible RO scenarios still yielded negative NPVs, indicating that expected benefits fall short of costs. These findings suggest that, without substantial public support or drastic cost reductions, deployment of such technologies is unlikely. Furthermore, most models neglected key aspects such as grid integration, economies of scale, and system-level interactions, making the quantified option value strongly case-specific and difficult to generalize to broader RES deployment strategies. The sole ROA study in our dataset discussing RE complementarity was that of Passos et al. [85]. They proposed an ROA framework to evaluate the option to invest in complementary RES, such as SHP plants (RoR) and wind farms intended to meet a fixed consumer demand of 1 MW (avg) in Brazil. According to their findings, there was an option value to invest in complementary RES projects, and this value increased when spot-price fluctuations were high. Three of the selected papers applied the ROA to compare investments in two RES technologies. Mancini et al. [87] evaluated investments in PV and wind power plants to investigate which was the more profitable technology in terms of future cash flows under uncertain energy production and subsidy amount. The produced energy was identified as the most important variable affecting the model's results. Wind power generation was boosted by incentives and was more profitable, even if PV power generation remained a good alternative together with the combination of both technologies. Gazheli and Van Den Bergh [40] modeled a community and/or firm diversification strategy across two RES investments: PV and wind power generation plants. They investigated different scenarios of learning curves, production costs, and electricity prices. Their major finding suggested that, while investing in both PV and wind power can be profitable, it is not always the optimal strategy under price and cost uncertainty. This counterintuitive result was mainly due to their specific modeling of uncertainty. Li et al. [88] proposed a similar model applied to PV and HP plants and reached the same conclusions. Across these contributions, the ROA was applied to evaluate complementarities and diversification among renewable technologies, such as combinations of wind and SHP power generation and PV and wind power generation under incentives, and diversification strategies between PV and wind power or between PV and HP under cost and learning curves uncertainty. The complementarities of RES were assessed in highly stylized settings and rarely grounded in detailed local data. In our view, capturing the real feasibility of multi-technology investments requires models that integrate location-specific variability and demand profiles, and include supply and demand dynamics and broader socio-economic or policy drivers. These limitations once again underline the relevance of internal uncertainty and the need to incorporate interactions between RES that account for user and sectoral diversity in decentralized systems, and integrate environmental and geopolitical factors into multi-technology investment assessments. One major objective of the present review is to delineate the state of the art of the ROA applied to multiple RES technologies suitable for applications at a community level, at small-scale contexts, or in off-grid systems. Among the selected publications, papers including NRE were related to the attractiveness of switching to RE and optimal investment strategies in different power generation assets; therefore, the following discussion regards emerging gaps solely in RE project papers. Possible future directions in the ROA framework include: (i) modeling the effects of the interaction between different RES in power production to address the issue of RES variability and intermittence and achieve a realistic feasibility of investing in multiple technologies; (ii) considering the dynamics of energy supply and demand

accounting for the diversity in user typologies and economic sectors; (iii) identifying the major factors affecting investments in multiple energy technologies (e.g., environmental and socio-economic factors, technological changes, and geopolitical and historical issues). Overall, the application of the ROA to technology mixes shows its potential in evaluating complementarities, diversification, and switching strategies across RE and NRE options. These contributions underline how technology mixes can create value; however, these models were often developed in stylized settings, with simplifying cost assumptions, simplified uncertainty processes, and poor adherence to real local demand or system integration. As a result, the quantified investments value remains highly context-specific and difficult to generalize. Advancing this research requires models that incorporate interactions among RES to capture RES variability, explicitly link investment outcomes to heterogeneous demand and decentralized energy use, and broaden the analysis to include environmental, socio-economic, and geopolitical drivers for the adoption of technology mixes.

4.4. HRES Overview

Hybrid RE systems have spread in both off-grid remote areas and urban regions to tackle the intermittent nature of variable energy resources. A wide body of literature has dedicated attention to this type of energy systems, and a consistent number of reviews have addressed specific topics on their application. The main reviewed issues deal with: (i) optimal sizing [128,129], energy management [130], control strategies [131], and modeling of HRES components [36,132,133]; (ii) application to microgrids [134–136], stand-alone systems [35,137,138], off-grid systems [139–141], micro-communities [142], and remote areas [143]; (iii) combination of specific technologies (e.g., PV and wind) [144–149]; and (iv) software tools for the design, optimization, and analysis, of economic viability of HRES [150,151]. In this context, Kozlova [39] highlighted a lack of literature on the ROA applied to HRES, indicating it as a potential topic for future research. After Kozlova [39], few papers attempted to fill the gap identified above (cfr. Section 4.3). Despite these recent efforts, we argue that more studies are still needed to address two key issues: first, how different RE technologies can be combined in a comprehensive energy system, and second, how to properly tackle the emerging gaps identified in the present review.

4.5. Practical Implications for Investors and Planners

The evidence from our review also suggests several practical implications for different stakeholders. From an investor perspective, the profitability of investments in RES often remains dubious without targeted incentives. As demonstrated by Biondi and Moretto [91] for PV plants in Italy, uncertainty in electricity prices and module costs induces investors to postpone investments although grid parity appeared close. Similarly, Or et al. [99] identify high upfront costs as a primary barrier for investments in residential PVs in Turkey and show, through policy scenarios aligned with past and ongoing incentive schemes, that reducing initial outlays (e.g., via low-interest loans) can make investments attractive for a wide range of households. Moreover, with current tariff and metering schemes, a large share of electricity produced by residential PV systems is exported to the grid [102]. This highlights the importance of policies that increase the value of self-consumed energy, for instance by supporting efficiency improvements, encouraging storage adoption, and enabling peer-to-peer exchanges within community schemes [101,103]. In PVB projects, managerial flexibility (to defer, scale, or stage) increases project value. However, sudden increases in investment costs or battery degradation can make these projects not profitable if adequate support mechanisms are not in place [104]. Overall, RO studies help investors to decide whether and when it is optimal to invest, and how to scale capacity or invest sequentially,

by quantifying threshold conditions under price/cost uncertainty and incentive schemes, and, consequently, providing actionable investment rules. In the context of community-led energy planning, especially within an REC framework, the ROA can support portfolio allocation across HP, PV, and hybrid power generation projects by valuing RES complementarities (e.g., hydro storage can buffer PV intermittency). Passos et al. [85] show that complementary RES projects (e.g., SHP plants combined with wind power plants) can reduce investments risks and provide cheaper energy if regulatory mechanisms allow such combinations to compete fairly in electricity markets. Their framework illustrates how institutional reforms, such as enabling technology-mix projects to participate in auctions otherwise restricted to single technologies, can stimulate less risky investments and provide a wealth of benefits to final consumers. In the context of RECs, the ROA can also capture properly the value of peer-to-peer trading and prosumers' participation. Castellini et al. [103] highlight that modeling entry, exit, and re-entry options into a REC can clarify contractual and regulatory implications for sustaining collective investment schemes. Empirical applications to single technologies further show that SG can increase the value of investments in domestic PV plants by 5–10%, reinforcing the role of prosumers and collective initiatives [101].

In the context of risk-mitigation and regional planning, the ROA offers a transparent framework to account for policy and climatic variability, infrastructure constraints, and regulatory risks. The profitability of RES varies significantly across spatial scales: differences in irradiation between Northern and Southern Europe, as well as zonal electricity price disparities, generate heterogeneous adoption thresholds and call for geographically differentiated support schemes. In some cases, access to the grid has delayed investment decisions, as observed in SHP licensing in Norway [114]. The grid itself becomes part of the risk-mitigation framework: the growing penetration of distributed generation increases balancing costs, congestion costs, and risks of service disruption, making grid reinforcement and optimization necessary in parallel with RES deployment (as demonstrated by recent events such as during April 2025 blackout in Spain). Particularly for HP projects (RoR, storage, and pumped storage), ROs are relevant because authorizations/concessions contracts and water-use conflicts (e.g., irrigation, electricity generation, and domestic water supply) directly influence investment timing and sizing. Linnerud and Simonsen [114] show that, in the absence of adequate incentive schemes, small investors tend to ignore the ROs embedded in investment projects and make their decisions as if the investment opportunities were lost if not undertaken immediately. Instead, Norwegian RoR plants' licenses grant the right, but not the obligation, to build within 10 years, effectively creating an American option. Moreover, studies on pumped-storage projects further illustrate how transmission constraints affect the option to invest [110,111]. The ROA enables regional planners and policy makers to integrate spatial heterogeneity and regulatory frameworks into investment valuation models. Embedding such system-level considerations into RO studies ensures that RES deployment strategies remain resilient to uncertainty and adaptable to local conditions.

Since papers on CC adaptation strategies were excluded by design from this review, explicit adaptation pathways are absent from the 38 studies. Few papers incorporate climate uncertainty in their valuation models—for example, meteorological or geographical variability [97] or CO₂ price [93]. For completeness, outside our dataset, several studies on large-scale HP plants have already combined the ROA with climate projections. Kim et al. [152] modeled future CC scenarios using representative concentration pathways to assess investments in HP plants in Korea; Gaudard [153] evaluated pumped-storage investments using global and regional climate models coupled together; and Swanson et al. [154,155] applied climate pathways generated by the Integrated Global System Model

to the Batoka Gorge project on the Zambezi, and compared ROA results with results obtained via alternative evaluation methods. These works show how climate scenarios can be integrated into the ROA to inform long-term adaptation strategies in the HP sector.

In summary, for both investors and policy makers, the findings discussed above imply that (i) incentive schemes should be calibrated on the volatility of up-front costs and revenues; (ii) regional planning should incorporate heterogeneity in resource availability, electricity prices, and grid capacity; and (iii) authorization and concession provisions that preserve managerial flexibility (options to defer, scale, or switch) reduce regulatory and grid-related risks, thereby enabling more resilient community-level and asset portfolio strategies. Taken together, these findings indicate that the ROA not only advances academic modeling but also offers concrete insights for individual investors, communities, and public authorities.

5. Conclusions

Recently, the literature on energy economics has grown significantly because of the increased relevance of energy and environmental-related issues. This review demonstrates that the ROA represents an effective and emerging technique for assessing investments in the RES sector. The global energy crisis, evolving policies addressing emission cuts, and unpredictability in weather and climate conditions make this technique a precious tool for incorporating uncertainty and flexibility into RES investment decision-making processes. We performed a systematic literature review of publications that appeared in international peer-reviewed journals in the Scopus database, selecting and analyzing a final set of 38 papers. This study provided an overview of the application of the ROA to the valuation of investments in HP, PV, and multiple energy technologies in the field of power generation appraisal. Results showed that Europe and China are leading the observed growth in this research area, in line with their policy efforts to foster the energy transition and reduce carbon emissions. From a technology perspective, HP and technological mixes have received less attention than PV, which have been widely analyzed in recent years (with more than 50 papers published in the period 2019–2023 [60]). Despite the central role of HP in RES production, only a few articles (six in total) covered the application of the ROA to investments in RES. Evidence of this is given by a dedicated Scopus query (“real option” AND “hydropower” OR “hydropower plant” OR “small hydropower” OR “small hydropower plant” OR “small hydro” OR “run-of-the-river hydropower”), which returned 36 hits in February 2024 (without filtering). The main subjects addressed in these papers were operational flexibility, climate change adaptation, risk hedging strategies, and policy evaluation, while only a limited number of contributions dealt directly with power generation and projects assessment. This imbalance explained the greater representation of PV systems in our dataset and conditioned the analysis of hybrid systems. Future reviews should therefore extend the scope to integrate studies on HP to improve the generalizability of results more systematically. The selected publications addressed a huge variety of IDM problems, mainly related to multiple sources of uncertainty, public incentives, and specific technological features. We examined the identified RO and their valuation approach, and the related sources of uncertainty. From a statistical perspective, ROs are typically evaluated using DP and simulations. Likewise, energy price and investment costs are recurrent sources of uncertainty addressed mainly through the estimation of GBM processes and simulations. We found that only 5% of the reviewed papers included the variability of RES input, even though this variability represents a major inner uncertainty affecting RES projects (e.g., solar irradiation in PV plants or streamflow in RoR plants). This neglect of resource variability reduces the robustness of current ROA assessment implementation. Explicitly accounting for such uncertainty should be considered a priority for future

methodological developments. Moreover, future research should integrate climate-related uncertainty and long-term adaptation strategies into the ROA, so that investment evaluation can better capture the resilience of projects. We explicitly acknowledge the limited treatment of design flexibility as a methodological restriction of this review, since most of the examined studies do not provide detailed engineering data or optimization algorithms. Future research should therefore develop multidisciplinary models that integrate economic evaluation with engineering design techniques to account more realistically for operating conditions and support more dynamic and resilient investment decisions. Likewise, the socio-community dimension was largely absent: factors such as user participation, institutional trust, collaborative preferences, and local governance were rarely addressed in the reviewed literature. Future research should therefore incorporate participatory approaches or multi-actor frameworks to capture the behavior of energy communities better. We also performed a qualitative analysis of each selected technology to assess current findings and emerging gaps in the ROA literature. This allowed us to identify a set of relevant future research directions in the context of the energy transition, which include the development of models for investments in: i) SHP plants with flexible design; (ii) PVB projects and SG-integrated PV systems in a community framework; and (iii) HRES projects incorporating the interaction between RES inputs. Hybrid systems were also analyzed as they proved to be essential to accelerate the energy transition process. They offer an attractive way to enhance the efficiency, stability, and reliability of the energy supply, especially in isolated and off-grid areas, while reducing grid instability [156]. The integration of these systems requires a revision of policy and regulation regarding the utilization of multiple resources (e.g., determining how concessions should be managed for the use of water for hydroelectric purposes when the plant is integrated into a hybrid system serving a local energy market). Moreover, since natural resource availability is strictly site-specific, the design and management of HRES are heterogeneous and could be challenging at times. Finally, we argue that, from an economic perspective, the ROA is the most effective method for assessing the viability of HRES, as it incorporates energy systems' uncertainty and flexibility into a coherent mathematical and economic framework.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/en18205535/s1>, PRISMA flow diagram: PRISMA_2020_flow_diagram.docx; PRISMA checklist: PRISMA_2020_checklist.docx; PRISMA abstract checklist: PRISMA_2020_abstract_checklist.docx.

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Abbreviations

The following abbreviations are used in this manuscript:

ROA	Real option approach
GHG	Greenhouse gas
EU	European Union

CC	Climate change
CEP	Clean Energy Package
CECs	Citizen energy communities
RECs	Renewable energy communities
RES	Renewable energy sources
RE	Renewable energy
HRES	Hybrid renewable energy systems
RO	Real option
R&D	research and development
PV	Photovoltaic
HP	Hydropower
SHP	Small hydropower
DP	Dynamic programming
O&M	Operation and maintenance
NRE	Non-renewable energy
GBM	Geometric Brownian motion
RoR	Run-of-river
NPV	Net Present Value
CER	Certified emission reductions
IDM	Investment Decision-Making
BESS	Battery energy storage systems
SGs	Smart grids
CAPEX	Capital expenditure
PVB	PV battery
BIPV	Building integrated photovoltaic
P2P	Peer-to-peer
LCOE	Levelized Cost of Energy
UET	Unconventional energy technology
RSHP	Ringwall storage hybrid power plant

Appendix A

Table A1. Summary table of the 38 reviewed papers in chronological order and classified according to different energy source(s) (hydro, solar, mix of energy sources).

Energy Source(s)	Authors and Ref.	Year	Power Generation Technology	Country	Option	Valuation Approach	Source of Uncertainty
HYDRO	Bockman et al. [113]	2008	SHP plants	Norway	To defer	DP	Electricity price
	Martínez-Ceseña and Mutale [109]	2011	Storage HP plants	Other	To defer	Decision tree	Electricity price
	Andersson et al. [110]	2014	Storage HP plants	Norway	To expand	DP	Electricity price
	Fertig et al. [111]	2014	Pumped-storage HP plants	Germany Norway	To defer	Simulations	Electricity price
	Linnerud and Simonsen [114]	2014	SHP plants	Norway	To defer	Simulations	Electricity price, policy (subsidies)
	Locatelli et al. [112]	2016	Pumped-storage HP plants	UK	Time-to-build	Simulations	Capital cost
	Kim et al. [115]	2017	SHP plants	Indonesia	Compound option (to fund/abandon)	Decision tree	O&M cost, energy production, tariff, CER price

Table A1. Cont.

Energy Source(s)	Authors and Ref.	Year	Power Generation Technology	Country	Option	Valuation Approach	Source of Uncertainty
SOLAR	Martínez-Ceseña and Mutale [89]	2011	Off-grid PV plants	UK	Time-to-build	Decision tree	Consumer demand
	Martínez-Ceseña et al. [90]	2013	Domestic PV plants	UK	To defer	Others	PV efficiency, PV cost
	Biondi and Moretto [91]	2015	Domestic PV plants	Italy	To defer	DP	Electricity price, PV costs
	Gahrooei et al. [92]	2016	Domestic PV plants	US	To defer	DP	Building energy demand, electricity price
	Zhang et al. [157]	2016	Domestic PV plants	China	To defer	DP	CO ₂ price, NRE cost, RE investment cost, electricity price
	Kim et al. [94]	2017	Domestic PV plants	South Korea	To defer	Decision tree	Electricity price
	Bertolini et al. [100]	2018	Domestic PV plants	Italy	To defer To switch	DP	Electricity price (selling)
	Moon and Baran [95]	2018	Domestic PV plants	US, Germany, Japan, and Korea	To defer	DP	PV Cost
	D'Alpaos and Moretto [101]	2019	Domestic PV plants	Italy	To switch To defer	Simulations	Electricity price (selling)
	Penizzotto et al. [96]	2019	Domestic PV plants	Argentina	To defer	Simulations	Electricity price, PV cost
	Di Bari [97]	2020	Domestic PV plants	Italy	To defer	Decision tree	Electricity price
	Kelly and Leahy [105]	2020	Not specified	Ireland	To defer	Simulations	Electricity price, future BESS CAPEX and degradation
	Ma et al. [106]	2020	Domestic PVBs	Australia	Compound option (to defer/expand)	Simulations	Peak power demand, diesel price and generator cost, PV-battery cost
	Castellini et al. [102]	2021	Domestic PV plants	Italy	To defer	DP	Electricity price (selling)
	Castellini et al. [103]	2021	Domestic PV plants	Italy	To defer	DP	Electricity price (selling)
	Andreolli et al. [104]	2022	Domestic PVBs	Italy	To defer	DP	Electricity price
	Hassi et al. [107]	2022	Domestic PVBs	Chile	Compound option (To defer/expand)	Simulations	Electricity price, PV and battery cost
	Li and Cao [108]	2022	Domestic PVBs	China	Compound option (to de-lay/abandon and defer/expand)	DP	Electricity price, CO ₂ price
	Biancardi et al. [98]	2023	Domestic/utility-scale PV plants	Italy	Compound option (to switch size)	Simulations	Electricity price
	Or et al. [99]	2024	Domestic PV plants	Turkey	To defer	Simulations	PV and inverter costs, electricity tariff and distribution price

Table A1. Cont.

Energy Source(s)	Authors and Ref.	Year	Power Generation Technology	Country	Option	Valuation Approach	Source of Uncertainty
MIX	Siddiqui and Fleten [83]	2010	UET and RE	Other	To deploy, to invest, to switch	DP	Electricity price, UET operating cost
	Kjærland and Larsen [79]	2010	Storage HP and thermal power plants	Norway	To switch	DP	Reservoir level
	Reuter et al. [84]	2012	Wind power and pumped-storage HP plants	Germany and Norway	To defer	DP	Electricity price, energy production
	Detert and Kotani [80]	2013	Coal-fired, wind, and solar thermal power plants	Mongolia	To switch	DP	Fuel price
	Passos et al. [85]	2014	Wind power and SHP plants	Brazil	To defer	Simulations	Electricity price
	Rohlfes and Madlener [81]	2014	Coal-fired, wind, and gas-fired power plants	Germany	To defer	Decision tree	Electricity, coal, natural gas prices
	Weibel and Madlener [86]	2015	Pumped-storage HP plant, wind power and PV plants (ringwall storage hybrid power plant)	Germany	To defer	Decision tree	Wind intensity and solar irradiation, electricity price
	Mancini et al. [87]	2016	Wind power and PV power plants	Italy	To abandon	Decision tree	Energy production, market
	Gazheli and Van Den Bergh [40]	2018	Wind power and PV plants	Other	To defer	DP	Electricity price, wind and PV costs
	Li et al. [88]	2019	Storage HP and PV plants	Other	To defer	DP	Electricity price, wind and hydro costs
	Zhang et al. [82]	2022	Coal-fired, gas-fired, wind power, PV, and biomass plants	China	To defer	DP	Electricity, fuel, carbon prices, RE certificates, wind and PV costs

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