

The Value of Investing in Domestic Energy Storage Systems

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Abstract. In this paper, we investigate whether investments in battery storage systems, coupled with existing PV plants, are profitable in the phasing out of incentives. In detail, we analyze the investment decision of a household, who has already invested in a PV plant and has to decide whether and when to invest in the adoption of battery storage systems (BSS). We provide a Real Option Model to determine the value of the opportunity to invest and its optimal timing. The existing PV plant gives the household the opportunity to invest in BSS adoption, and this opportunity is analogous to a call option. Our findings show that negative NPV investments may turn to be profitable if the household optimally exercises the option to defer. The greater the volatility of energy prices, the greater the option value to defer, and the greater the opportunity cost of waiting (i.e., the greater the energy prices drift), the smaller the option value to defer.

Keywords: Energy storage system · Photovoltaic power plant · Real options

1 Introduction

In the last decade, the European Union set priority targets to mitigate climate change effects and promote energy transition from fossil fuels to renewable energy sources (RES). European Directives 2009/28/EC [1] and 2009/29/EC [2] classified the power sector as one of the most relevant sectors in accelerating the achievement of both the 20-20-20 targets and those set in the 2030 Climate and Energy Framework. Key targets for 2030, as revised upwards in 2018, are a 40% cut in greenhouse gas emissions compared to 1990 levels, at least a 32% share of renewables and at least 32.5% improvement in energy efficiency [3]. RES are therefore expected to play a key role in achieving these challenging goals and in the near-future global energy portfolio [4–7].

Compared to other RES, solar photovoltaic (PV) power plants have a large potential for electricity generation and represent a milestone in the pathway from a fossil-based to a carbon-neutral power sector [8]. In recent years, a large market penetration of PV plants occurred due to price reductions by over 80% from 2008 to 2016 in most competitive markets [9] and to policy incentives [10, 11]. PV already reached cost competitiveness in 2012 in several EU regions (e.g. Southern Germany, Southern Italy, Crete, etc.) and, according to the International Renewable Energy

© Springer Nature Switzerland AG 2020
O. Gervasi et al. (Eds.): ICCSA 2020, LNCS 12250, pp. 148–161, 2020.
https://doi.org/10.1007/978-3-030-58802-1_11

Agency (IRENA), cheaper modules are accelerating the achievement of grid parity in the global solar industry by 2020. Consequently, solar PV may become the competitive backbone of energy transition [12]. Nonetheless, there still exist several barriers to a widespread penetration of PV power generation. PV electricity generation is intermittent and energy storage is required to favor its large-scale deployment [13, 14]. Battery storage systems (BSS) can in fact increase the profitability of residential PV plants and in turn counterbalance the progressive reduction of policy supports, which are expected to be completely abolished in the next years [9, 15–17]. Storage represents a valuable solution to increase electricity self-consumption and reduce households' energy costs [18–21]. Storage units can store excess electricity generated when PV production exceeds demand and reduce the need for grid-purchased electricity when the PV plant is inactive (e.g., when solar irradiation is low or at nighttime). By reducing electricity bills, which represent a hidden housing ownership cost, BSS can contribute reducing households' operating expenses and increase property market value [22, 23][1]. In this context, lithium-ion and lead-acid batteries are the mostly investigated storage systems in literature. Compared to other batteries (e.g., sodium-Sulphur, vanadium redox flow), they proved to be the most cost-effective technologies in increasing self-consumption shares, especially in residential projects [4, 15, 26, 27]. Nonetheless, according to a recent literature review by D'Alpaos et al. [28], there is an ongoing debate in literature on the profitability of investments in small-scale PV plants paired with BSS. Naumann et al. [29], Cucchiella et al. [4], Cuchiella et al. [5], Hassan et al. [30] and Uddin et al. [31] argued that BSS investment costs represent still a barrier to investments. According to Naumann et al. [29], Hassan et al. [30] and Schopfer et al. [9], a cost-effective scenario may arise conditional to their costs reducing by at least 50%. In contrast with the above findings, Arik et al. [26], Olaszi and Ladanyi [32], Abbas et al. [33] and Koskela et al. [8] found that investments in domestic BSS are already profitable, although incentives or real-time pricing schemes are fundamental factors in their widespread adoption. Whereas, Hoppmann et al. [15] proved the need for incentive schemes in the short run as long as investment costs are high.

This paper contributes to this debate. Investments in PV power plants coupled with storage are characterized by high irreversibility and significant uncertainty over energy prices, which affect the trade-off between investment costs and the present value of expected benefits arising from increases in self-consumption. Traditional capital budgeting techniques and, specifically the Net Present Value (NPV) rule, fail to capture the strategic impact of investment projects and the additional value deriving from the opportunity to delay an investment decision. The NPV rule informs investment decisions according to a now-or-never proposition, that is if the investor does not make the investment now, the opportunity is lost forever. By contrast the Real Option approach, firstly proposed by Myers [34], Kester [35] and McDonald and Siegel [36, 37], provides a theoretical framework to account for the value of flexibility of deferring investments, by drawing valuation procedures from the body of knowledge developed for financial options [38].

[1] Real estate assets, which are powered by RES and generate smaller carbon footprints, are in fact more attractive for prospective homebuyers [24, 25].

In this paper, we analyze the investment decision of a grid-connected household, who had already invested in a PV power plant and has the opportunity to decide whether and when it is optimal to invest in a storage system, namely a rechargeable lithium-ion battery. In detail, we develop and implement a Real Option model to determine BSS investment value and optimal investment timing. Due to the growth option embedded in the existing PV plant, the opportunity to invest in the storage system is analogous to a call option, which can increase the PV plant value if optimally exercised.

The remainder of the paper is organized as follows. In Sect. 2 the stochastic optimization model is provided; Sect. 3 illustrates model calibration and parameters estimates; in Sect. 4 results are illustrated and discussed; Sect. 5 concludes.

2 Model

Starting from the seminal works by Bertolini et al. [17] and D'Alpaos et al. [28], we investigate the investment decision of a grid-connected household, who has already invested in a domestic PV plant and has to decide the optimal investment strategy in BSS, in order to increase self-consumption (i.e., the share of total PV production directly consumed by the plant owner).

The opportunity to install BSS and store PV energy production permits to reduce energy quotas grid-purchased to satisfy demand during time intervals of plant inactivity.

We introduce the following simplifying assumptions.

Assumption 1
Household's energy demand d per time unit is normalized to $d = 1$ and specifically:

$$d = \xi a + \gamma \tag{1}$$

where a is total PV power generation per unit of time, ξa is the self-consumption quota per unit of time, and γ is the grid-purchased energy quota per unit of time.

Stored energy quota is:

$$s(a) = \eta(a - \xi a) \tag{2}$$

where $\eta \in [0,1]$ is the rate of battery efficiency losses. As in Schopfer et al. [9] and D'Alpaos et al. [28], we assume that battery capacity fades out linearly over time and, due to this capacity degradation [31, 39, 40], the effective usable capacity (i.e., η) can be approximately set in between 100% and 80% of nominal battery capacity, namely 90%.

Assumption 2
In order to increase self-consumption and consequently reduce grid-purchased energy quotas, the household can decide to install a battery. According to literature, it is in fact

possible to increase self-consumption by 13–30% points with a battery storage capacity of 0.5–1.5 kWh per installed kW PV power [4, 5, 18, 41] compared to initial self-consumption rate. Whereas by installing a battery storage capacity of more than 1.5 kWh per installed kW PV power, self-consumption does not significantly increase, and the investment is not cost-effective [41][2].

For the sake of simplification, we assume that the increase in self-consumption quota due to BSS adoption is equal to stored energy quota:

$$s(a) = \eta(a - \xi a) = \Delta(\xi a) \tag{3}$$

where $\Delta(\xi a)$ is the increase in self-consumption.

Assumption 3
BSS investment costs I are irreversible and related to the Levelized Cost of Storage [17, 28]. The Levelized Cost of Storage (LCOS) is a metric, which reflects the unit cost of storing energy. It relates to the "minimum price that investors would require on average per kWh of electricity stored and subsequently dispatched in order to break even on their investments" [46, p.1].

Operation and maintenance costs are negligible [17, 41, 47–49] and consequently set equal to zero. The battery salvage value S is set equal to zero as well.

Assumption 4
Energy produced by the PV plant is not sold in the electricity market, nor energy stored in the battery. Battery adoption is meant to store excess energy quotas produced by the PV plant (i.e., not instantaneously self-consumed) for future self-consumption (e.g., when solar irradiation is low or at nighttime). The above assumption is non-restrictive and it reasonably mimics real world situations, in which BSS are usually installed to increase self-consumption and reduce grid-supplied energy quotas [15, 18, 30, 31, 50–55].

Assumption 5
The buying price of energy is stochastic and evolves over time according to a Geometric Brownian Motion (GBM). This assumption is line with many contributions in literature which adopt a GMB to describe price dynamics [17, 28, 56–59]:

$$dp_t = \mu p_t dt + \sigma p_t dz_t \quad p_0 = p \tag{4}$$

where dz_t is the increment of a Wiener process, μ is the drift term (lower than the market risk-adjusted rate of return $\hat{\mu}$, i.e. $\mu < \hat{\mu}$) and σ is instantaneous volatility.

[2] For larger capacities, BSS can only partially discharge during night and the next-day excess PV power will limit battery charge. Since nowadays energy consumption is particularly high in the evening, when there is not PV power generation, BSS are mostly used to satisfy night-time energy demand [17, 42–45]. By storing surpluses in PV production during daytime activity, BSS discharge in late afternoon, night, and early morning, when PV generation is insufficient [18].

According to assumptions 1–5, the household's net benefit Π generated by BSS adoption is:

$$\Pi_t = p_t \Delta(\xi a) + S_t \tag{5}$$

and the battery system present value V[3] in a risk-neutral world [60–62] is:

$$V(\Pi_0) = E\left\{ \int_0^{T_r-\tau} \left(e^{-rt}\Pi_t^A\right) dt \right\} \equiv \frac{\Pi}{\delta}\left(1 - e^{-\delta(T_r-\tau)}\right) \quad \Pi_0 = \Pi \tag{6}$$

where E is the expectation operator under a risk-neutral probability measure, r is the risk-free discount rate, T_r is the PV plant residual life, τ is the investment exercise time and δ (i.e., $\delta \equiv \hat{\mu} - \mu > 0$) is the opportunity cost of investing at time t = 0 in the battery instead of in a same-riskiness financial security [36][4].

The value of BSS is strongly related to the increase in self-consumption and the reduction in grid-purchased energy, which in turn generates cost savings.

The opportunity to invest in BSS is analogous to a European call option on a constant dividend-paying asset (i.e., the BSS):

$$F(\Pi_t, t) = E_t\left\{ e^{-r(\tau-t)} \max\left[(V(\Pi_t) - I)^+, 0 \right] \right\} \tag{7}$$

The solution of (7) is given by the well-known formula derived by Black and Scholes [63]:

$$F(\Pi_t, t) = e^{-\delta(\tau-t)}\Phi(d_1)\mathrm{V}_t - e^{-r(\tau-t)}\Phi(d_2)I \tag{8}$$

subject to the terminal condition [62]:

$$\lim_{\tau \to \mathrm{T_r}} F(\Pi_\mathrm{t}, \tau) = \lim_{\tau \to \mathrm{T_r}} \max\left\{ (V(\Pi_\mathrm{t}) - I)^+, 0 \right\} = 0 \tag{9}$$

where

$$d_1(V_t) = \frac{\ln(V_\mathrm{t}/I) + \left(r - \delta + \sigma^2/2\right)(\tau - t)}{\sigma\sqrt{\tau - t}}, \quad d_2(\mathrm{V}_t) = d_1(\mathrm{V}_t) - \sigma\sqrt{\tau - t} \tag{10}$$

and $\Phi(x)$ is the cumulative standard normal distribution function.

[3] Under the hypothesis that markets are complete, the investment present value coincides with the expected value of discounted cash flows it generates.

[4] It can be easily demonstrated that $\delta \equiv \hat{\mu} - \mu > 0$ [36, 62]. In addition, $\hat{\mu} = r + MRP$, where MRP is market risk premium and $r - \delta$ is the certainty equivalent rate of return.

3 Model Calibration

As in D'Alpaos et al. [28], we consider a household connected to a national grid under a variable rate contract[5], whose expected energy demand on a yearly basis is constantly equal to 1 MWh/y. The household has already invested in a 3 kW PV plant, which represents the average nominal power installed in domestic PV plants in Italy[6].

To calibrate the model we use data driven from the Italian electricity market, recorded in the period April 2004-September 2019.

- The PV plant production a for a 3 kW PV plant is equal to 1500 kWh/year[7].
- The PV plant lifetime T_u is 25 years [10] and its residual life is $T_r = 20 < T_u$.
- The battery lifetime is $T_b = 13$ years [53, 64].
- The price p_t paid by household consumers for grid-purchased energy is indexed to the National Single Price (PUN). It can be demonstrated that p_t evolves over time following a GBM [17, 56–59, 65]. According to recent estimates by D'Alpaos et al. [28], we set $\mu = 1\%$, $\sigma = 34.87\%$ and $p_0(t = 0) = 54$ €/MWh[8].
- Based on Ciabattoni et al. [66], Kastel and Gilroy-Scott [10] and Cucchiella et al. [5], we set $\xi = 0.4$. In addition, according to literature we assume that self-consumption increases by 15%, 20% and 30% points respectively with a battery storage capacity of 0.5, 1.0 and 1.5 kWh per installed kW PV power, respectively [4, 18, 41]. In other words, $\Delta(\xi a) = 15\%$, 20% and 30% respectively.
- Investments costs I accounts for construction and installation costs, plus maintenance and operating costs, integration costs, and indirect costs related to efficiency losses in storage capacity. Following Bertolini et al. [17] and D'Alpaos et al. [28], we assume, as reference value for LCOS, LCOS = 220 €/MWh [9, 67]. Battery investment costs are reported in Table 1.
- The risk free rate of return is equal to the interest rate on Italian Treasury Bonds (BTPs) maturing at 20 years. According to the Italian Department of the Treasury (Dipartimento del Tesoro)[9] $r = 2\%$.
- The opportunity cost $\delta = \hat{\mu} - \mu$, is equal to $\delta = 3.5\%$ and it is estimated by calculating the risk-adjusted rate of return according to the Capital Asset Pricing

[5] In Italy, variable rate contracts are based on the National Single Price (PUN), i.e., the average of Zonal Prices in the Day-Ahead Market, weighted for total purchases and net of purchases for Pumped-Storage Units and of purchases by Neighboring Countries' Zones (http://www.mercatoelettrico.org/en/). Under these contracts, prosumers are price-takers.

[6] This installed power can satisfy the average demand of a household of four people. (http://www.fotovoltaiconorditalia.it/idee/impianto-fotovoltaico-3-kwdimensioni-rendimenti).

[7] On average, in Northern Italy, a 1-KW plant produces about 1100 1500 KWh/year, whereas in the South, due to more favorable weather conditions, the average is 1500–1800 KWh/year (www.fotovoltaicoenergia.com; http://re.jrc.ec.europa.eu/pvgis/).

[8] p_0 at time t = 0 is calculated as the average of PUN yearly prices in the period January 2016-September 2019 provided by Gestore Mercati Energetici (GME), a company owned by the Ministry of Economy and Finance, which operates power, gas and environmental markets, vested with the organisation and economic management of the wholesale Power Market.

[9] http://www.dt.tesoro.it/export/sites/sitodt/modules/documenti_it/debito_pubblico/dati_statistici/Principali_tassi_di_interesse_2015.pdf.

Model, i.e. $\hat{\mu} = r + \beta RP$, where βRP is the market risk premium and β measures systematic risk. In line with Bertolini et al. [17], we set $\beta = 0.5$ and $RP = 5\%$.

Table 1 summarizes parameters estimate.

Table 1. Parameters estimates.

Parameter	Value		
a	1500 kWh/kWp		
T	25		
T_r	20		
T_b	13		
μ	1%		
σ	34.87%		
p_0	54 €/MWh		
ξ	40%		
Δ(ξa)	Increase in self-consumption due to BSS adoption	0.5 kWh/kWp	15%
		1 kWh/kWp	20%
		1.5 kWh/kWp	30%
I	Battery storage capacity (kWh/kWp)	0.5 kWh/kWp	2967 €
		1 kWh/kWp	5934 €
		1.5 kWh/kWp	8901 €
r	2%		
$\hat{\mu}$	4.5%		
δ	3.5%		

4 Results and Discussion

According to our results, when $\mu = 1\%$ and $\sigma = 34.87\%$, the investment NPV is negative and it is equal to −2443 Euros, −5235 Euros and −7853 Euros for battery storage capacity kWh per PV kWp of 0.5, 1.0 and 1.5 kWh per installed kW PV power, respectively. Nonetheless, as shown in Fig. 1, by postponing the decision to invest, BSS adoption becomes profitable although the value of the opportunity to invest is negligible. When $\tau = 1$ year, the value of F is non-negative but approximately zero, for any increase in self-consumption rate. F is concave in τ and when $\tau = T_r = 20$ years F is null, for any self-consumption rate. The optimal investment timing when $\Delta(\xi a) = 15\%$ is equal to $\tau = 11$ years and the opportunity to invest is $F = 5.20$ Euros. For increasing self-consumption rates, F decreases, due to significant increases in BSS investment costs.

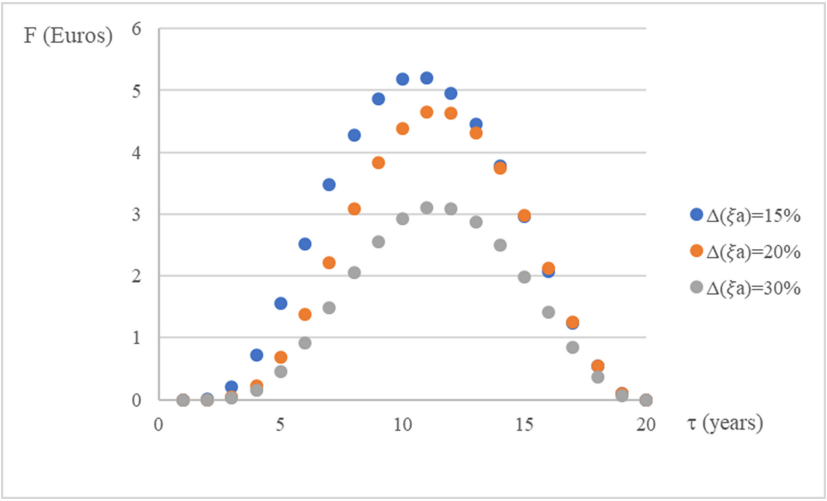


Fig. 1. Value of the opportunity to invest F for $\mu = 1\%$, $\sigma = 34.87\%$, $\Delta(\xi a) = 15\%, 20\%, 30\%$.

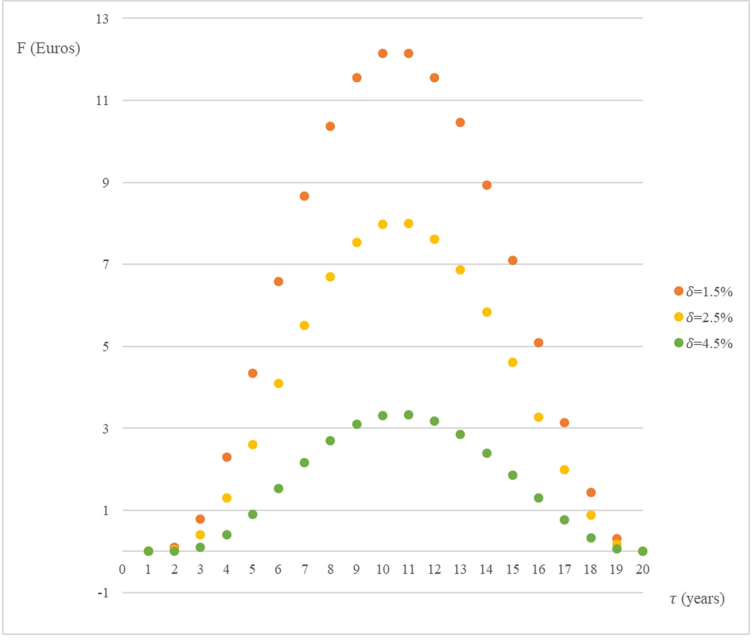


Fig. 2. Value of the opportunity to invest F for $\sigma = 34.87\%$, $\Delta(\xi a) = 15\%$, $\delta = 1.5\%, 2.5\%, 4.5\%$.

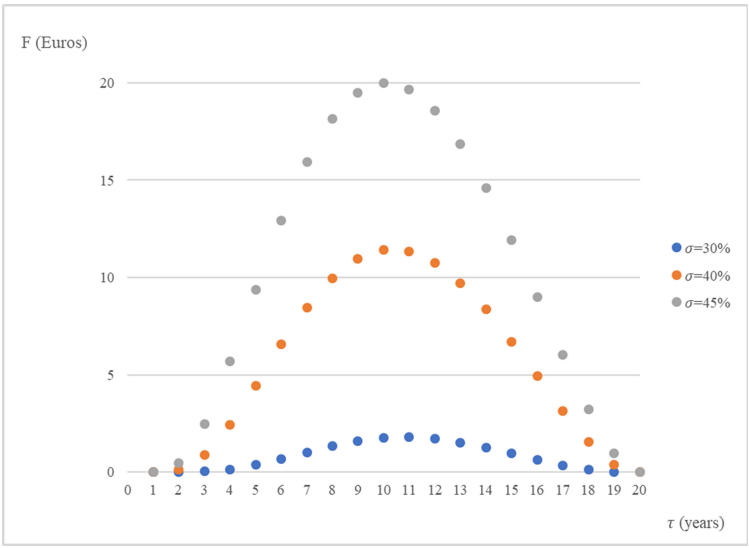


Fig. 3. Value of the opportunity to invest F, for $\Delta(\xi a) = 15\%$, $\mu = 1\%$ and $\sigma = 30\%$, 40%, 50%.

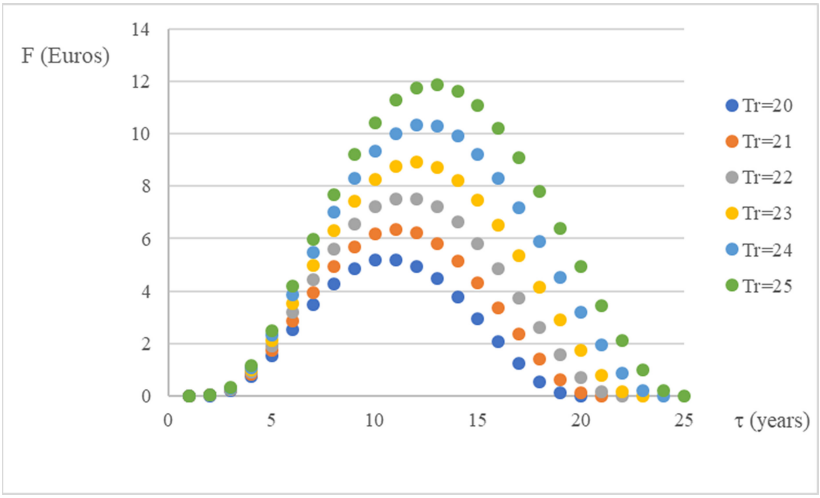


Fig. 4. Value of the opportunity to invest F for $\mu = 1\%$, $\sigma = 34.87\%$, $\Delta(\xi a) = 15\%$, and $T_r = 20$, 21, 22, 23, 24, 25 years.

To test the model results, we performed comparative statics by considering $\Delta(\xi a) = 15\%$. Ceteris paribus, for increasing values of the opportunity cost of waiting δ (i.e., when μ increases), the value of the opportunity to invest decreases and, in turn, the option value to defer decreases (Fig. 2). By contrast, in line with usual Real Options theory results, for increasing volatility of energy prices σ, the option value to defer

increases and, in turn, the value of the opportunity to invest F increases (Fig. 3). As volatility increases, the value of new information to come, which allows to avoid costly errors and reduce potential losses, increases.

It is worth noting that for increasing values of PV plant residual life T_r, the value of the opportunity to invest and the optimal investment timing increase.

Results illustrated in Fig. 4 clearly show the trade-off between the option value to postpone and the opportunity cost of waiting to invest. The longer the household waits to invest in BSS adoption, the lower the benefits arising from costs saving throughout the PV plant residual life.

In our simulations, battery salvage value is set equal to zero. Nevertheless, by introducing a positive salvage value, results would not substantially change and F would be still concave in τ. A positive salvage value might affect the optimal investment timing and the value of the opportunity to invest. Under the hypothesis of a null salvage value, we obtain a cautious estimate of the option value.

Our results show that, in line with literature [4, 5, 29–31], at current investment costs, batteries are not profitable and their costs represent a significant barrier to BSS adoption. As long as the value of the opportunity to defer is positive, households prefer to postpone BSS adoption, regardless BSS guarantee high self-consumption rates (i.e., 30%) and thus ensure high cost savings.

By considering the value of investment timing flexibility, the set of households' investment strategies enlarge: a negative (static) NPV project, rejected a priori, might be a positive NPV project according to the Real Option approach.

5 Conclusions

In this paper, we investigated whether households may be willing to invest in BSS adoption at current energy market prices, regardless incentive schemes. In detail, we proposed a theoretical and methodological framework, based on the Real Options approach, to determine the value of investing in BSS and its optimal timing. We modeled the opportunity to invest as a call option and investigated whether and to which extent investment value is affected by energy price volatility and investment timing flexibility. The Real Options theory suggests that investment timing flexibility, and specifically the option to defer, has a monetary value and guarantees to limit potential losses by reducing the cone of uncertainty and hedging investment risks.

Our results show that negative NPV investments may turn to be profitable in the future, whenever households exercise the option to defer optimally. At current energy prices, the optimal investment strategy is to defer investment, as the investment NPV is negative. By waiting to investment one year, the investment turns out to be a non-negative NPV investment. The value of the opportunity to invest is concave in exercise time and the investment value is maximum if undertaken at its optimal investment timing. Our findings provide households the optimal investment strategy: i.e., to postpone investment until the optimal investment timing is reached. The higher the volatility of energy prices, the higher the option value to defer; whereas the higher the energy prices drift, the higher the opportunity cost of waiting and, in turn, the smaller the option value to defer.

Future research opportunities will focus on modeling potential decreases in battery costs in order to identify BSS price that triggers investment and investigating whether incentive policy designed to promote self-consumption, rather than PV power generation, can effectively accelerate investments in storage systems.

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