A SOLAR PV PROFITABILITY STUDY AS A FUNCTION OF WHOLESALE MARKET PRICE VARIATION PATTERNS

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ABSTRACT: Non-incentivized utility-scale PV systems (typically relying on selling the produced electricity on the wholesale spot day-ahead market) have been appearing on the market in the last years. In 2021, 17% of the global annual market was deployed under such business models and it is expected that this share will continue to grow [1][2]. In parallel, key components of the energy transition (higher PV penetration, electrification of heating, cooling and mobility needs, astorage, power-to-X, …) may impact wholesale electricity price patterns by altering electricity supply demand imbalance in one direction or the other. Therefore, this study is a prospective analysis which assesses how different variations of electricity price patterns could impact PV profitability. Based on the developed methodology, the impacts of different wholesale electricity price patterns (daily patterns, seasonal patterns and occurrence of negative prices) on the profitability of a 50 MWp PV system under two business models have been assessed. Results take the form of charts displaying the NPV (Net Present Value).
Keywords: Economic Analysis, Price Modelling, Electricity Markets, Large Grid-connected PV systems

1 CONTEXT

Non-incentivized utility-scale PV systems have been increasingly appearing on the market in the last years. In 2021, 17% of the global annual market was developed under such business model. Most of this share is attributable to the annual Chinese non-incentivized centralized PV market, but merchant PV development can also be seen in Europe (e.g., Germany, Spain). Moreover, this trend is anticipated to reinforce in the next decade, especially considering the phasing out of support mechanisms on mature PV markets. A recently published report suggests that between 2021 and 2030 as much as 60GW of subsidy-free solar PV could be installed in north-western Europe (UK, Germany, France, Ireland, the Netherlands and Belgium) [1][2]. For non-incentivized solar PV, the applied business models often rely on selling the produced electricity on the wholesale spot day-ahead market. This is also the case for installations with corporate Power Purchase Agreements (PPAs), where the agreements rarely cover the whole production, and the remaining electricity will also be sold on the wholesale market.

In parallel, key components of the energy transition (higher PV penetration; electrification of heating, cooling and mobility needs; battery storage deployment, …) will impact wholesale electricity prices' patterns as they will alter the supply-demand balance. Depending on the relative pace at which these different elements develop, opposite impacts on wholesale electricity prices' variations may be observed. Therefore, electricity prices and their variations, will be a decisive variable to take into account in the future when estimating the profitability of utility-scale photovoltaic systems. However, regardless of the timeframe considered, the evaluation of this impact is complex since wholesale market prices are influenced by a great variety of factors arising from the demand side (electrification, demand-side flexibility, …), from the supply side (renewable energy systems' penetration, fossil fuels' prices, carbon prices…) or from other independent factors such as the weather [3].

2 AIM AND APPROACH

Previous studies have focused on determining electricity wholesale market prices' patterns at different time scales, in the frame of a fully decarbonized power systems on the long term (2050 horizon) [4]. Other studies focused on determining the average electricity wholesale market price in the frame of different scenarios on the medium term or on highlighting the correlation between variable renewable energy (penetration or daily combined generation) and average wholesale electricity prices (daily or annual averages) [5][3][6]. These assessments are based on a precise quantitative description in terms of electricity generation mix, electricity demand of the industry and transport sectors, power-to-X and electrification of the demand.

However, these studies do not assess the various direct impacts of these variations of electricity wholesale market prices, for instance on the profitability of renewable energy assets. Moreover, the trajectory towards the assumed fully decarbonized power systems' scenarios is highly uncertain. Therefore, it remains very difficult to determine with a satisfactory level of certainty how electricity wholesale market prices will evolve in terms of time-dependent patterns (and not averages), on the short to medium term. Hence, it is important to consider multiple possible pathways of evolution when assessing the impacts of the variation of these electricity wholesale market prices. Otherwise, the analysis and its conclusions might reveal to be incomplete, thus irrelevant.

Such analysis is of primary importance for conventional actors of the PV sector, as it can help them foresee the evolution of their revenue streams and estimate the level of risk associated with solar PV assets. Even for those who already anticipated the paradigm shift from subsidized to unsubsidized business models, it is crucial to understand to what extent different possible patterns of electricity wholesale market prices on an hourly/daily/seasonal/annual basis as well as their variations could impact the profitability of solar PV assets. Indeed, one of the rising questions for stakeholders active in developing and operating large-scale PV power plants is related to the profitability of their installations in the context of rapidly evolving electricity markets.

This paper will address some of their key concerns by studying how two major business models could potentially be affected by changes in wholesale electricity pricing patterns. For this purpose, this paper deals with the economic and financial impact of wholesale electricity market prices' variation patterns on PV profitability, for various business models. The impact will be quantified through net present value calculations based on a Monte-Carlo analysis (given the inherent stochastic behavior of the selected modelling process). It is also strongly tied to the evolution of the renewable energy market at large (including electricity generating and storing units).

2.1 Simulation of electricity wholesale market prices

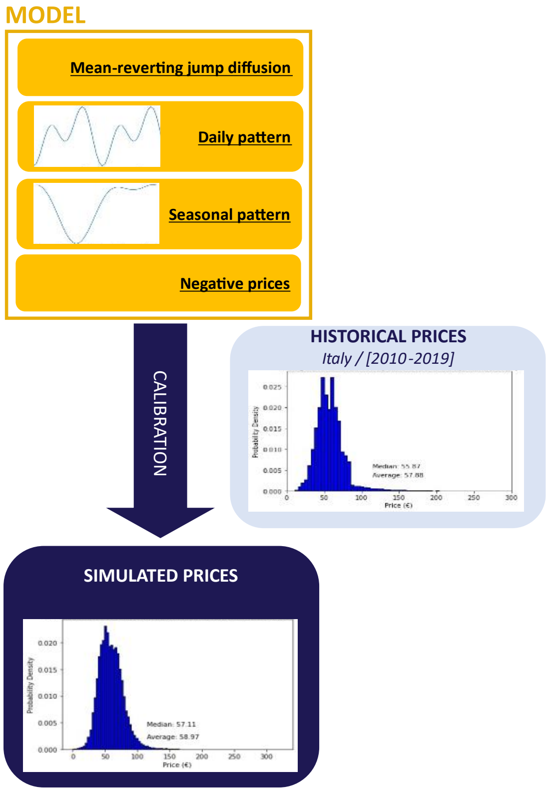

Figure 1: Schematic representation of the wholesale electricity price model developed and used.

Wholesale electricity market prices constitute the basis of this study. They have been simulated on an hourly basis, using Python thanks to a stochastic model (see formula below) based on four key characteristics of wholesale electricity price patterns (See Figure1).

a. Daily pattern: this component reflects the average evolution of electricity's supply-demand imbalance throughout the hours of the day. Typically, the highest prices are found during the morning and evening consumption peaks, while the lowest prices are found in the middle of the day and during the night when consumption is low.

b. Seasonal pattern: this component reflects the average evolution of electricity's supply-demand imbalance throughout the months of the year. Typically, the highest prices are found during the winter (respectively in the summer) when electricity consumption is increased to meet heating or lighting needs (respectively cooling needs), depending on the concerned region.

c. Mean-reverting and jump-diffusion process: this has been presented in several studies and papers as one of the relevant functions to model commodities such as electricity prices [7][8]. This process allows for volatility in prices and the occurrence of prices jumps which however rapidly revert to an average value.

d. Probability of occurrence of negative prices: this component reflects the occurrence of extreme electricity supply-demand imbalances throughout the year, on an hourly basis. Typically, the highest occurrence of negative prices is found during the night and at around mid-day when electricity consumption is particularly low while production (typically limitedly- or non-controllable) of electricity (e.g., nuclear or renewables) is high.

The following equations were used:

$$\log(Pt) = s(t_s) + d(t_d) + Xt$$

With:

Pt: the wholesale price of electricity

$s(t_s)$: a seasonal component

$s(t_s) = a0 + a1*\sin(2*pi*t_s) + a2*\cos(2*pi*t_s) + a3*\sin(4*pi*t_s)+a4*\cos(4*pi*t_s)$

t_s is the period of the sine and cosine functions used for the seasonal pattern (i.e., one year)

$d(t_d)$: a seasonal component

$d(t_d) = b0 + b1*\sin(2*pi*t_d) + b2*\cos(2*pi*t_d) + b3*\sin(4*pi*t_d)+b4*\cos(4*pi*t_d)$

t_d is the period of the sine and cosine functions used for the daily pattern (i.e., one day)

$$dXt = (\alpha - \kappa Xt)dt + \sigma dWt + J(\mu J,\sigma J)d\Pi(\lambda)$$

With:

α: mean reversion parameter

κ: mean reversion parameter

σ: volatility

Wt: standard Brownian motion

$J(\mu J, \sigma J)$: jump size with μJ a normally distributed mean and σJ a standard deviation

$\Pi(\lambda)$: Poisson process with a jump intensity of λ

In addition, a long-term decreasing trend is applied to the modelled electricity prices to reflect how the increased PV penetration will lead to an enhanced merit order effect. Considered PV penetration evolution scenario is based on the net-zero emission by 2050 in Europe scenario of researchers from Lappeeranta University of Technology (LUT) in Finland [9].

To set the different parameters used for the wholesale electricity market prices' simulation model, calibration based on real historical price data was conducted. Used historical dataset is a 10-years dataset (2010-2019) of hourly prices on the Italian market retrieved from Terna (Italian TSO) website [10]. The used historical dataset does not include 2020, 2021 and 2022, as prices during these years have been affected by highly conjunctural events (Covid-19, Ukraine war) and would have biased the wholesale electricity market prices modelling.

2.2 Studied deviations

Deviations from the current base case (based on real historical data) for three components of the wholesale electricity market price patterns have been studied. These are: daily patterns, seasonal patterns and occurrence of negative prices. These deviations can be supported by one or the other expected change(s) in terms of electricity usage, consumption and production in the energy transition context as non-exhaustively described below.

a. Daily pattern: Exacerbated daily price gaps (i.e., purple arrows) could be induced by higher PV penetration, higher electrification of energy consumption (e.g., heating, cooling and mobility needs). Attenuated daily price gaps (i.e., yellow arrows) could be induced by increased penetration of battery storage units, smart charging or stimulated electricity demand at times of the day when prices are the lowest.

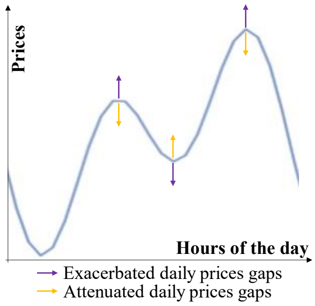

Figure 2: Studied deviations for wholesale electricity market prices' daily patterns

b. Seasonal pattern: Exacerbated seasonal price gaps (i.e., purple arrows) could be induced by higher PV penetration, higher electrification of season-dependent energy consumption (e.g., heating and cooling needs). Attenuated seasonal price gaps (i.e., yellow arrows) could be induced by increased penetration of seasonal storage units based on pumped hydro or green hydrogen, by power to X in general and by increasing interconnexion degrees of the national or regional European grids.

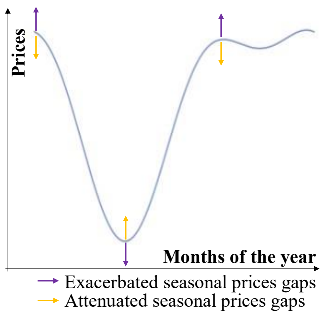

Figure 3: Studied deviations for wholesale electricity market prices' seasonal patterns

c. Occurrence of negative prices: the combination of an increased penetration of electricity generating units with low or inexistent marginal costs of production and with variable generation (such as renewables) as well as the preservation of electricity generating units with higher marginal costs (coal and gas-based power plants and to a lesser extent nuclear power plants), could lead to an increase of negative prices periods. This trend can already be observed on European wholesale electricity markets, with a twofold increase of negative prices hours in summer and spring between 2016 and 2017 and a four to fivefold increase between 2016 and 2019. [11]

As presented, given the high uncertainty related to the way and extent to which these wholesale electricity prices' patterns will be impacted in the short and medium term, they have been studied as part of a sensitivity analysis.

2.3 Reference case and business models for the analysis

The impact on PV profitability has been studied for a utility-scale ground-mounted PV system whose technical and economic characteristics are found in **Table I**.

Table I: Technical and economic characteristics of the studied utility-scale PV system

Variable	Value	Unit
Type	Ground-mounted	-
Capacity	50	MWp
Orientation	South	-
Tilt	30	°
AYI*	1,800	kWh/m².a
System lifetime	30	years
CAPEX	0,55	€/Wp
OPEX	9	€/kWp.a
WACC	6	%

* Average yearly irradiation

The impact on PV profitability has been studied for two different business models whose characteristics are found in **Table II**. The choice of these analyzed business models is supported by their increasing relevance for utility-scale PV and high dependency on wholesale market prices [2]. Note that many types of PPAs (Power Purchase Agreements) exist on the market. In order to facilitate the readability of the results and to focus on the analysis on the impact of wholesale electricity prices' pattern on PV profitability, only the case of a fixed price PPA has been studied.

Table II: Characteristics of the studied business models

Business model 1	Business model 2
Years 1 to 30: 100% of the production is merchant-PV-based	Years 1 to 15: 50% of the production is valued through a fixed price PPA* *and* 50% of the production is merchant-PV-based Years 16 to 30: 100% of the production is merchant-PV-based

* 50 €/MWh

2.4 Indicator(s) used

The two indicators used are economic indicators namely the net present value and the internal return rate. Used formula can be found below.

$$\mathbf{NPV = -I \sum_{i=0}^{T} \frac{Free\ Cash\ Flow_i}{(1+d)^i}}$$

Where:

NPV: Net Present Value calculated for a theoretical system lifetime of N years

Free Cash Flow$_i$: free cash flow (positive and negative) in year i

I: the initial investment

d: the discount rate

T: theoretical system lifetime

i: a year in the theoretical system lifetime

Based on this formula, the internal return rate is then the discount rate for which the NPV equals to zero.

3 RESULTS AND SENSITIVITY ANALYSIS

3.1 Impact of different daily patterns

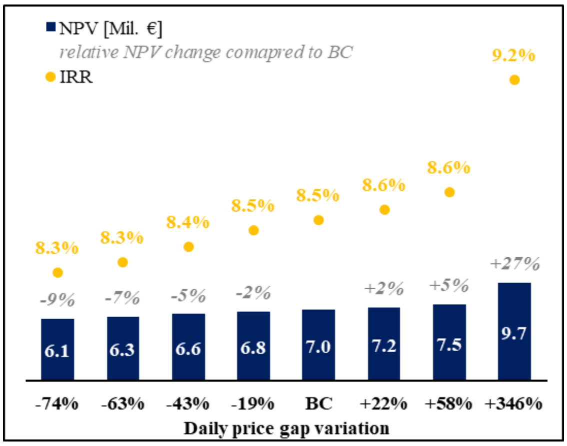

Figure 4a: Relative impact (percentage above bars) of different daily price gap variations (represented on the X axis) on the PV profitability assessed through the NPV (label on the bars) and on the IRR (label above the dots) for BM1.

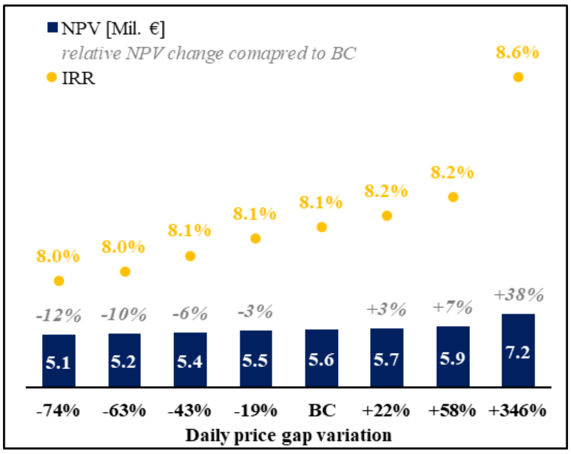

Figure 4b: Relative impact (percentage above bars) of different daily price gap variations (represented on the X axis) on the PV profitability assessed through the NPV (label on the bars) and on the IRR (label above the dots) for BM2.

An exacerbation of daily price gaps (measured between the lowest prices in the early afternoon and the highest prices during the evening) leads to an increase of PV profitability.

This can be explained by the fact that by exacerbating the daily price gaps (purple arrows in Figure 2), PV production benefits more from the higher prices during the morning consumption peak than it suffers from the lowest prices during the low consumption in the early afternoon.

The higher the exposure to hourly market prices (i.e., the higher the share of PV production which is merchant-PV-based), the higher the impact of the daily pattern variations on PV profitability.

3.2 Impact of different seasonal patterns

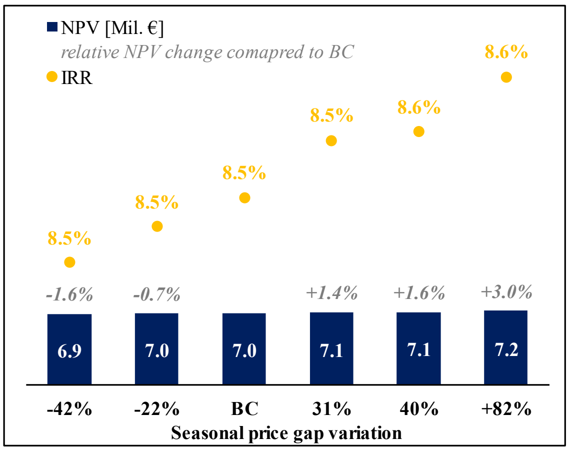

Figure 5a: Relative impact (percentage above bars) of different seasonal price gap variations (represented on the X axis) on the PV profitability assessed through the NPV (label on the bars) and on the IRR (label next to the dots) for BM1.

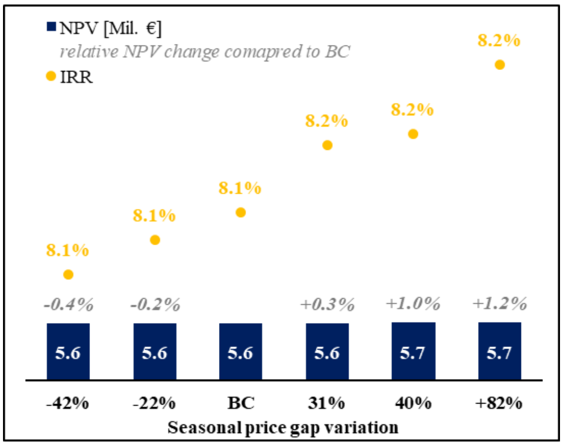

Figure 5b: Relative impact (percentage above bars) of different seasonal price gap variations (represented on the X axis) on the PV profitability assessed through the NPV (label on the bars) and on the IRR (label next to the dots) for BM2.

An exacerbation of seasonal price gaps (measured between the lowest prices in the early spring and the highest prices during the winter) leads to an increase of PV profitability.

This can be explained by the fact that by exacerbating the seasonal price gaps (purple arrows in Figure 2), PV production benefits more from the higher prices during the summer which are observed in Italy than it suffers from the lowest prices during the early spring.

The higher the exposure to hourly market prices (i.e., the higher the share of PV production which is merchant-PV-based), the higher the impact of the daily pattern variations on PV profitability.

3.3 Impact of different negative prices occurrences

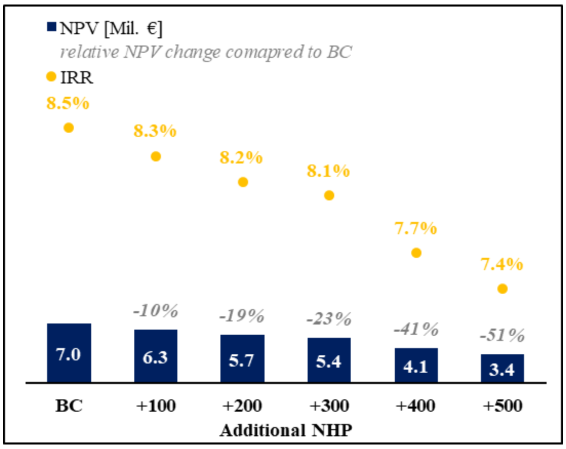

Figure 6a: Relative impact (percentage above bars) of different negative hourly prices (NHP) occurrence (represented on the X axis) on the PV profitability assessed through the NPV (label on the bars) and on the IRR (label next to the dots) for BM1.

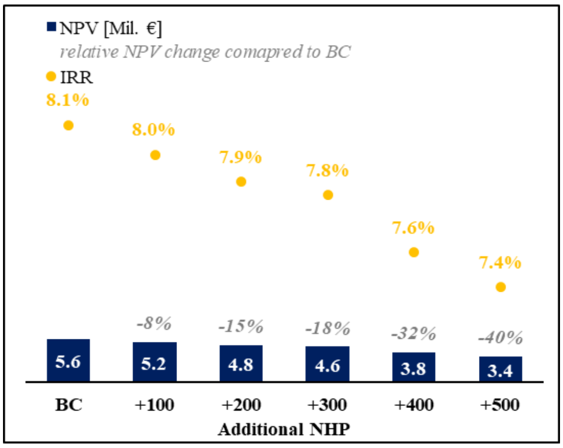

Figure 6b: Relative impact (percentage above bars) of different negative hourly prices (NHP) occurrence (represented on the X axis) on the PV profitability assessed through the NPV (label on the bars) and on the IRR (label next to the dots) for BM2.

Unsurprisingly, an increase of the occurrence of negative hourly prices leads to a deterioration of PV profitability.

Under the used model to simulate hourly wholesale market price, negative prices take place predominantly during the night but not only. Under a configuration of limited wind energy and nuclear penetration combined with a high penetration of PV energy, the impact of the same number of negative hourly prices would be more detrimental to PV profitability as episodes of negative prices would concentrate at times when PV generation is important.

The higher the exposure to hourly market prices (i.e., the higher the share of PV production which is merchant-PV-based), the higher the impact of the daily pattern variations on PV profitability.

When the number of negative hourly prices increases by 500 compared to the base case (approximately. 50 hours per year), PV profitability under the studied cases is approximately halved. As a reference, in 2020, in Germany about 300 hours with negative hours took place in a context of exceptionally low demand (COVID19-related lockdowns during spring) [6].

4 CONCLUSIONS

In the energy transition context (more solar PV, e-mobility, heat pumps, battery storage, …), wholesale electricity prices patterns are bound to vary. As the shift towards non-incentivized utility-scale PV occurs, wholesale electricity prices patterns will directly impact PV profitability.

Nonetheless, our research shows that while the profitability of solar PV plants exposed to wholesale market prices' volatility can be damaged, it is robust enough to remain attractive. Moreover, this is true even in extreme cases.

Indeed, our results show that the exacerbation of daily price gaps (e.g., through higher electrification of demand and higher PV penetration) increases the PV profitability by 5% when the gap is increased by 50%. On the contrary, the PV profitability decreases by 5% when the gap is decreased by 40%.

The exacerbation of seasonal price gaps (e.g., through higher electrification of demand and higher PV penetration) leads to a similar outcome, with an increase of the profitability of solar PV by 2% when the gap is increased by 50%. On the contrary, the PV profitability decreases by 1,5% when the gap is decreased by 40%.

The last trend tested, i.e. the occurrence of negative prices, shows a decrease of the profitability of PV of 20% when the number of negative prices is increased by 4 (from 50 h/a to 200 h/a).

Overall, this demonstrates that although the shift from subsidized-based business models to market-based ones come with an increase of exposure to market prices' shocks, profitability of solar PV under such business model remains attractive. The risk of "cannibalization" due to an increase of solar and other renewables that has been for long highlighted by multiple stakeholders thus seems limited.

Other work should be conducted to evaluate the impact of a combination of PV with various energy storage systems (batteries or electrolyzers).

5 FUNDING AND ACKNOWLEDGMENT

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