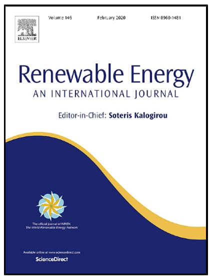

Valuation of defer and relocation options in photovoltaic generation investments by a stochastic simulation-based method

Rolando Pringles, Fernando Olsina, Franco Penizzotto

PII: S0960-1481(19)31775-6
DOI: https://doi.org/10.1016/j.renene.2019.11.082
Reference: RENE 12630

To appear in: *Renewable Energy*

Received Date: 30 April 2019
Accepted Date: 15 November 2019

Valuation of defer and relocation options in photovoltaic generation investments by a stochastic simulation-based method

Rolando Pringles[a,b,*], Fernando Olsina[a,b], Franco Penizzotto[a,b]

[a]National Scientific and Technical Research Council (CONICET)

[b]Institute of Electrical Energy (IEE), CONICET-National University of San Juan (UNSJ),

Av. Lib. Gral. San Martín 1109(O) J5400ARL San Juan, Argentina

* Corresponding author.

Tel.: +54-264-4226444 / Fax: +54-264-4210299/ E-Mail: rpringles@iee-unsjconicet.org

Abstract

Risk management is crucial when committing investments in electricity markets. Investment projects for the generation of electricity are capital-intensive, in large part irreversible and future performance is subject to high uncertainty. Fortunately, most power generation projects have strategic flexibility for handling uncertainty and for mitigating risks under unfavorable scenarios. Modern corporate finance recognizes Real Option analysis (ROA) as the correct way to value investment projects with these characteristics. Due to both, environmental concerns and escalation of fuel prices, electricity generation from renewable sources has grown dramatically worldwide over the last decade. Renewable investment projects share many of the features mentioned. As such, option valuation methods should be applied to estimate the monetary value of flexibility in renewable energy investments. This work presents an appropriate methodology for assessing the economic value of a photovoltaic power plant under uncertainties. ROA is applied to determine the value of delaying the investment decision while waiting for better market information that would reduce acquisition costs due to progress in solar technology. The flexibility of relocating the solar facility in the future upon the appearance of a more attractive site in terms of cost, network accessibility or regulatory policies is also valued. The problem of option valuation is solved through stochastic simulation combined with recursive approximate dynamic programming techniques. The methodology developed might be used by investors for more efficient decision-making and by regulatory agencies for designing adequate support policies that encourage investment in renewable energy generation.

Keywords
Flexibility, uncertainty, irreversibility, real options, solar energy, Monte Carlo

1. Introduction

Today, the clean energy industry is one of the most dynamic sectors of economy worldwide. Many different types of support policies for the use of renewable energies sources (RES) have been established throughout the world in order to diversify the energy mix, lessen dependency on fossil fuels and reduce greenhouse gas emissions while meeting the growth in electricity consumption.

During the last 25 years, solar photovoltaic generation (PV) has evolved from small-scale off-grid applications to utility-scale power plants connected to public electricity networks. The compound growth rate of PV installed capacity in the world is about 30% in the last five years [1],[2]. By the end of 2018, the global cumulated installed PV generation capacity crossed the 500 GW milestone [2]. Nowadays, solar PV has become a mainstream generation source representing around 7% of the total installed capacity worldwide and 2.6% of the global electricity consumption [2]. By year 2040, the International Energy Agency (IEA) anticipates solar PV to be the first power source, amounting 4240 GW of cumulated capacity (29% of world generation capacity) and meeting 17% share of the global electricity demand under a sustainable development scenario [3].

Only in 2018, 102 GW of new PV power capacity were installed all over the world, exceeding the combined net capacity additions of coal, gas and nuclear together [4]. This represented a flow of about 161 billion USD in solar energy investments [5],[6]. Massive solar expenditures will continue in the next years. Over 1TW cumulated solar power capacity is expected to be reached before 2023 [4]. Building this huge solar generation infrastructure would entail roughly 1 trillion dollars in investment decisions within the next five years.

The extraordinary surge in solar investments poses a very significant question on the economic efficiency of decision rules used to allocate the massive capital resources needed for meeting these anticipated targets. In the liberalized electricity industry, investment projects in power generation are exposed to numerous uncertainties related to competition, volatility of fuel and electricity prices, technological advances, environmental issues and changing regulatory policies, among others [7]. An increase in levels of uncertainty causes greater perception of risk by agents participating in the generation business when evaluating, executing and recovering investments by traditional valuation techniques.

Classical decision rules based on discounted cash flows (DCF), such as the net present value (NPV) or the internal rate of return (IRR), are often inappropriate for assessing real investment projects which present embedded flexibility in decision-making for contingently managing uncertainties [8-9]. This is due to the fact that classical DCF-based rules do not consider the flexibility for dynamically changing investment decisions as uncertainties are resolved progressively over time. When market conditions are highly uncertain, as it is indeed the case for solar investments, projects with flexibility and options can add significant economic value and may turn investment opportunities very attractive [10].

Investment opportunities in real assets may readily be assimilated to options traded in financial markets [11]. Real Options provide the conceptual and theoretical framework for appraising strategic flexibility in real projects to dynamically revise or change investment decisions upon the arrival of new market information.

Option pricing models are used to determine the theoretical value of an option for a set of stochastic variables. Different approaches have been developed to value financial options, e.g. models based on closed-form solutions of stochastic differential equations [12], dynamic stochastic programming approaches [13] and simulation models [14].

The analytical models proposed in [12] and [13] present important limitations when applied to the evaluation of real options in power infrastructure investments, mainly because the behavior of market variables do not comply with some theoretical provisions, i.e. returns must obey a log-normal probability distribution and return volatility should remain constant over time [12],[15],[16].

Unlike analytical approaches, simulation models are flexible and adapt well to the observed behavior of variables in the electrical market. Simulation-based models are readily applicable when the value of the options depends on multiple factors, the options present both path-dependent or American-style characteristics, and the state variables follow general stochastic processes, such as jump diffusions, non-Markovian processes, etc. In addition, stochastic simulation models allow considering projects with various sequential and interacting options (compound options). A widely used stochastic simulation technique is the Monte Carlo method. Compared to other numerical approaches, the convergence rate of the sampling error is independent of the problem's dimension, which is given by the number of uncertainty sources. Moreover, valuation models based on simulation are amenable to distributed computing, allowing for important benefits in terms of computational speed and efficiency. Longstaff and Schwartz proposed an approach to pricing complex American-style financial options known as the Least Square Monte Carlo (LSM) [17]. This method is based on Monte Carlo simulation and uses least squares regression to estimate recursively at each time interval the value of the Bellman equation for the optimal exercise rule.

Over the last few years, research has increasingly focused on the application of the Real Options theory to electrical generation projects. Nevertheless, literature addressing the assessment of renewable generation projects continues to be scarce and not very systematic, and tends to neglect interactions between the various Real Options embedded in renewable projects [18].

A critical review of Real Options theory and its applications for generation projects can be found in [19-20]. In the field of renewable energy, wind generation projects stand out [21-24]. The real options commonly evaluated are deferment [21-22] and growth options [18-19]. Pricing of relocation options of renewable generation projects is an issue overlooked in the current literature. Comprehensive reviews on the state of the art of current research trends on the application of Real Options to renewable energy investments have been recently published in [25-26].

Compared to wind investments, the use of Real Options for solar PV generation projects is much more scarce [20]. Hoff *et al*. [27] were the first to illustrate the application of real options analysis to solar PV investments, implementing a simple binomial tree model. Sarkis and

Tamarkin [28] extended this approach by establishing a quadrinomial tree model. Martinez-Cesena and Mutale [29] apply a binomial tree approach to assess the value of applying demand response programs to off-grid photovoltaic systems. In a follow up work, they also evaluate investments in residential PV systems subject to uncertainty on generation efficiency, as well as uncertainty on the future development of costs of new photovoltaic modules [30].

Sarkin and Tamarkin [28] and Ashuri and Kashani [31] determine the value of real options under uncertainty on the price of electricity and the evolution of the price of PV panels. Martinez-Cesena *et al*. [30] and Weibel and Madlener [32] focus on the effect of technological impacts on the value of a project, while Gahrooei *et al.* [33] concentrate on the uncertainty of demand. Finally, Cheng *et al*. [34] analyze the value of the option to defer and the optimal investment timing for solar PV projects in China. This study demonstrates that uncertainty on electricity market reforms increases the value of the option to postpone, which causes PV energy projects to be delayed.

Assessment of energy policies is another important area of application for real options analysis in solar PV energy projects [31-34]. Several incentive policies have been discussed from feed-in tariffs (FIT) schemes [35-37] to subsidy mechanisms and public investments [38-39]. Zhang *et al.* [35] and Lin and Wesseh [37] have applied binomial tree valuation models to assess current FIT schemes in China and conclude that a correct FIT value could encourage PV investment. However, the main objective of [37] was to study the impact of externalities on the value of the option, while the work in [35] was aimed assessing FIT policy from the perspectives of both private investors and the government.

With respect to the exogenous sources of uncertainties considered in the current literature in the context of PV project valuations, we find the price of electricity [21,24,27,31], the technological uncertainty [28,33], uncertainty regarding demand growth [29,33] and uncertainty of the renewable resource [23,24]. Additional uncertainties affecting renewable generation projects are mainly associated with environmental policies, among them the price of carbon, CO_2 emissions certificates, subsidized tariffs, etc. [21,22,24,28,31,34]. In the vast majority of these works, uncertain variables are assumed to follow a simple stochastic process known as Geometric Brownian Motion (GBM).Despite the important theoretical limitations of analytical models for appraising real options previously pointed out, the current literature reflects the common misuse of binomial lattices to solve the problem of valuing flexibility embedded in PV generation projects. In addition, the value of the flexibility if the solar plant is moved to a better location upon the arrival of new information has not been acknowledged by current research.

The objective of the present work is to present a methodology for the assessment of investments in electrical energy generation based on renewable sources. More specifically, we develop a valuation framework for grid-connected solar PV generation plants, taking into account the strategic flexibility that the deferral and the relocation options provide for managing ongoing uncertainties.

The Real Options Analysis technique is applied to determine the value of delaying investment decisions while awaiting better market information and to reduce acquisition costs due to technological progress. Independently of the deferral option, we additionally consider the contingent value of moving in the future the solar plant to a more attractive site in terms of costs, grid access or regulatory policies. In order to overcome the limitations of the lattice-based valuation techniques currently employed, this paper proposes to solve the option valuation problem through the use of stochastic simulation combined with recursive approximate dynamic programming techniques. Mixed and pure Poisson jump processes are postulated for describing the stochastic dynamics of relevant uncertainties. The methodology developed may be utilized by investors for efficient decision-making and by regulatory agencies for the design of adequate support policies that encourage immediate investment in renewable generation.

The remainder of the article is organized as follows. In Section 2, the option valuation model for solar PV investments is developed. Then, in Section 3 the proposed appraising framework is applied to an exemplary solar plant project for pricing the deferment and the relocation options. The discussion and implications of the results presented in Section 4 conclude the paper.

2. Description of the valuation model

The developed assessment methodology seeks to value the economic performance of investments in solar generation in order to allow for optimal decisions to be made in scenarios of uncertainty. Below, we present the valuation model and the stochastic processes that describe the involved uncertain variables. Lastly, we describe the simulation-based valuation technique applied to solve the optimal exercise problem of the considered real options.

2.1. Economic valuation model

Firstly, we must establish the parameters of the system (capacity, energy yield, etc.), identify the project flexibilities (options) and recognize the sources of uncertainty that affect the project performance and estimate parameters of the corresponding stochastic processes. In this step we define the project's financial data, such as initial investment outlay, annual expenses, relocation expenditures, site leasing and/or acquisition costs, project lifetime, risk-adjusted discount rates, risk-free rates and option expiration dates.

The average annual energy generated by the PV plant is obtained from specific engineering programs for modelling the renewable resource (e.g. PV*SOL, PVWatts, etc.). Through the use of a technical-economic model, we simulate sample cash flows that the solar investment project could deliver for each realization of the exogenous stochastic processes. Stochastic realizations of uncertain variables are generated by Monte Carlo simulations. Subsequently, a classic appraisal of the investment project is determined by the conventional NPV method. Project's Real Options are priced by applying the Least Square Monte Carlo simulation method. Finally, the flexible NPV is calculated for the solar investment project allowing the estimation of the value of project flexibility. Decision regions and threshold values triggering decisions are determined by carrying out sensitivity analysis. The proposed conceptual framework is illustrated schematically in Figure 1.

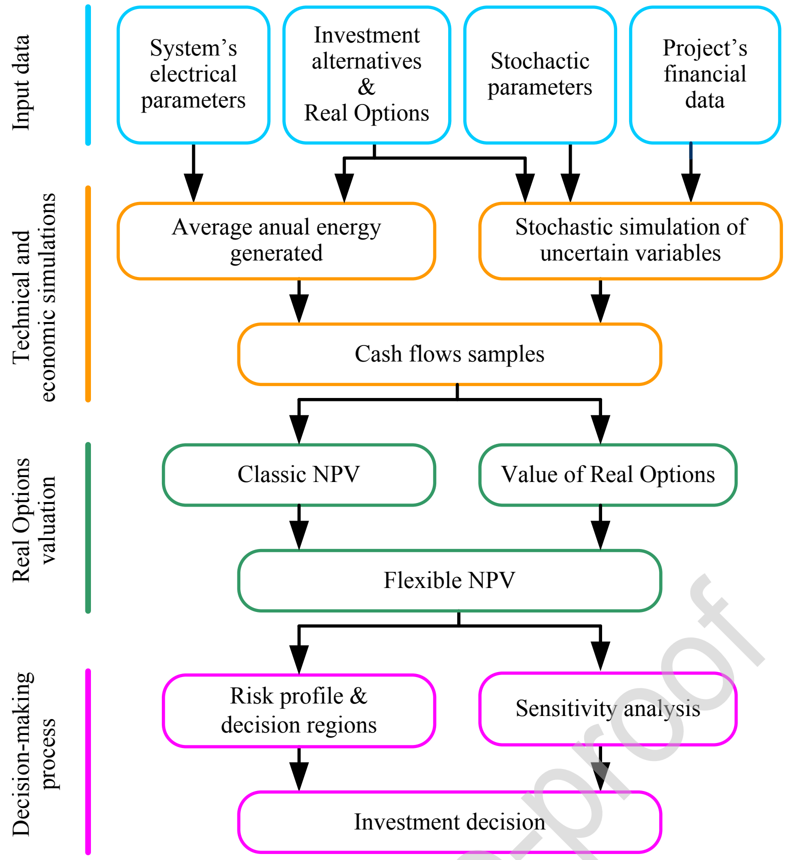

Fig. 1. Overview of the option valuation framework for PV investments

2.2. Uncertainty modeling

Future is not deterministic and as such it cannot be perfectly anticipated. Therefore, uncertainty is a key feature of reality that must be considered when assessing irreversible investments. Indeed, project returns may drastically be affected if future market conditions eventually change. The random dynamics of time-varying uncertain variables driving the project's profitability can be described by stochastic processes.

In order to keep numerical examples simple, we take into account a single source of uncertainty when assess each option. Nevertheless, the proposed methodology is flexible for accommodating multiple and simultaneous sources of uncertainty. For pricing the postponement option we only considered uncertainty on the future development of the initial capital outlay of solar projects, which itself is strongly linked to the price of inverters and PV modules. In the case of the valuation of the relocation option we are only concerned with uncertainty on the net revenue accrued by the investment project.

2.2.1. Initial investment cost

The initial cost of building the PV generation facility is directly affected by the price of photovoltaic panels and power inverters. These prices depend on the technological advances in cell manufacturing and/or on the development of new materials as well as advances in power electronics. Figure 2 illustrates the historical evolution of the combined panel [42,43] and inverter prices in USA (cf. Fig. 5 in [44] and the references therein). It can be observed that sum of panel and inverter prices have sharply declined over the last 30 years. Furthermore, at some times the combined prices depict upward and downward sudden movements or jumps.

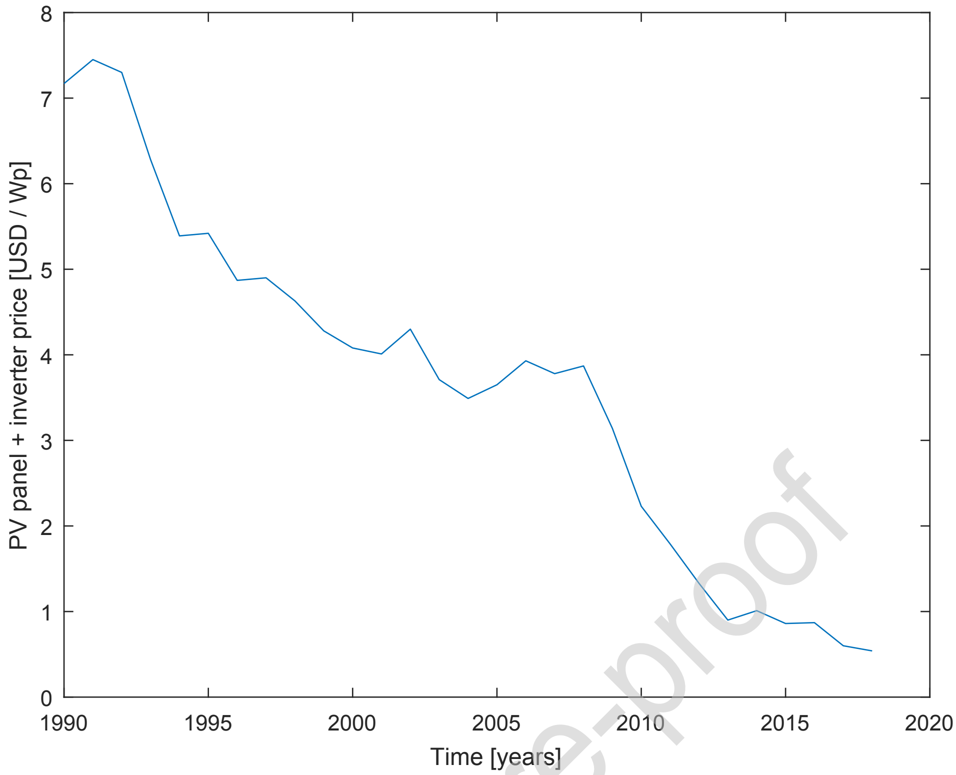

Fig 2. Historical development of the aggregate PV panel and power inverter prices

To model the uncertainty on future investment costs, a mixed stochastic model known as Geometric Brownian Motion (GBM) [45],[46] with Poisson jumps was implemented [47],[48]. The GBM movement has a negative slope or drift, stemming from a steady decline in the costs of both, the materials and the manufacturing processes of photovoltaic cells, panels and inverters. The stochastic part of the GBM process represents normal market fluctuations of panel and inverter prices. The Poisson jumps have great and sudden impact on prices, resulting from the possible discovery of a new material, a significant improvement in the production process, a change in photovoltaic technology, or the installation of a nearby PV panel manufacturing facility. Increasing cost jumps due to for instance wars, financial crisis, energy price escalations, shipping costs, taxes and other economic shocks can also happen. Negative or positive jumps occur randomly with a known mean frequency rate[1]. In the literature, hybrid stochastic models combining a GBM process with Poisson jumps have been used for modeling influence of stochastic innovations upon market prices and for describing cost development under technology progress [49],[50].

The equation that describes the stochastic dynamics of the investment cost I_t of the PV plant incurred at time t affected by uncertainty on technological progress is given by [48],[51]:

[1] If the average rate of jump arrivals is time invariant, the time elapsed between jumps events are distributed exponentially with parameter equal the mean frequency rate.

$$I_t = I_0 \exp\left[\left(\alpha + \frac{\sigma^2}{2} + \lambda_{TP}\theta\right)t + \sigma W_t\right]\cdot\prod_{j=1}^{N_t}(V_j) \qquad (1)$$

where I_0 is the investment cost at initial time $t = 0$; α and σ are the drift and volatility of the investment cost, respectively; $W_t = \varepsilon\sqrt{t}$ is a Wiener process with ε being a Gaussian random variable with average zero and variance one. N_t are Poisson processes representing technological progress with mean jump arrival rate per unit of time λ_{TP} and $\theta = E[V_j - 1]$ with $(V_j - 1)$ being the proportion of the reduction of the PV panel cost due to technological innovation j. $\prod(V_j) = 1$ when there is no jump in the interval $[0, t]$. The magnitude of the jumps V_j is normally distributed with mean μ_V and standard deviation σ_V. The jumps are independent and not correlated to the Wiener process W_t.

Parameters of the stochastic investment cost model are fitted by the maximum likelihood estimation (MLE) method based on historical PV panel and inverter prices datasets. The application of the MLE in the Itô process is discussed in [52-53], where consistency, asymptotic normality and asymptotic efficiency of the method are proven. Here, the maximum log-likelihood has numerically been computed by means of a metaheuristic optimization method called Mean-Variance Mapping Optimization (MVMO) [54]. By using the Monte Carlo method for simulating Eq. 1 with the estimated parameters, numerous samples of possible future developments of the PV investment cost can be generated. This synthetic stochastic ensemble representing the investment cost uncertainty is afterwards used for valuing the deferral option.

2.2.2. Net revenue of the PV investment

For valuing the relocation option, we examine the possibility of a significant positive change in project revenues, if more favorable market conditions arise in a location different of that in which the plant was originally placed. We consider that at the current location the PV plant receive a fixed tariff for the energy sold to the grid during the project lifespan. The variable subjected to uncertainty is the project's net revenue if the solar plant were relocated, which is defined by the value of the energy sold minus the costs of leasing the land parcel where the PV facility would be placed. This uncertainty is modeled as a homogeneous Poisson stochastic process [55].

The model considers that a sudden arrival of information modifies the net revenue randomly. This new information (favorable or unfavorable) may represent, for instance, the appearance of a more advantageous PV energy tariff in a competing jurisdiction seeking a rapid solar development, a reduction in the cost of leasing the project site because of regional incentive policies, or a reduction of the energy sold at the current site because of adverse changes in congestion patterns of the transmission network[2].

[2] For instance, this may occur if considerable solar capacity is increasingly installed in the same area. After some time, these additions may cause that aggregated PV output must be constrained during peak solar hours by the

The equation (2) models the arrival of new information on the investment project's net revenue if solar facilities were relocated to another jurisdiction at time t [55]:

$$R_t = R_0 \exp\left[\beta \cdot t + \varphi_t \left(V_j - 1\right)\right] \tag{2}$$

$$\varphi_t \begin{cases} 0 & \text{with probability} \quad 1 - \lambda_R.dt \\ 1 & \text{with probability} \quad \lambda_R.dt \end{cases} \tag{3}$$

where R_t denotes the net revenue from the PV generation plant at time t, β is an annual rate of growth/contraction of the net revenue, produced for instance by some macroeconomic effect, e.g. inflation rate. The parameter φ_t represents the arrival of a Poisson event at the alternative project site, where λ_R denotes the average arrival rate of new information on solar tariff in other jurisdiction during an infinitesimal interval of time dt. The probability that a tariff event will occur is given by $\lambda_R dt$ and the probability that the event will not occur is given by $1 - \lambda_R dt$. Finally, $\psi = V_j - 1$ is the jump magnitude by which the net revenue modifies if the PV project were moved. The magnitude of the revenue change is normally distributed with mean μ_ψ and standard deviation σ_ψ. Negative values of ψ represent decreasing revenues. Only one revenue jump is admitted during the lifetime of the solar project, i.e. it is a non-renewable random process.

Likewise the stochastic model for investment cost under technological progress, parameters of the stochastic solar tariff model of Eq. 2 and Eq. 3 can be estimated by the MLE method. As we do not have available historical data on solar tariff development across regions and time, we assumed some plausible values for stochastic parameters and investigated the impact on the relocation option value for a broad interval.

2.3. Real Options Analysis

Solar investments present very distinctive features. Typically, PV projects need very high upfront outlays, but thereafter require low operating expenditures. These high initial investment costs are mostly irreversible and are expected to be recovered over several years. For this reason, returns on investments are subject to considerable long-term uncertainties.

In the presence of uncertainties, flexibility has significant economic value and it can be expressed in monetary terms so as to be compared with other costs and benefits. Therefore, it is necessary to have methods that recognize the economic value of the options which are intrinsic part of

---

transmission system operator (TSO) in order to avoid exceeding operating limits of the transmission network. Such solar-driven transmission congestion might lead to spillage of potential PV production, therefore reducing the amount of energy sold to the grid. Furthermore, if the PV plant would sell energy at prevailing spot prices, revenues can be further reduced as locational marginal prices (LMP) at the connecting electrical bus can fall to a very low value during congestion. These harmful circumstances may motivate the relocation of the PV plant to an unconstrained area of the network in order to restore the economics of the project.

investment opportunities. In general, flexibility or optionality is an important component and contributes considerably to the value of an asset or investment project.

The Real Options approach, unlike NPV, appropriately treats flexibility in order to dynamically change or revise decisions when uncertainties surrounding critical variables are resolved with the arrival of new information. Real Options represents a conceptual extension of financial options theory [8] applied to tangible or real assets. A financial option gives its owner the right, but not the obligation, to buy or sell an asset at a fixed price. Analogously, a company that carries out strategic investments has the right, but not the obligation, to take advantage of these opportunities to obtain benefits in the future. These Real Options provides owners protection against losses without constraining potential profits.

Real Options are present in flexible business plans, projects or investments. These options may include: postponing construction, abandoning or selling the investment project before its conclusion, modifying the project's use or technology, switching inputs, changing outputs, extending lifespan, invest in modular capacities, etc. Some of these options may occur naturally while others need to be strategically planned or constructed at a given cost.

The Real Options analysis delivers the correct value of projects where the investment is partially or totally irreversible, uncertainty exists with respect to the future returns, management has flexibility to take contingent decisions and where it is possible to acquire new information about the future evolution of a relevant variable, though this information is always incomplete.

The value of a real investment with flexibility is determined as the value of the inflexible project, i.e. without options, calculated classically by the traditional NPV, plus the value of flexibility provided by the embedded options as follows [56]:

$$E\left[NPV_{flexible}\right] = E\left[NPV_{classic}\right] + E\left[\text{Real Options value}\right] \tag{4}$$

Real Options can be classified into different types. In this work, we analyse only two of the most important and common flexibilities embedded in solar investment opportunities [56]:

Deferment: implies the right to postpone an investment foregoing immediate cash flow in order to acquire new and better (though never complete) information.

Relocation: confers the right to move project facilities to a new site if market conditions, regulatory policies and system and/or jurisdictional status for the project change unfavourably in the current site or turn more attractive in the new location.

The real options of deferring or relocating the project can be readily assimilated to financial call options. These are American-style options, meaning they can be exercised at any time until the expiration date, and their value $F(t,w)$ at time t and for the sample realization w is given by [41]:

$$F(t,w) = \max_{\tau \in (t,T)} \left\{ E_Q \left[e^{-r(\tau - t)} \Pi(\tau, w) \right] \right\} \tag{5}$$

where ¡ (t,T) denotes the set of optimal exercise times in the interval $[t,T]$, $E_Q[\cdot]$ represents the expected present value under neutrality of cumulated profits conditional upon information available in t, and $P(t, X_t)$ is the cumulated revenue function of the option at an instant of time t. The value of the option at the expiration date T is given by:

$$F(T,w) = P(T,w) \tag{6}$$

The revenue function of the defer option at a point in time t_i is:

$$P(t_i,w) = \max\left\{\left(R_t^w - R_D^w\right) - \left(I_t^w - I_0\right), 0\right\} \tag{7}$$

where R_t^w is the present value of the cumulated revenues obtained in the w stochastic sample since the start of the project at time t_i to the end of lifetime. R_D^w is the present value of cumulated revenues which has been relinquished by not having started the project at point in time $t = 0$, in other words, the difference $R_t^w - R_D^w$ is the value of the underlying asset denoted as $S(t_i,w)$. Likewise, $I_t^w - I_0$ is the exercise price K, i.e. difference in the cost of executing the project between the instant of time t_i and $t = 0$.

$$F(t_i,w) = \max\left\{S(t_i,w) - K, 0\right\} \tag{8}$$

For the relocation option, the revenue function $P(t_i,w)$ is the maximum value between the present value of the project at the relocation site PV_{RS}, minus the present value of the project placed at the current site, PV_{CS}, from t_i until the end of the project's lifespan $t = T_L$.

$$P(t_i,w) = \max\left\{PV_{RS}^w - PV_{CS}^w, 0\right\} \tag{9}$$

$$P(t_i,w) = \max\left\{\left(R_{RS}^w - C_{RS}\right) - R_{CS}^w, 0\right\} \tag{10}$$

where R_{RS}^w is the present value of the revenue in the new project location from t_i until the end of the project lifetime. C_{RS} denotes the contingent cost of relocating generation infrastructure. Finally, R_{CS}^w is the present value of the project's remaining cash flow at t_i, if location keeps unchanged. The value of the underlying asset for the relocation option is $S(t_i,w) = R_{RS}^w - R_{CS}^w$ and the exercise price is $K = C_{RS}$.

Previous to the expiration date and at any time t_i, the optimal strategy results from comparing the immediate exercise value versus the expected cash flows from continuing, i.e. keeping the option alive. The optimal decision is to exercise if the immediate exercise value (intrinsic value) is positive and greater than the conditional expected value of continuing.

The arbitrage-free valuation theory implies that the continuation value $\phi(t_i, w)$, assuming it has not been exercised before the instant of time t_i, is given by the expectation of the cash flows generated by the option $\Pi(t_i, w)$ discounted with respect to a measure of risk-free valuation *Q*, and being r the risk-free discount rate.

$$F(t_i, w) = \max\{\Pi(t_i, w), \phi(t_i, w)\} \tag{11}$$

$$\phi(t_i, w) = (1 + r)^{-1} E_Q\left[F(t_{i+1}, w)\right] \tag{12}$$

In order to approximate the conditional expectation function at each of the time instant t_i, a linear combination of subsets of orthonormal basis functions $\{L\}$ are used. Generally, the basis functions used are Hermite functions, Legendre, Chebyshev, Jacobi polynomials, Fourier series, polynomial powers, among others [17]:

$$\phi(t_i, w) = \sum_{m=1}^{\infty} \varphi_m(t_i) \cdot L_m(t_i, w) \tag{13}$$

The values of φ_m are estimated by least-square regression of $\phi_M(t_i, w)$ with M elements of the selected basis functions and $M < \infty$.

Once the continuation function is estimated, a denoted as $\hat{\phi}_M(t_i, w)$, for the instant t_i, we can determine whether the exercise of the option is optimal or not. Then, the optimal exercise moment $\tau^*(w)$ for each sample w and at each instant of time t_i occurs if the condition $\Pi(t_i, w) > \hat{\phi}_M(t_i, w)$ is satisfied.

As soon as the exercise decision is identified for time t_i, it is possible to determine the path of the cash flows of the option for the instant t_{i-1}. In this way, the recursive process continues backward, repeating the procedure until the exercise decisions are determined for each exercise time along each path w. This recursive procedure determines the optimal exercise time for each one of the w paths simulated.

Finally, the estimated value of the option $F(t_0)$ is computed by discounting the cash flow resulting from the optimal exercise of the options back to the instant $t = 0$, at the risk-free rate and taking the arithmetic average over all simulated sample paths W:

$$E[\text{Real Options value}] = F(t_0) = \frac{1}{W} \sum_{w=1}^{W} (1 + r)^{t_w^*} F(\tau^*, w) \tag{14}$$

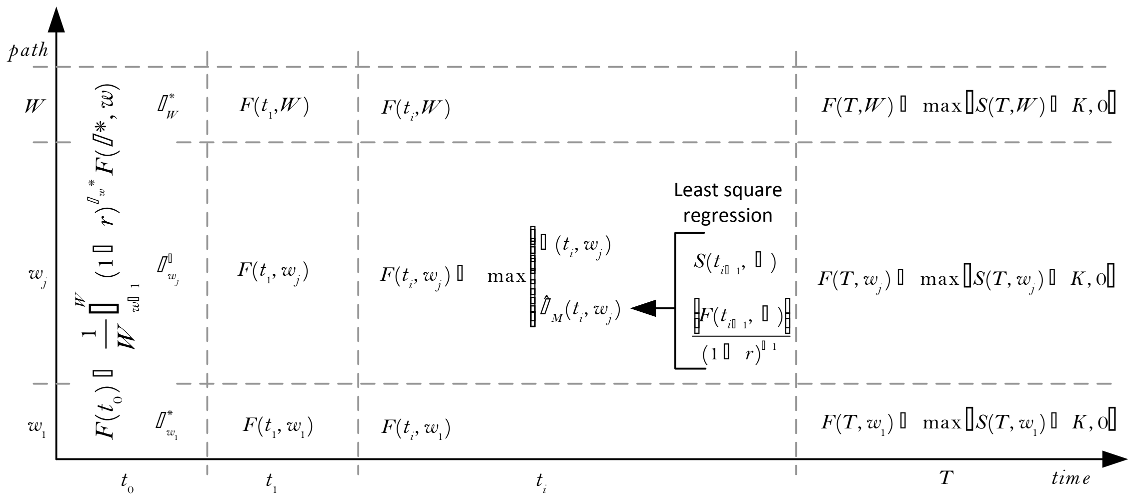

Fig. 3. General procedure of the valuation of an American-style real option based on the LSM method

The recursive calculation procedure above described is schematically depicted in Figure 3. This simulation-based option valuation methodology is known Least Square Monte Carlo (LSM) [17]. The method combines the stochastic simulation technique (Monte Carlo) with backward dynamic programming. The LSM method builds on the least square regression to approximate the value of the optimal exercise function of the fundamental recurrence relationship of the dynamic programming, i.e. the Bellman equation. The principal advantage of this method is that it overcomes the serious limitations imposed by both analytical methods and binomial trees, to value American-style options with underlying assets with varying probability distributions, and to incorporate uncertain variables following different types of stochastic behavior. Furthermore, LSM option pricing framework does not present the problem of dimensionality that characterizes conventional stochastic dynamic programming algorithms. Further details of the LSM method applied to real options problems can be found in [40],[41].

3. Real Options valuation of a PV generation project

In order to demonstrate the feasibility of the proposed option valuation approach, we carry out an economic assessment of an exemplary PV generation facility with 10 MWp of installed peak capacity[3]. We consider that the project's network access and environmental permits will expire within ten years. As such, we contemplate the flexibility of deferring plant construction and the option of relocating the solar project before these permits expire[4].

[3] The PV generation project is located at 33.38ºS 68.45ºW, with a mean solar radiation of 5.31 kWh/m^2/day. It is estimated an overall system capacity factor of 16.8% with 20º tilted panels and fixed structures.

[4] In this exemplary case study, the deferral and the relocation options are valued independently. Nevertheless, in many cases the options interact as they might be sequentially exercised. Indeed, the exercise of the first option (defer) may originate the possibility of subsequently exercising the second option (relocation). This type of options is named compound options, and the full value of the flexibility result of the joint pricing. The LSM method is particularly suitable for the proper valuation of sequential options.

The option of deferring supposes that the investment can be postponed while waiting for new information regarding technological progress in photovoltaic cell manufacturing. An improvement in manufacturing technology and/or in solar materials would imply a reduction in the project's initial investment cost.

In the second case, we assume that the investment cost in the PV plant is decided to be incurred immediately, e.g. the investment cost is not subject to uncertainty. The option of relocating will be exercised if during the project lifespan certain uncertainties are resolved regarding a new potential site which turns more attractive due to, for example, a change in regulation, incentive policies or transmission network access. Having this flexibility typically implies incurring in additional costs at the moment of building the project, but it opens up the possibility of the investor obtaining significant profitability from moving the pant while limiting economic losses.

The parameters describing the economics of PV investment project and the uncertain variables are presented in Table I and Table II, respectively. These tables show values related to the production and commercialization of the PV energy as well as parameters of the stochastic models that describe the random behavior of uncertain variables.

For valuing the deferral option it is considered that only the initial investment cost is subject to uncertainty. In the case of the valuation of the relocation option we take only into consideration the stochastic arrival of information turning attractive moving the solar project to an alternative site. For the sake of simplicity, each flexibility option has been valued under only one source of uncertainty.

Table I. Parameters of the solar investment project

General parameters	
Installed capacity	10 MWp
Unitary investment cost[a] I_0	0.75 USD/Wp
O&M costs (2% I_0)[b]	150000 USD/year
Site area	15 ha
Site leasing[c]	300 USD/ha/year
Relocation cost[d]	1600000 USD
Solar energy production parameters	
Expected annual energy (AC)[e,f,g]	14741.54 MWh/year
Energy sale price[h]	57.58 USD/MWh
Economic parameters	
NPV assessment period (lifetime)	25 years
Capital cost[i] k	8%/a
Risk-free discount rate	5%/a
Expiration of deferral option	10 years
Expiration of relocation option	10 years
Number of simulated cash flow samples[j]	10000

[a] Initial capital outlay considers project engineering, environmental and grid access permits, network connection, land preparation, civil works, water supply, material and component procurement (structures, PV panels, inverters, cables, transformers, switching, protections, weather station, etc.), metering, SCADA, control and communications, labour and commissioning costs.

[b] O&M costs comprise panel cleaning, preventive maintenance, repair works and spare parts.

[c] Typical rental cost of wasteland unusable for agriculture or other type of economic exploitations. The very low land value reflects the situation of a deserted, dry region, plenty of unproductive parcels. Nonetheless, site leasing costs may notably be higher when PV facilities are installed in productive regions.

[d] Contingent relocation costs include site conditioning, environmental license and network access permits, civil works, grid connection, water supply, disassembly and mounting of PV facilities and logistic costs.

[e] The annual production of the PV plant has been estimated by the PVWatts software from NREL [57].

[f] System losses are estimated as 14% and inverter efficiency is set at 96%.

[g] The interannual variability of the solar generated energy is represented by a zero-mean Gaussian distribution with normalized standard deviation $\sigma_E = 5\%$ [58].

[h] Weighted average contracting price observed in August 2019 from long-term tendering process RenovAr Round 3 in Argentina [59].

[i] Interest rate of the loan to finance construction of the solar plant.

[j] This sample size ensures statistical convergence and a low sample error of the estimated option values.

Table II. Parameters of stochastic processes

Technological progress	**Variable**	**Value**
Drift	α	0.07
Volatility	σ	0.12
Expected jump magnitude	μ_V	1.2
Volatility of jump magnitude	σ_V	0.05
Average arrival rate of jump	λ_{TP}	1/5 year^{-1}
Energy sale contract	**Variable**	**Value**
Annual revenue change	β	0
Expected jump magnitude	μ_y	1.6
Volatility of jump magnitude	σ_y	0.15
Average arrival rate of jumps	λ_R	1/10 year^{-1}

3.1 Stochastic simulation of uncertainty

Investment cost: By simulating the stochastic model in Eq. 1 we obtain realizations of future PV investment costs. Figure 4 illustrates only ten simulated sample time series out of 10000 possible future trajectories of the investment costs which evolve mainly due to technological progress. Together with the selected sample realizations is depicted the 90% confidence interval (in dotted line) estimated for the parameters of the mixed stochastic process. PV investment costs exhibit a clear decreasing trend (negative drift) in addition to sudden negative jumps caused, for instance, by new materials or technologies that cut production costs of PV cells and panels, cheaper power electronics, installation of nearby manufacturing facilities that reduce logistic costs, etc. Moreover, positive jumps may also occur which may be attributed to financial crises, fuel price escalations, wars or other exogenous events that could raise the price of panels. It is interesting to observe that uncertainty first grows rapidly, but in the long term confidence intervals get narrower.

Energy sale tariff: By Monte Carlo sampling the stochastic model of revenues (Eq. 2 and Eq. 3), a dataset of 10000 possible realizations of the future PV tariff if the project were moved to another jurisdiction with a more attractive solar remuneration regime can be generated. In Figure 4, ten possible samples showing the arrival of favorable Poisson events in the alternative project locations are illustrated. The expected value of the energy selling price and the 90% confidence interval if we allow the project to be moved in the future to another tariff jurisdiction is also depicted in Figure 5. Since the mean magnitude of jumps is $m_y = 1.6$ and standard deviation is $s_y = 0.15$, the probability of observing unfavorable tariff events is very low. If these detrimental conditions would take place, they do not have any impact as the PV plant does not be relocated. In Figure 6, the probability density functions (PDF) of the solar tariff offered in the new site for different time points in the future are plotted.

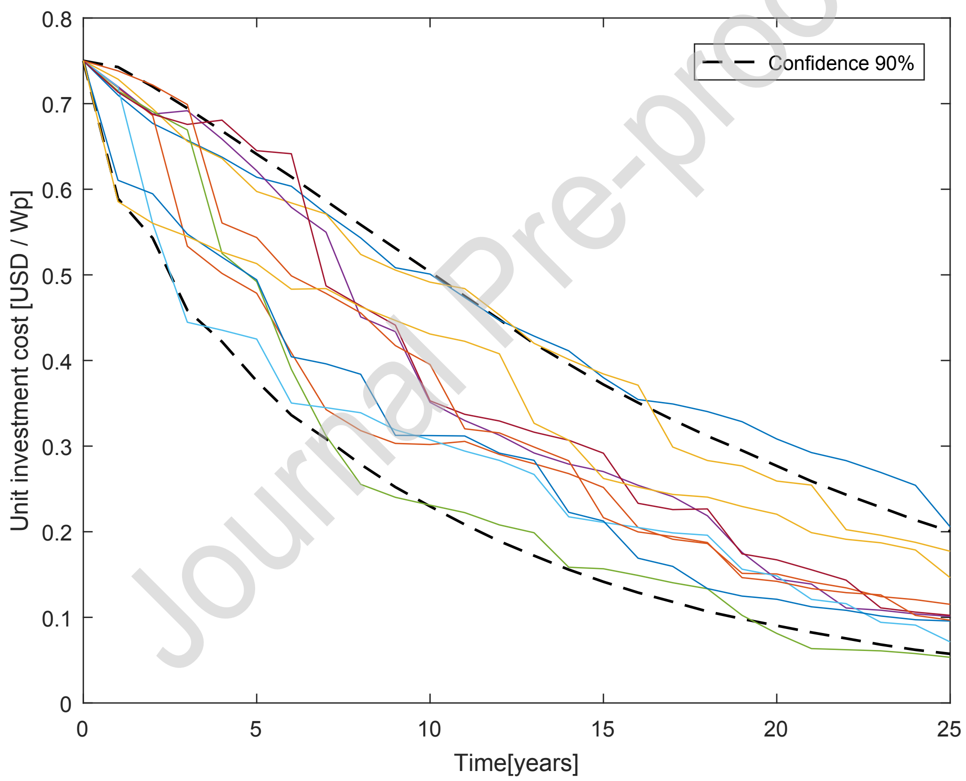

Fig. 4. Ten exemplary synthetic samples of PV investment costs. Future PV costs will fall within the plotted confidence intervals with 90% probability.

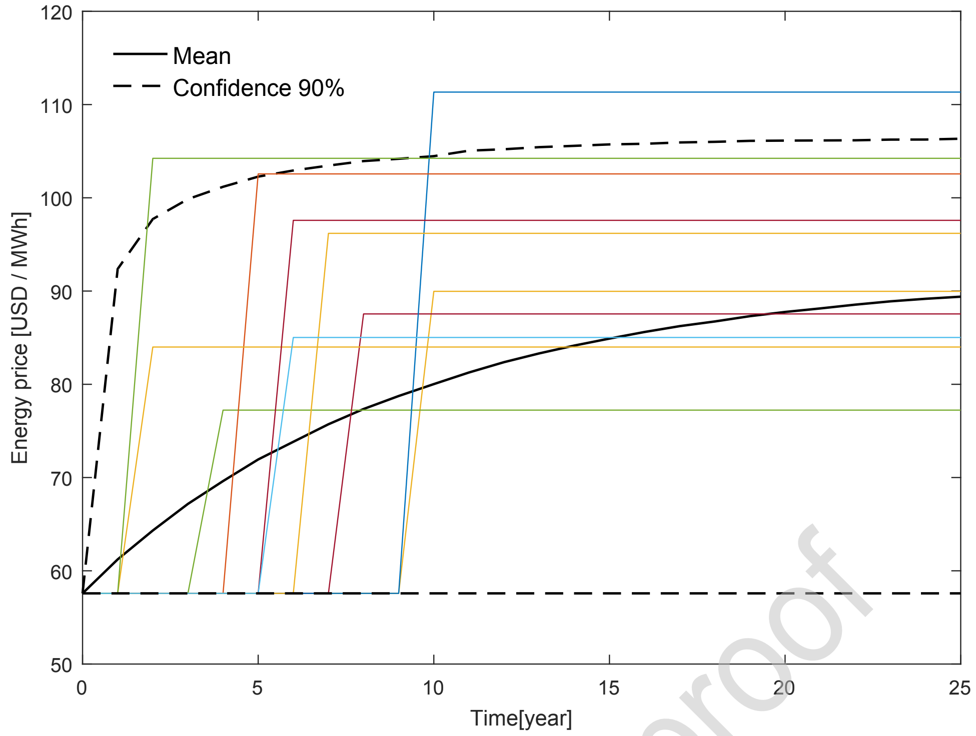

Fig. 5. Simulated samples of possible solar tariffs arising in the future on another jurisdiction. Along with stochastic tariff paths, it is depicted the expected value and the 90% confidence interval of solar energy prices in the new site

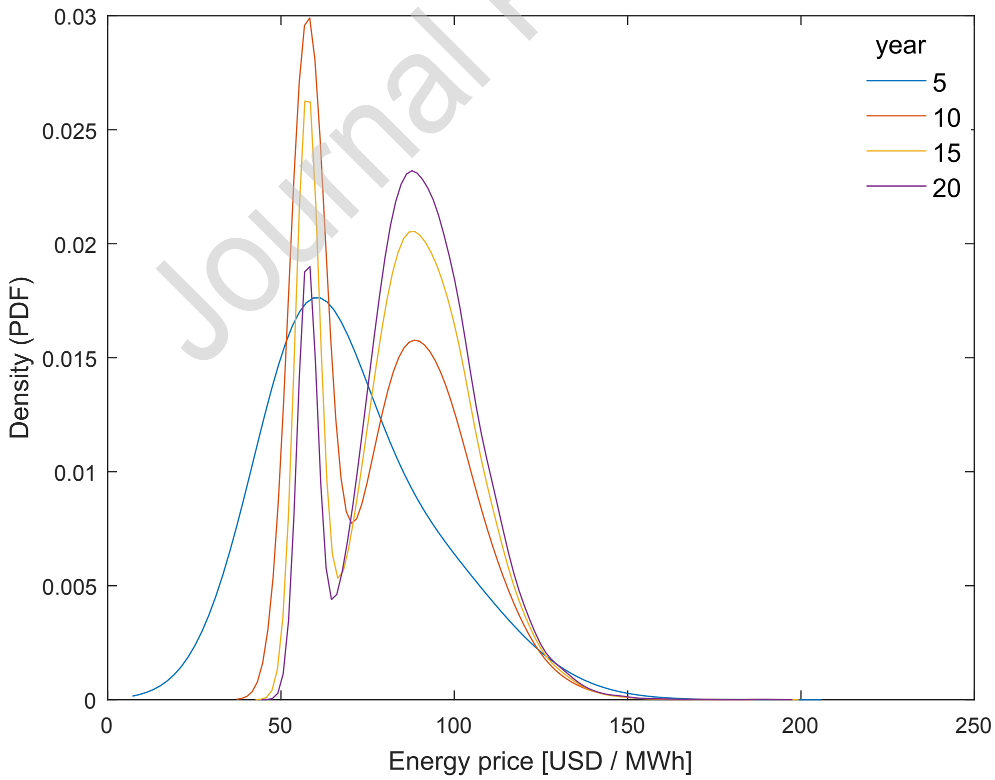

Fig. 6. Probability density functions of solar tariffs in the alternative project locations prevailing at different years

3.2 Traditional Valuation

The classical Net Present Value (NPV) of the solar investment project without considering flexibility is calculated by using the following equation [60]:

$$NPV_{classic} = E\left[\sum_{t=1}^{T_L} \frac{R_t - C_{O\&M}}{(1+k)^t} - I_0\right] \quad (15)$$

where k is the risk-adjusted opportunity cost of capital[5], R_t is the annual revenue in year t, $C_{O\&M}$ are the annual expenses in operation and maintenance, I_0 is the initial investment outlay, and T_L is project useful life[67]. The expected value of the NPV can be estimated by Monte Carlo sampling of project's revenues under a set of stochastic realizations of the uncertain variables, as follows:

$$N\hat{P}V_{classic} = \frac{1}{W}\sum_{w=1}^{W}\sum_{t=1}^{T_L}\left[\frac{R_t^w - C_{O\&M}}{(1+k)^t} - I_0\right] \quad (16)$$

where W is the total number of realizations simulated and R_t^w is the w-th stochastic realization of the annual revenue in year t. In this case study, the sample size has been established in 10000, which warrants a low statistical sampling error.

By applying (16) and considering the initial outlay I_0 equal to 7.5 million USD, the expected project's net present value is estimated by means of stochastic simulation as:

$$N\hat{P}V_{classic} = -97470 \text{ USD}$$

The resulting expected negative NPV implies that there is no creation of value in investing in this PV generation project. Consequently, the risk-neutral decision under the classic appraisal framework would be to reject the project and not carry out the investment. This result conforms to the current empirical observation that profitability of medium-scale PV generation projects still depends on the specific subvention policies.

3.3 Real Option Valuation

Real Options Analysis allows us to calculate the economic value that strategic flexibility adds to the renewable generation project. In the following, we focus on the valuation of both, the deferment and relocation options.

3.3.1. Deferral Option

[5] The risk-adjusted discount factor is calculated as the weighted average cost of capital (WACC) [60], which represent the minimum return that the project must deliver for honoring capital resources of creditors and owners. The WACC is computed as the average of the cost of debt and the opportunity cost of equity weighted by their relative share. If the solar project is entirely financed with debt, as it is assumed in this study, the capital cost is equal to the interest of the lend capital (8% per year)

[6] Tax structure and tax rates widely differ across countries. Therefore, the project is pre-tax valued as federal and state taxes are excluded in the present analysis.

[7] Dismantling costs and scrap value of the solar facility at the end of the lifetime has been neglected, though the can readily be incorporated.

First, we prove that the theoretical conditions for applying an analytical valuation approach are not satisfied in the case of an investment in a solar generation plant. For valuing the deferral option by means of the binomial lattice method, one condition is that project returns must follow a log-normal probability distribution. As we can observe in Figure 7 (left), logarithmic returns noticeably diverge from a normal probability distribution. Indeed, the higher-order statistical moments differ considerably from normal distribution and the Jarque-Bera (JB) test for Gaussianity is clearly rejected at a 5% level of significance[8].

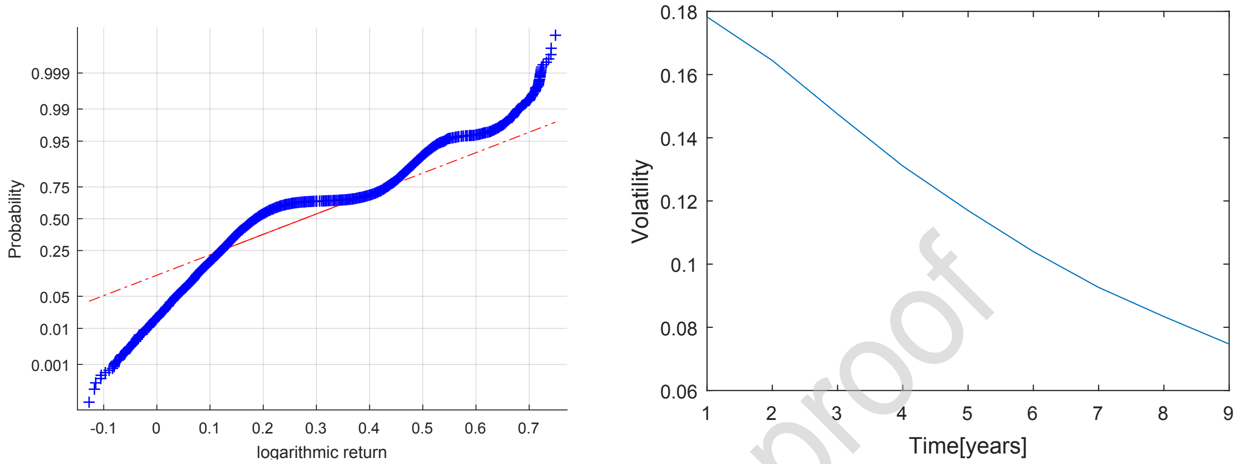

Fig. 7. Normal probability plot of logarithmic returns (left) and volatility of logarithmic returns over time (right)

The second condition is that volatility of logarithmic returns must remain constant over time. Figure 7 (right) shows that this condition is not fulfilled neither, as volatility clearly declines with increasing time. As conditions for applying lattice-based methods are not verified, we rely on the Least-Square Monte Carlo valuation approach.

Applying the LSM-based calculation procedure described in Section 2.3, we determined the expected monetary value of the option to defer construction of the PV power plant. The deferral option expires in ten years, i.e. the investor has permits and rights to the site for a period of ten years in order to construct the solar project. Upon expiration, the project cannot be constructed.

Table III illustrates exemplary intermediate calculations when applying the LSM option valuation method for 13 arbitrary stochastic sample paths w of the annual revenues R_t^w and the investment costs I_t^w. The last column (right) shows the intrinsic option value at the expiration time $T = 10$ computed according to Eq. 8. If the difference between the present value of the cumulated net revenues up to the end of the project lifetime $S(t_i, w)$ and the option exercise price $K(w) = I_{10}^w - I_0$ is negative, the option value at expiration time is zero. Hence, it is optimal to

[8] Skewness and kurtosis of logarithmic returns are 0.56 and 2.16 respectively. The statistic of the JB test is 813.25, largely exceeding the critical value of 5.9864 at a significance level α=5%. The *p*-value is $p=0.001$, clearly below the 5% significance level.

left the option unexercised, i.e. the PV project should be discarded. In this demonstrative example of numerical calculations, this occurs only for paths 2500 and 8400.

For other sample realizations, the intrinsic value is positive. By recursively going backward in time along each simulated path w, in each time interval t_i the value of immediate exercising (intrinsic value) is compared with the present value of the future cash flows if decision is delayed (denoted as continuation value $f(t_i, w)$). The central idea of the LSM algorithm is that the continuation function $f(t_i, w)$ at each time step is estimated by linear regression with respect the underlying asset $S(t_i, w)$ considering only the paths w in which the option take positive value $F(t_i, w) > 0$.

In each sample path w, the algorithm storages the option value only if the value of immediate exercising exceeds the value of deferring investment decision one year. According to the future development of the uncertain variables, this may happen at different times before expiration (highlighted values). The year $t^*(w)$ in which is optimal executing the investment option for each path w is summarized in the third column of Table III. In the second column, the option values at time t_i corresponding to each path are discounted to present time by the risk-free interest rate r. Finally, the expected option value is computed as the arithmetic mean over all simulated sample paths.

Table III. Exemplary calculations for estimating the expected value of the deferral option

Sample path w	Option value $F(t_0, w)$	Optimal exercise $\tau^*(w)$	Optimal option exercising value [millions USD] $\Pi(t_i, w) > \hat{\phi}_M(t_i, w)$									Intrinsic value $\max\{S(T,w) - K(w), 0\}$
			t_1	t_2	t_3	t_4	t_5	t_6	t_7	t_8	t_9	$t_{10} = T$
1	3.05	7	-	-	-	-	-	-	**4.23**	-	-	4.56
2	0.71	10	-	-	-	-	-	-	-	-	-	**1.17**
3	2.83	6	-	-	-	-	-	**3.80**	-	-	-	4.14
4	3.32	2	-	**3.67**	-	-	-	-	-	-	-	3.31
5	2.74	8	-	-	-	-	-	-	-	**4.04**	-	4.63
1000	2.91	4	-	-	-	**3.53**	-	-	-	-	-	4.90
2500	0.00	NO	-	-	-	-	-	-	-	-	-	0.00
5000	3.38	5	-	-	-	-	**4.31**	-	-	-	-	3.00
7500	3.42	6	-	-	-	-	-	**4.59**	-	-	-	5.78
8400	0.00	NO	-	-	-	-	-	-	-	-	-	0.00
9998	1.75	10	-	-	-	-	-	-	-	-	-	**2.85**
9999	3.13	4	-	-	-	**3.80**	-	-	-	-	-	3.94
10000	3.56	1	**3.73**	-	-	-	-	-	-	-	-	5.51

$\mathbb{E}[F(t_0)] = 2.773$ **mill. USD**

By following the described calculation procedure, the expected value of the deferral option $\mathbb{E}[F(t_0)]$ estimated by means of the LSM method over 10000 samples is:

Deferral Option = 2773778 USD

As a result, the expected value of the investment project considering the flexibility of delaying decision to initiate construction is:

$$NPV_{flexible} = NPV_{classic} + \text{ Deferral Option}$$

$$NPV_{flexible} = 2676308 \text{ USD}$$

The deferment option yields a considerable economic value as there is significant uncertainty regarding the arrival of new information about technological advances in photovoltaic cell and panel manufacturing, as well as power inverters. Notwithstanding the significant negative value of the classic NPV, the value of the deferral option turns positive the flexible NPV. Unlike the classical assessment, which suggested rejecting the investment project, option-based valuation shows that the project would be economically viable, though the immediate decision would be to wait for better information to begin construction of the solar generation plant.

In Figure 8, the histogram of frequencies and the estimated probability distribution of the classic and the flexible NPV are plotted together. Note that the classic NPV is not deterministic and the observed variability is given by the uncertainty on the solar energy generated. If the PV project admits the flexibility to postpone the investment decision, we can observe that the investment is never exercised if it delivers a negative value. Consequently, the expected flexible value is considerably higher than the static NPV. The optimal time to exercise the investment option depends on the particular path of the development of future investment costs. The histogram of the best time to invest is depicted in Figure 9. The decision-maker would wait to invest for better information on the development of investment costs until the expiration date with a probability of 30.47%. The PV project will be executed any time before expiration of with a probability of 68%. The probability of rejecting the solar investment project is 1.51%.

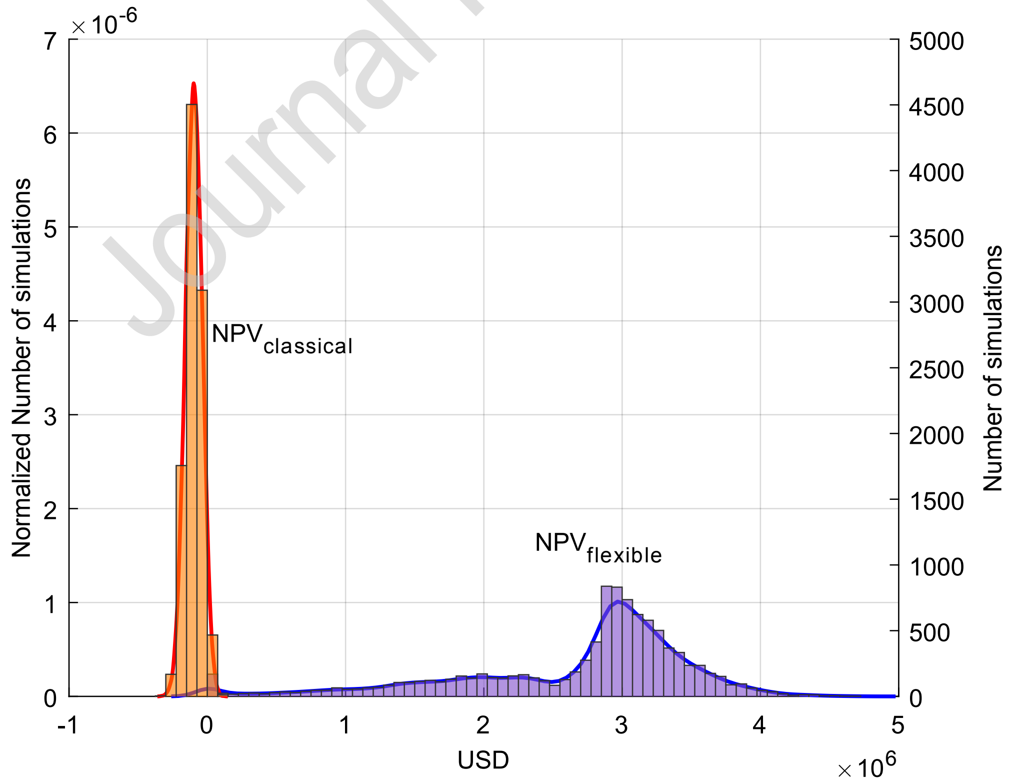

Fig. 8. Histogram and probability distribution of the classic NPV and the project value with flexibility to defer investment decision.

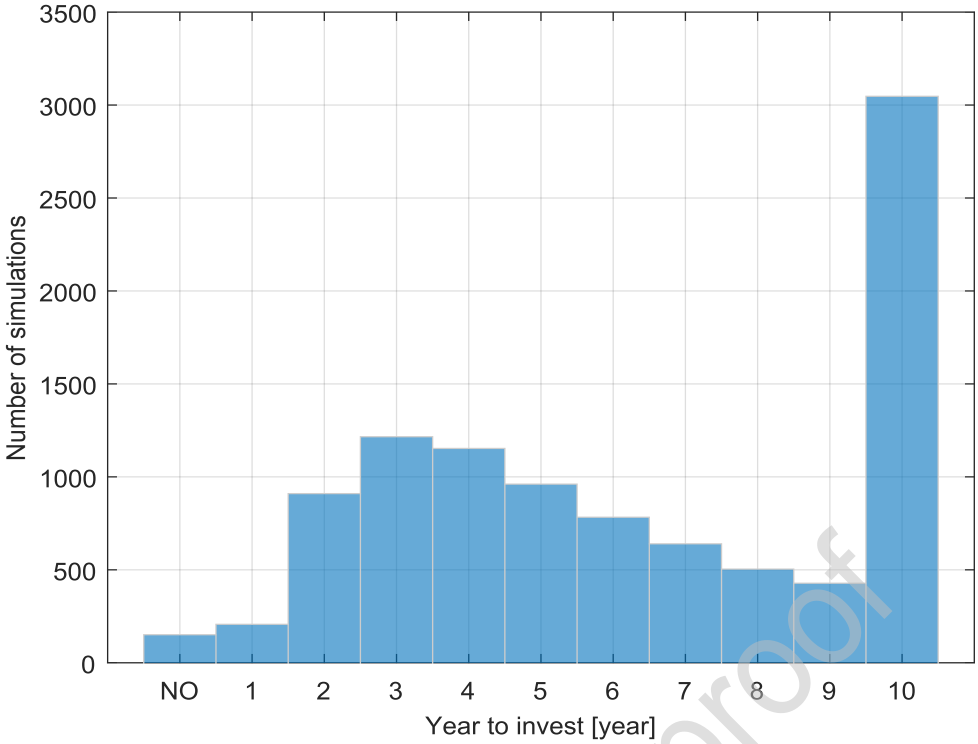

Fig. 9. Histogram of optimal exercising time to invest in the PV power plant

In order to build the deferment option, the investor must spend money, which could be the cost of applying for permits and leases the project parcel with the option to buy the site in the future. Acquiring this right provide the investor a limit on possible losses. In consequence, if favorable information regarding the reduction of infrastructure costs, project losses would be limited only to the cost of permits and leasing the site until the right expires. The maximum costs that investors would be willing to pay for the deferral option is that would make the flexible NPV zero.

To assess the behavior of the deferral option value in function of the expiration date of the right, we carried out the sensitivity analysis, as it is illustrated in Figure 10. We observe that as the expiration time of the option increases, its value also increases. This behavior is due to the fact that there is a longer period of time during which new information can arrive, and thus under uncertain conditions the investor can decide to postpone the construction of the PV plant, maximizing expected returns and limiting losses.

The jump magnitude associated with the relevance of the arriving information has an important impact on the value of the defer option and consequently on the investor's decision. Similarly, the arrival rates of the Poisson process have significant influence on the value of flexibility. Figure 11 shows the value of the option to defer based on the magnitude and the arrival rate of information regarding technological progress.

In Figure 11 we observe that as the magnitude of the arriving information increases, so too does the value of the deferral option. Additionally, if the arrival rate is low (news come more frequently), the value of the option to defer has a high value as incoming new information improves project value. As such, as it can be observed, in both cases uncertainty regarding the arrival of information on investment costs improves the project's value.

Given the importance that the magnitude of the jump in technological progress has on the value of the defer option, we conducted a sensitivity analysis on the standard deviation of jump magnitude, as it is shown in Figure 12. We observe that greater volatility in jump magnitude (greater uncertainty) yields increased value of the option. These results explain the common intuition of delaying irreversible investment decisions in environments with great uncertainty.

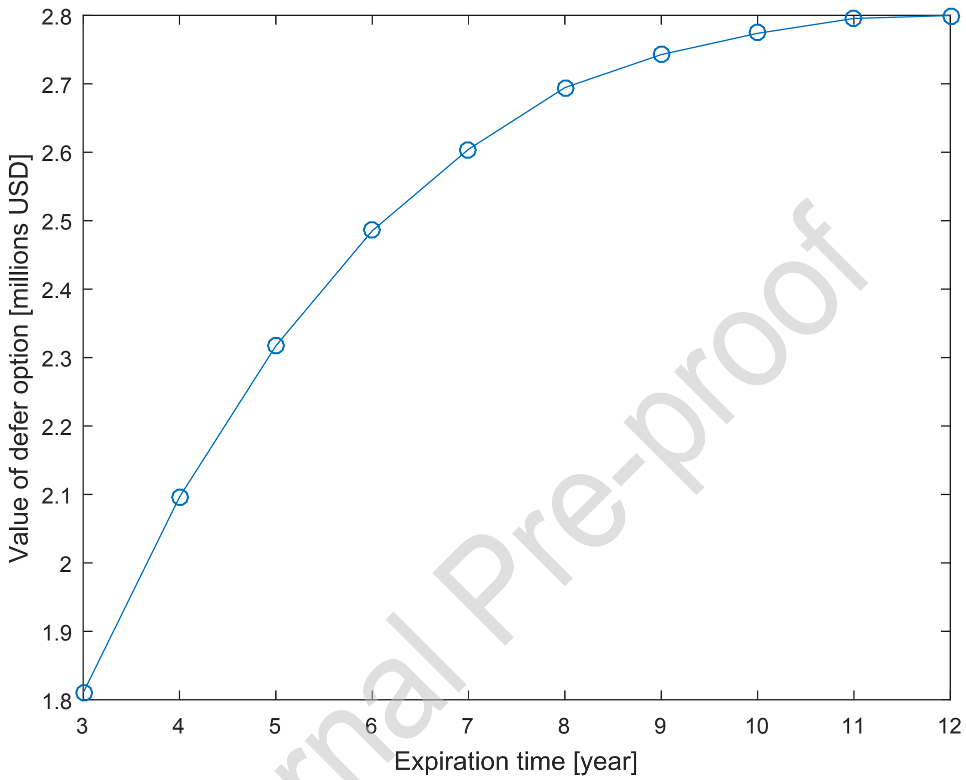

Fig. 10 – Value of the option to defer decision as a function of expiration time

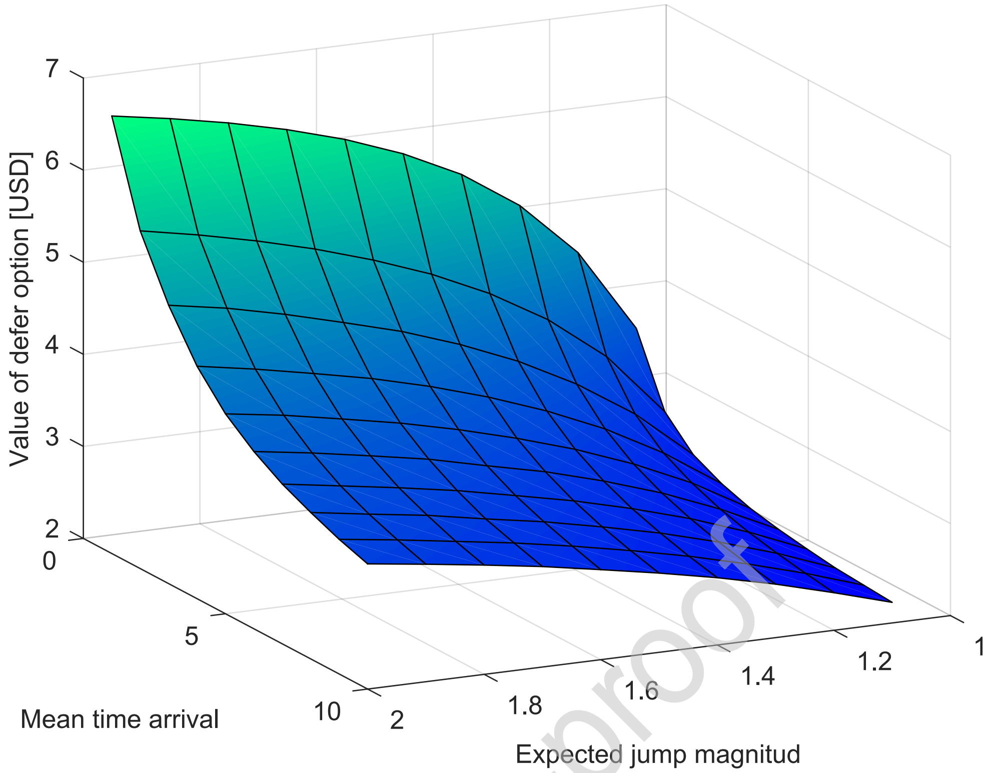

Fig. 11 – Value of the option to defer as a function of jump magnitude and average time of arrival of technological advances

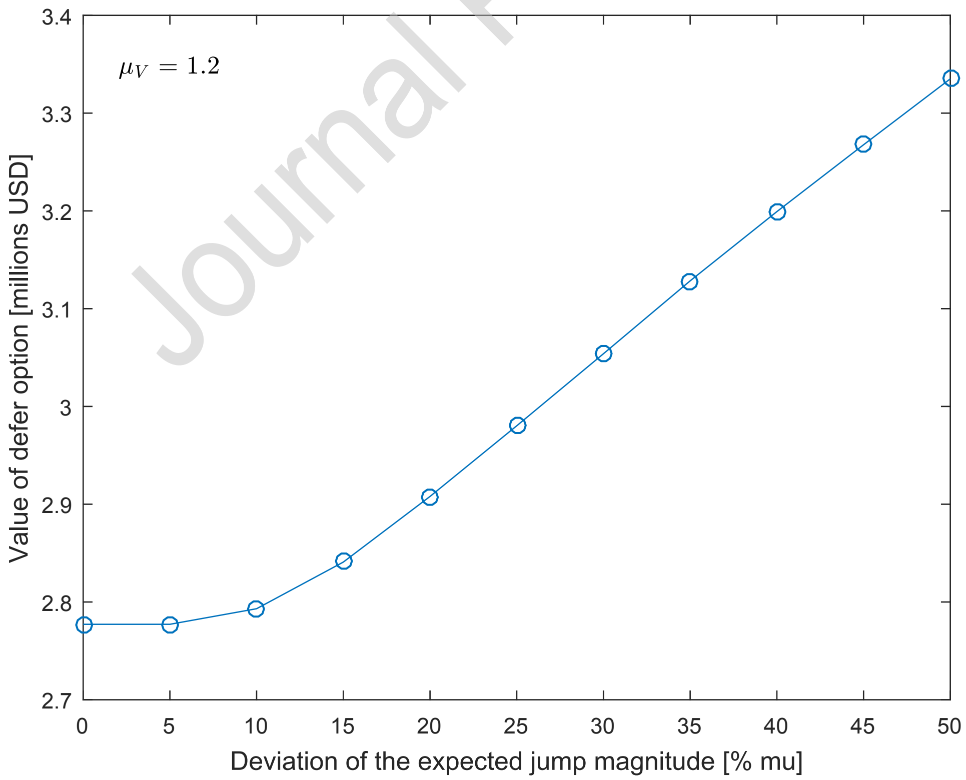

Fig. 12. Sensitivity of the deferral option value upon the deviation of the Poisson jump magnitudes (expressed as percentage of the mean jump magnitude m_j)

Real Options analysis allows establishing an optimal decision-making region based on the value of the driving parameters. In addition to the classic NPV rule, these decision regions are defined by both, the deferral option value and the project's flexible NPV value. Table IV provides the rules that establish each of the decision-making regions. In Figure 13, Invest, Defer and Reject regions are charted as a function of the unitary cost of investment and the option expiration time. In Figure 14, decision regions are plotted as a function of the unitary cost of investment and energy sale price. Note the points in the decision region diagrams where the PV project is situated under the current circumstances.

In both figures, we observe that the zone of immediate investment is rather small and that it corresponds to those cases where investment costs are very low. Quite the opposite, the region of deferring commitments is quite broad. This is due to the fact that the value of uncertainty on the arrival of information regarding technological progress is significant. Therefore, the flexibility to defer decision to go ahead with the investment project has a considerable economic value. Finally, there appears a zone in which the investment project would be discarded given that the value from flexibility to delay decision does not compensate for the high investment costs. In this zone, the flexible NPV is less than or equal to zero.

Table IV. Rules for optimal decision-making in a flexible project

Decision	**Condition 1**	**Condition 2**	**Condition 3**
Invest now	$NPV \geq 0$	Option = 0	------------
Defer decision	------------	Option > 0	$NPV_{flexible} > 0$
Reject project	$NPV < 0$	-------------	$NPV_{flexible} \leq 0$

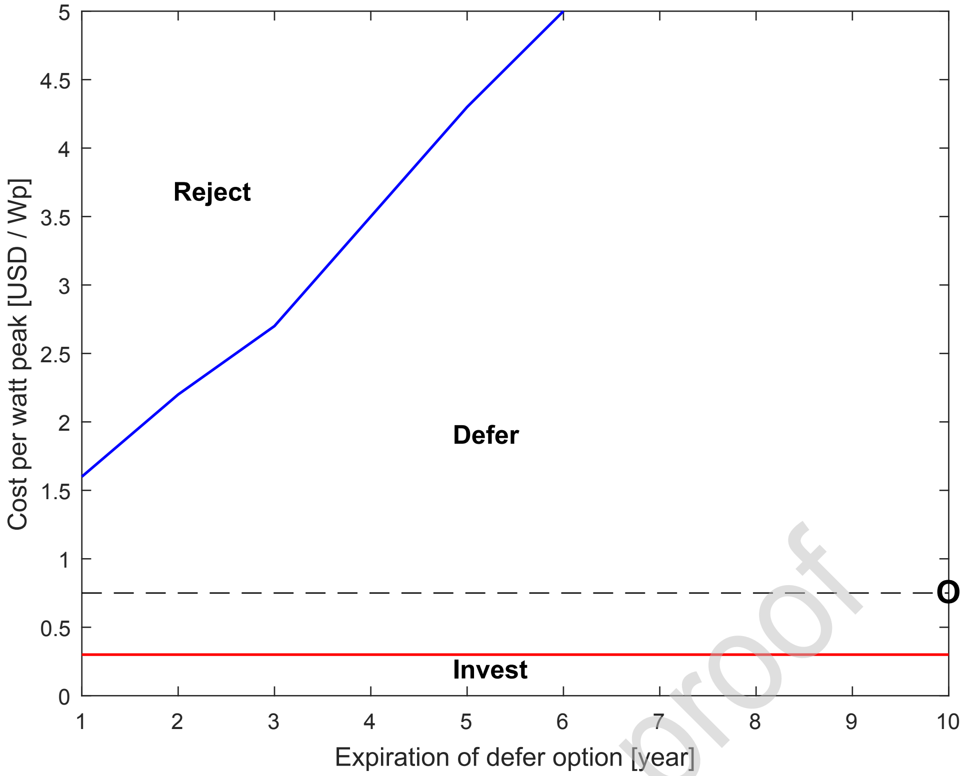

Fig. 13. Decision-making regions as a function of option expiration and the unitary investment cost, assuming a PV tariff of 57.58 USD/MWh

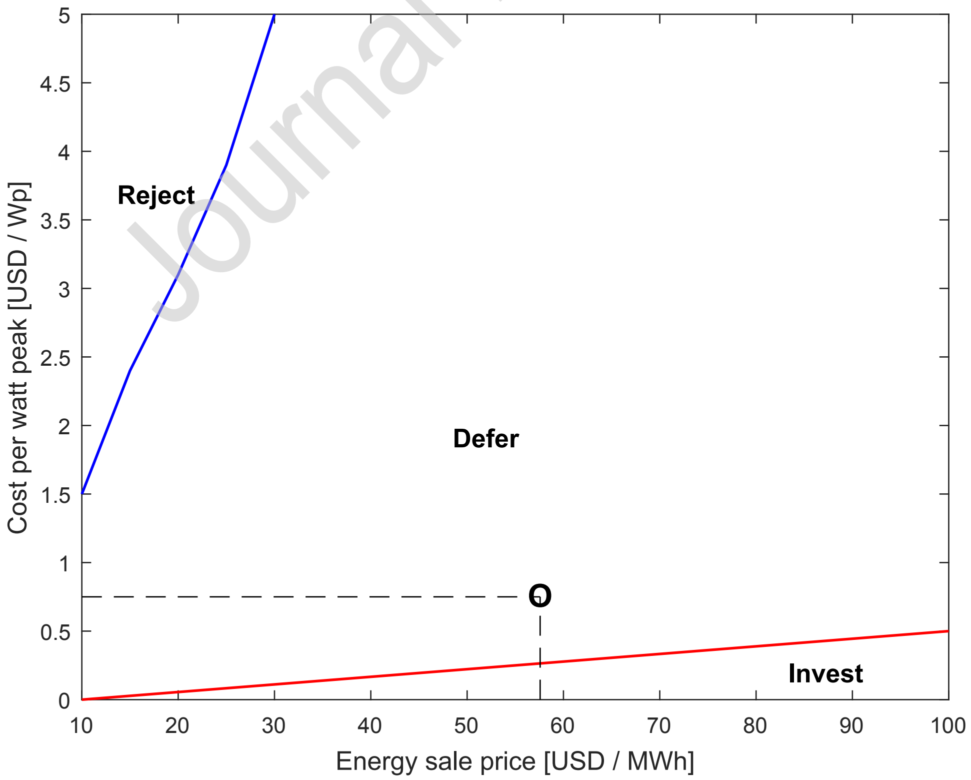

Fig. 14. Decision-making regions as a function of the solar energy sale price and the unitary investment cost, for an option expiration time of 5 years

3.3.2. Option to relocate

Assuming that the photovoltaic generation plant must be constructed now anyways, we evaluate the Real Option of relocating the PV facility in the future to a more attractive site in order to improve the investment project's financial feasibility. One possible scenario that might give value to the flexibility of relocation is the advent of aggressive regional regulatory incentives improving the revenue of the investment project in another jurisdiction[9]. Other possible scenario is a potential congestion of the transmission network caused by the connection of multiple renewable generation projects in the same area which limits maximum production capacity at peak solar hours, thereby reducing the investment project's net revenue. Under these circumstances, the PV project could be better off if it is relocated to an uncongested point of the transmission grid.

In this section, we analyze the relocation option based on improvements in net revenue from the sale of produced energy, under the hypothesis that another jurisdiction (e.g. a nearby federal state) decides to grant a differential solar tariff or a more profitable contract for PV generation in order to rapidly attract investments in renewable generation to the area.

The value of this option arises from the net benefits of moving the project to a new site if the uncertainty regarding regulatory incentives is resolved in the short term, and allows for relocation of the PV plant to an area which is economically more attractive. Consequently, a PV project with the option to relocate will have more value than one without this flexibility.

With the relocation option, it is necessary to consider the leasing terms at the alternative site where the PV facility is to be relocated for the period while the option is alive. This is an additional cost that appears during the valuation of relocation options. Moreover, additional costs should be considered for the use of special infrastructure that facilitates the relocation of the generation plant (dismantling and reassembling of support structures), as well as the costs incurred by site preparations, civil works, grid connection, permits and the logistical costs related to the transport of the plant components. First, we will prove that necessary conditions to apply analytical valuation approaches, such as the binomial tree method, are not fulfilled in the case of the relocation option. In fact, the distribution of the logarithmic returns deviates significantly from the normal distribution, as illustrated in Figure 15 (left). In the same sense, volatility of the log returns are not strictly constant and instead increase over time, see Figure 15 (right).

[9] A jurisdiction is defined as an area under a legal authority with faculties for establishing the remuneration tariffs to PV generation produced in its territory. In practice, municipalities, districts, federal states, provinces and countries are jurisdictional authorities that may set financial incentives to solar investments.

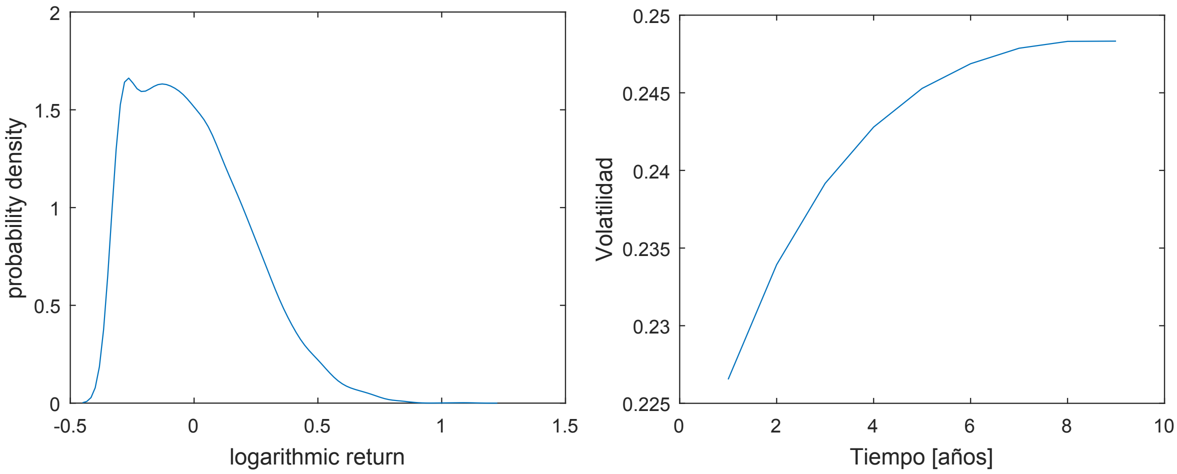

Fig. 15. Probability density function of the log of the returns (left). Time varying volatility of logarithmic returns (right).

Next, we analyze the case in which PV solar energy price at the current location keep constant over time and a random regulatory event with favorable information about solar tariffs in a nearby jurisdiction may arrive in the future with an expected arrival rate of 1/10 year^{-1}. Random changes in the value of the solar tariff have an expected magnitude of $m_y = 1.6$, distributed normally with a standard deviation of $s_y = 0.15$.

If the project is decided to be relocated, a contingent relocation cost C_{RS} of 1.6 million USD must be incurred. The expenditures for project relocation amount about 21% of the initial investment outlay. Under this setting, the expected net value of the relocation option computed by the LSM valuation approach is:

$$\text{Relocation Option} = 2043351 \text{ USD}$$

As a result, the expected value of the investment project considering the flexibility of moving the photovoltaic plant to a new, more favorable site is:

$$NPV_{\text{flexible}} = -97\,470 + 2043351 = 1945881 \text{ USD}$$

This result suggests that the relocation option may provide considerable value to the solar investment project. Although the project has now a negative classic NPV value, the presence of this flexibility changed an economically unfeasible project into an attractive investment. As a consequence, the economic value incorporated by the flexibility encourages the immediate execution of the photovoltaic generation project while awaiting new and better information on solar tariffs which would improve economic profitability. The value of the flexible NPV must be interpreted as the maximum upfront relocation expenditures that can be incurred in order to prepare the PV facility to be movable in the future upon the arrival of favorable tariff conditions.

The sensitivity of the relocation option to various factors is consistent with what is expected according to option valuation theory. Figure 16 shows the sensitivity analysis of the relocation option value as a function of the expiration period of the right to move the project, while keeping constant the remaining parameters. Though the monetary value of relocation flexibility increases with the expiration date of the right, we observe that it has no significant impact on the value of the option. As the average arrival rate is ten years, after this time the growth of the relocation option stabilizes given that, for the majority of scenarios, the good news has already arrived.

The value of the option as a function of the time rate in which new information regarding financial incentives arrives has the opposite effect. We observe that the quicker this information is made known, the greater the value of the relocation option, given that this allows for rapid decision-making to improve the project's economic returns. The evolution of the value of the relocation option as a function of the average information arrival rate λ_R is depicted in Fig. 17.

Under real option analysis, the value of the flexible investment project (i.e. with the option to relocate) improves as uncertainty regarding the magnitude of tariffs for the solar energy increases. Figure 18 depicts the considerable influence of the mean jump magnitude parameter m_y on the option value. Likewise, Figure 19 presents the behavior of the relocation option when the standard deviation s_y of the PV energy sale price in the competing jurisdiction increases. It can be clearly observed that the value of the relocation option rises substantially for higher volatility of the magnitude of the tariff jump.

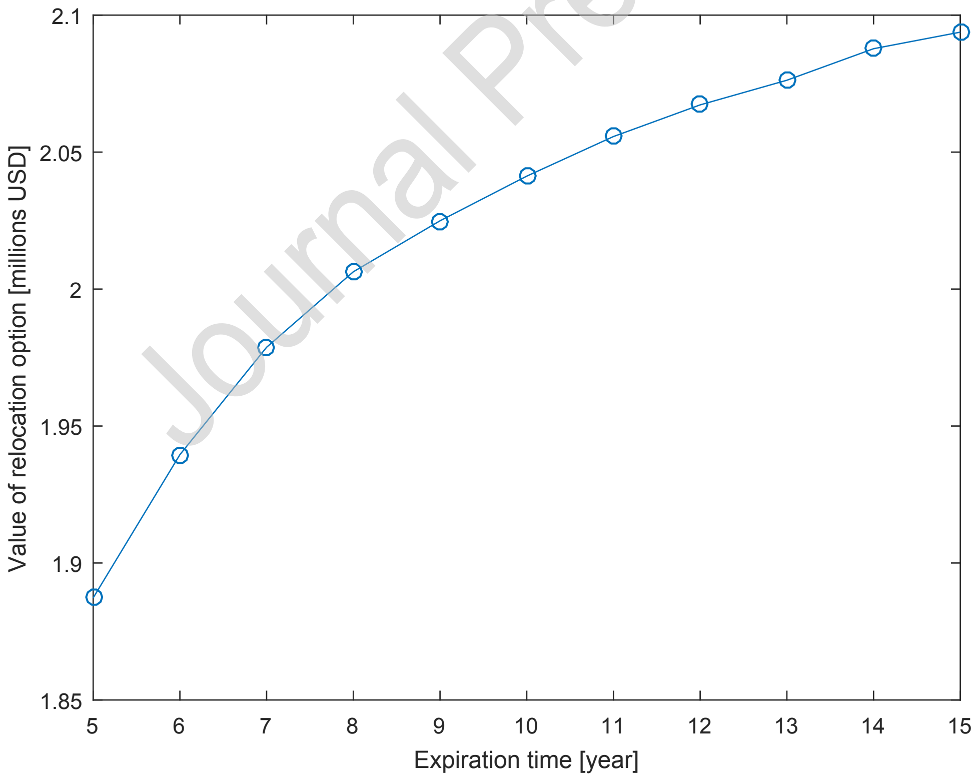

Fig. 16. Value of the relocation option with respect to the option expiration date

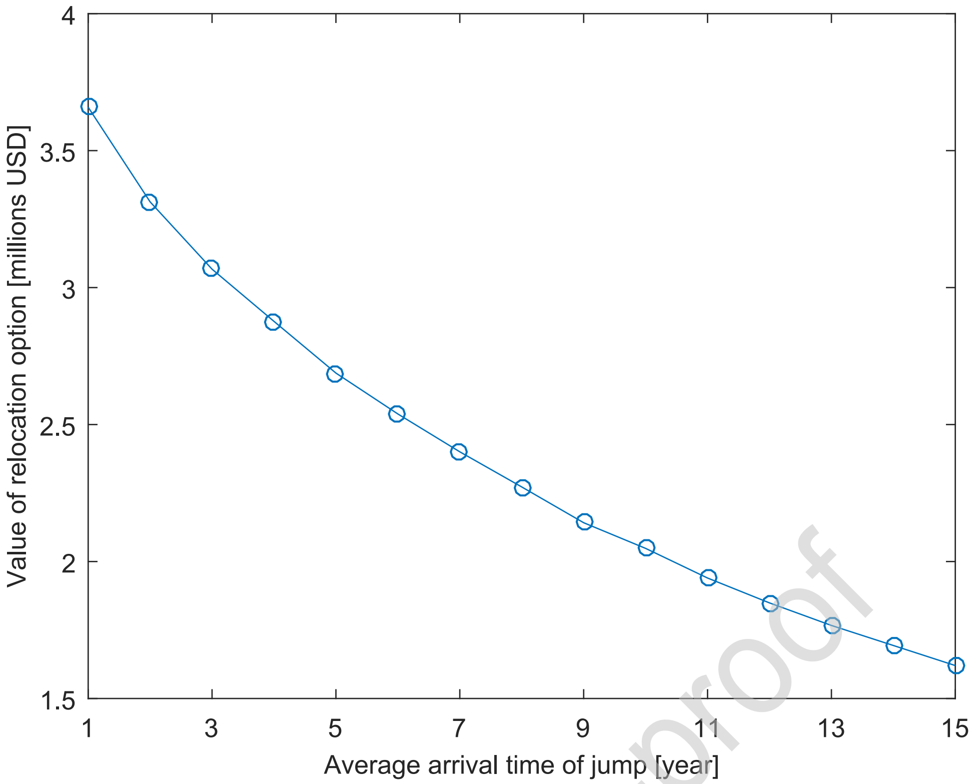

Fig. 17. Value of the relocation option with respect to mean time of information arrival λ_R^{-1}

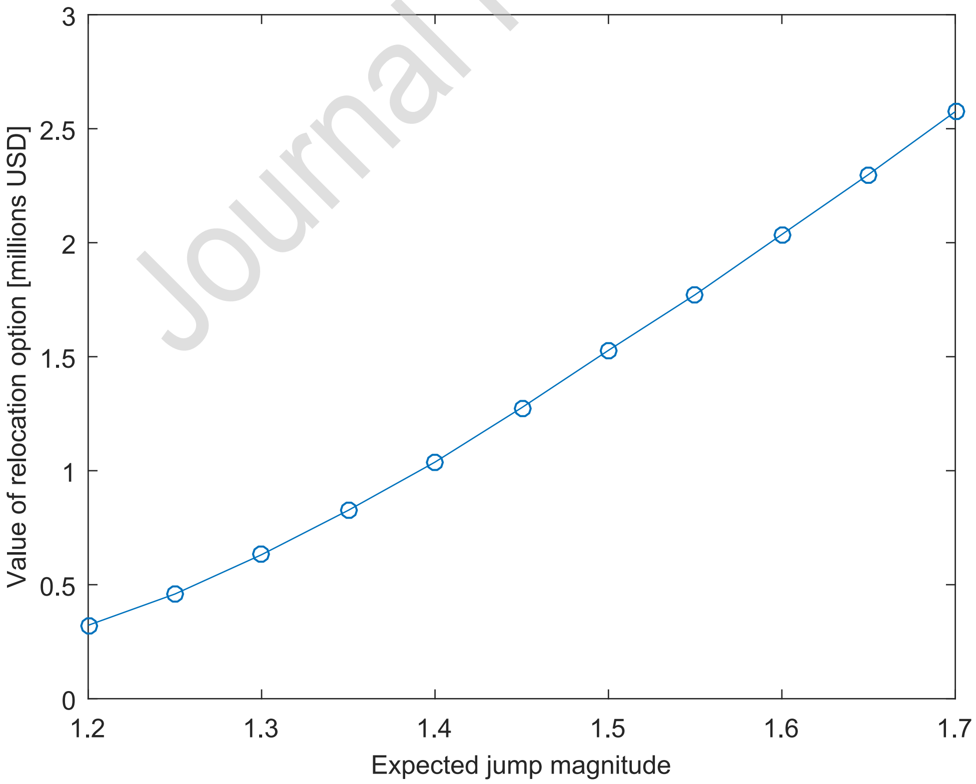

Fig. 18. Value of the relocation option as a function of the mean jump magnitude m_J

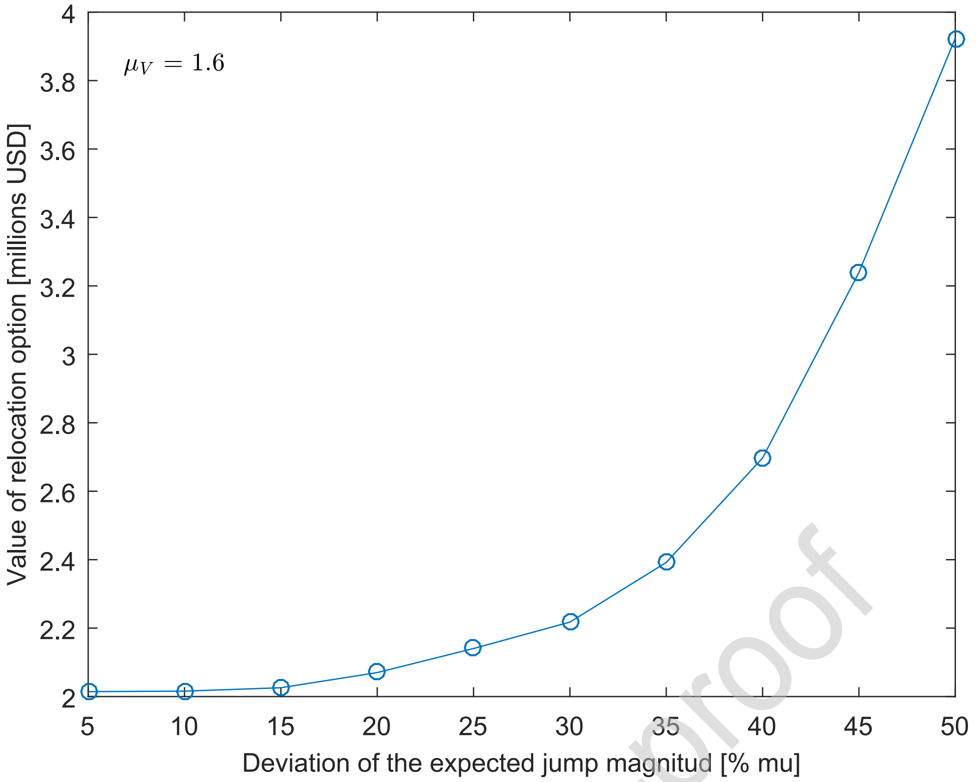

Fig. 19. Value of the relocation option as a function of the deviation s_y of the Poisson arrival magnitude

The case analyzed assesses the value of the flexibility of relocating the PV project under revenue uncertainty because tariff changes. A similar case could be the arrival of information regarding a drastic reduction of the cost of leasing a land parcel in an alternative site. For example, having available a more economical site which does not currently have accesses to the electrical grid, though this could change in the near future. The option to relocate could consider the benefit of moving the project to this new site if uncertainty about access to the transmission network is resolved in a fixed period of time.

Conclusion

In free electricity markets, besides having the technical tools necessary to supervise, operate and control electrical systems, it is essential to have appropriate valuation tools so that market participants can make efficient investment decisions under irreversibility and uncertainty.

Modern literature on the assessment of investments recognizes Real Options Analysis as an advanced approach for valuing (partially or totally) irreversible investment projects in environments subject to significant uncertainties and which have embedded managerial flexibility for decision-making. Given that renewable energy generation projects commonly possess these features, the potential of options analysis can be exploited completely.

This work developed a methodology to assess investments in electrical energy generation from renewable sources, particularly solar-photovoltaic generation, facing highly uncertain environments. The monetary values of the embedded Real Options of deferring investment decision and relocating the PV project to a better site have been assessed. The option to defer investment decision waiting for better information on cost development and the option to relocate project to an alternative site if more attractive conditions emerge have been analysed in this work. At the best knowledge of authors, the value of flexibility to relocate a PV plant is an issue that has not received attention before.

We propose random processes with jumps to suitably represent stochastic dynamics of the relevant uncertainties surrounding the PV investment problem. Statistical tests on theoretical conditions for applying analytical valuation approaches reject the possibility of using binomial tree methods for assessing options present in PV investments. Therefore, the option pricing technique implemented was based on a simulation method, known as Least Square Monte Carlo. This valuing framework allows one to properly value American-style options and to consider various sources of uncertainty with different types of stochastic behaviour. Option values are mapped for a range of input variables in order to find threshold values that establish decision regions. This form of presenting evaluation results greatly aids decision-makers to decide invest now, defer and abandon the PV project.

Upon evaluating the option to defer, the risks of losses were mitigated as the project is not implemented if an unfavourable scenario occurs before the option's expiration. On the contrary, profit opportunities are maximized, given that the project is only carried out within a favourable cost development scenario. We observed that as the defer option's expiration increases, the economic value of having flexibility is greater due to the fact that the investor has more time to make decisions using better information.

The option analysis suggests that the value of the option to move the PV plant contingent to the favourable development of tariffs in an alternative jurisdiction may be considerable for a wide range of parameters values. We observed that as the expected arrival frequency for new information increased, the value of the relocation option augments rapidly. These results suggest that relocation option of PV projects should be never neglected without a thorough analysis.

Finally, the analysis of real options allows considering investments that would prematurely be rejected if using traditional DCF-based assessment techniques. Our results suggest that at present many PV investment projects are being discarded too early if classical NPV rules are applied. The problem of the allocation efficiency of massive capital resources in the PV sector is of paramount significance as a trillion-dollar investment flow in PV capacity is expected to happen in the next few years over the world.

In addition to the assessment of individual PV projects, it is important to note that the option valuation framework may be used for designing optimal regulatory incentives to trigger immediate solar investments. For this reason, the application of this tool would be beneficial for encouraging more efficient investments in renewable generation, which in turn would help to accelerate transition to carbon-free power systems.

4. Acknowledgments

The authors would thank to Energía Provincial Sociedad del Estado (EPSE) and INAR Ingeniería Sustentable SRL from San Juan, Argentina for the kind provision of up-to-date data on actual regional construction costs of PV generation facilities.

5. References

[1] International Energy Agency (IEA), PVPS Report Snapshot of Global PV 1992-2013, Report IEA-PVPS T1-24, 2014.

[2] International Energy Agency (IEA), 2019 Snapshot of Global PV Markets, Report IEA PVPS T1-35, 2019.

[3] International Energy Agency (IEA), World Energy Outlook 2018, Nov. 2018.

[4] SolarPower Europe, Global Market Outlook for Solar Power, 2019 – 2023, 2019.

[5] Frankfurt School-UNEP Centre/BNEF. Global Trends in Renewable Energy Investment 2018.

[6] A. Jäger-Waldau, PV Status Report 2018. Joint Research Centre (JRC), European Commission.

[7] B. Fernandes, J. Cunha, P. Ferreira, "The use of real options approach in energy sector investments," Renewable and Sustainable Energy Reviews, vol. 15, pp. 4491–4497, 2011.

[8] E. S. Schwartz, L. Trigeorgis. Real options and investment under uncertainty: classical readings and recent contributions, MIT Press, Cambridge, MA, 2004.

[9] S. P. Feinstein, D. M. Lander, "A better understanding of why NPV undervalues managerial flexibility," The Engineering Economist, vol. 47, no. 4, pp. 418-435, 2002.

[10] A. Keswani, M. B. Shackleton, "How real option disinvestment flexibility augments project NPV." European Journal of Operational Research, vol. 168, no. 1, pp. 240-252, 2006.

[11] S. C. Myers, "Finance Theory and Financial Strategy," Interfaces, vol. 14, no. 1 pp. 126-137, 1984.

[12] F. Black, M. Scholes, "The pricing of options and corporate liabilities," Journal of Political Economy, vol. 81, no. 3, pp. 637-654, 1973.

[13] J. Cox, S. Ross, M. Rubinstein, "Option pricing: a simplified approach," Journal of Financial Economics, vol. 7, pp. 229-263, 1979.

[14] P. Boyle, "Options: A Monte Carlo approach," Journal of Financial Economics, vol. 4(3), pp. 323-338, 1977.

[15] R. Merton, "An intertemporal capital asset pricing model", Econometrica, vol. 41(5), pp. 867-887, 1973.

[16] J. Cox, J. Ingersoll, S. Ross, “An intertemporal general equilibrium model of asset prices”, Econometrica, vol. 53(2), pp. 363-384, 1985.

[17] F. A. Longstaff , E. S. Schwartz, “Valuing American options by simulation: A simple least squares approach”, Review of Financial Studies, vol. 14, no. 1, pp. 113-147, 2001.

[18] H. B. Nembhard, A. Mehmet, Real options in engineering design, operations, and management. London, CRC Press, 2010.

[19] R. Pringles, F. Olsina, F. Garcés, “Opciones reales en la evaluación de inversiones en mercados eléctricos competitivos – Estado del arte,” Proceedings of the XII ERIAC - CIGRÉ, Foz do Iguazú, Brasil, May 2007.

[20] E. A. Martinez-Cesena, J. Mutale, “Real option theory applied to electricity generation projects: A review,” Renewable and Sustainable Energy reviews, vol. 19, pp. 573-581, 2013.

[21] K. Dykes, R. de Neufville, “Real options for a wind farm in Wapakoneta, Ohio: Incorporating uncertainty into economic feasibility studies for community wind”, World Wind Energy Conference, Ontario, Canada, 2008.

[22] H. Cheng, Y. Hou, F. Wu, “Wind power investment in thermal system and emissions reduction. Proceedings of IEEE PES General Meeting. Minneapolis, USA, 2010.

[23] J. Muñoz, J. Contreras, J. Caamano, P. Correia, “Risk assessment of wind power generation project investments based on real options,” Proceedings of IEEE Power Tech, Romania, 2009.

[24] M. Monjas-Barroso, J. Balibrea-Iniesta, "Valuation of projects for power generation with renewable energy: A comparative study based on real regulatory options," Energy Policy, vol. 55, pp. 335–352, 2013.

[25] M. Kozlova, “Real option valuation in renewable energy literature: Research focus, trends and design”, Renewable and Sustainable Energy Reviews, vol. 80, pp. 180-196, 2017.

[26] L. Liu, M. Zhang, Z. Zhao, “The application of real option to renewable energy investment: A review”, Energy Procedia, vol. 158, pp. 3494-3499, 2019.

[27] Hoff, T.E., Margolis, R., Herig, C., 2003. A simple method for consumers to address uncertainty when purchasing photovoltaics, http://www.cleanpower.com/Research, 2003.

[28] J. Sarkis, M. Tamarkin, “Real options analysis for renewable energy technologies in a GHG emissions trading environment” in Emissions trading: Institutional design, decision making and corporate strategies. New York: Springer; 2008. pp. 103-119.

[29] E. A. Martinez-Cesena, J. Mutale, “Assessment of demand response value in photovoltaic systems based on real options theory”, Proceedings of IEEE PowerTech, Trondheim, Norway, 2011.

[30] E. A. Martinez-Cesena, B. Azzopardi, J. Mutale, “Assessment of domestic photovoltaic systems based on real options theory”, Progress in Photovoltaics: Research and Applications, vol. 21, pp. 250–262, 2013.

[31] B. Ashuri, H. Kashani, "A real options approach to evaluating investment in solar ready buildings," Proceedings of Congress on Computing in Civil Engineering, Florida, USA, 2011.

[32] S. Weibel, R. Madlener, "Cost-effective design of Ringwall storage hybrid power plants: a real options analysis", Energy Conversion Management, vol.103, pp. 871-885, 2015.

[33] M. R. Gahrooei, Y. Zhang, B. Ashuri, G. Augenbroe, "Timing residential photovoltaic investments in the presence of demand uncertainties", Sustainable Cities and Society, vol. 20, pp. 109-123, 2016.

[34] C. Cheng, W. Zhen, L. Mingming, C. Qiang, P. G. Abimelech, R. Xiaohang, "Defer option valuation and optimal investment timing of solar photovoltaic projects under different electricity market systems and support schemes", Energy, vol. 127, pp. 594-610, 2017.

[35] M. Zhang, D. Zhou, P. Zhou, "A real option model for renewable energy policy evaluation with application to solar PV power generation in China", Renewable and Sustainable Energy Reviews, vol. 40, pp. 944-955, 2014.

[36] J. Sesmero, J. Jung, W. Tyner, "The effect of current and prospective policies on photovoltaic system economics: An application to the US Midwest", Energy Policy, vol. 93, pp. 80-95, 2016.

[37] B. Lin, P. K. Wesseh, "Valuing Chinese feed-in tariffs program for solar power generation: A real options analysis", Renewable Sustainable Energy Reviews, vol. 28, pp. 474-482, 2013.

[38] K. Torani, G. Rausser, D. Zilberman, "Innovation subsidies versus consumer subsidies: A real options analysis of solar energy", Energy Policy, vol. 92, pp. 255-269, 2016.

[39] C. Jeon, J. Lee, J. Shin, "Optimal subsidy estimation method using system dynamics and the real option model: Photovoltaic technology case", Applied Energy, vol. 142, pp. 33-43, 2015.

[40] R. Pringles, F. Olsina, F. Garcés, "Real option valuation of power transmission investments by stochastic simulation," Energy Economics, vol. 47, pp. 215–226, 2015.

[41] A. Gamba, "Real Options Valuation: A Monte Carlo Approach", Faculty of Management, University of Calgary, WP No. 2002/3, EFA 2002 Berlin Meetings Presented Paper, 2003.

[42] Annual Energy Review, Energy Information Administration (EIA), US Department of Energy, Washington, DC. 2011.

[43] 2018 Monthly Solar Photovoltaic Module Shipments Report, Energy Information Administration, US Department of Energy, Washington, DC, 2018.

[44] F. Penizzotto, R. Pringles, F. Olsina, Real options valuation of photovoltaic power investments in existing buildings, Renewable and Sustainable Energy Reviews, vol. 114, art.109308, 2019.

[45] A. Dixit, R. Pindyck, Investments under Uncertainty, Princeton University Press, 1994.

[46] R. Marathe, S. Ryan, "On the validity of the geometric Brownian motion assumption", Engineering Economics, vol. 50(2), pp. 159–192, 2005.

[47] S. Martzoukos, L. Trigeorgis, "Real (investment) options with multiple sources of rare events", European Journal of Operational Research, vol. 136, pp. 696-706, 2002.

[48] S. Martzoukos, E. Zacharias, "Real option games with incomplete information and spillovers", International Real Options Conference 2002, Paphos, Cyprus.

[49] Y. Daming, Y. Xiaohui, D. D. Wu, C. Guofan, "Option game with Poisson jump process in company radical technological innovation", Technological Forecasting and Social Change, vol 81, 341-350, 2014.

[50] R. Merton, "Option pricing when underlying stock returns are discontinuous", Journal of Financial Economics, vol. 3 (1-2), 125-144, 1976.

[51] M. Ohnishi, "An optimal stopping problem for a geometric Brownian motion with Poissonian jumps", Mathematical and Computer Modelling, vol. 38(11-13), pp. 1381-1390, 2003.

[52] M. Sørensen. Likelihood methods for diffusions with jumps, in NU Prabhu & IV Basawa (eds.), Statistical Inference in Stochastic Processes. Marcel Dekker, New York, USA, pp. 67-105, 1991.

[53] Ramezani, Cyrus A. and Zeng, Yong, Maximum Likelihood Estimation of Asymmetric Jump-Diffusion Processes: Application to Security Prices, Dec. 1998. Available at SSRN: http://dx.doi.org/10.2139/ssrn.606361

[54] I. Erlich, G. Venayagamoorthy, N. Worawat, A mean-variance optimization algorithm, IEEE Congress on Evolutionary Computation, Barcelona, Spain, July 2010.

[55] R. Cont, P. Tankov, "Financial modelling with jump processes", in Chapman & Hall/CRC, Financial Mathematics Series, Chapman & Hall, CRC Press, 2003.

[56] L. Trigeorgis, Real Options: managerial flexibility and strategy in resource allocation, MIT Press, 1996.

[57] PVWatts® Calculator. National Renewable Energy Laboratory (NREL). Available at: https://pvwatts.nrel.gov/

[58] G. Maclaurin, W. Cole, A. Lopez, A. Reimers, E. Rosenlieb, B. Roberts, "Understanding inter-annual variability of PV energy production in the contiguous United States", 2018 International Conference on Probabilistic Methods Applied to Power Systems (PMAPS), Boise, ID, USA, 24-28 June 2018.

[59] Argentinean Secretary of Energy, Disposition DI-2019-91-APN-SSERYEE#MHA. Aug 02, 2019. Available at: http://licitaciones.cammesa.com/wp-content/uploads/2019/08/DI-2019-69455178-APN-SSERYEE-MHA.pdf

[60] R. Brealey, S. Myers, F. Allen, Principles of Corporate Finance, 12th edition, McGraw-Hill/Irwin, 2016.

Highlights

- *Uncertainty and flexibility are key in photovoltaic generation investments*
- *Defer and relocate solar investments allow flexibility to handle uncertainties*
- *Classic valuation approaches neglect flexibility and undervalue solar projects*
- *Real Options analysis accounts for the flexibility value embedded in PV investments*
- *Valuation framework may change investment decisions and renewable energy policies*