

Hedging Volumetric Risks of Solar Power Producers Using Weather Derivative Smart Contracts on a Blockchain Marketplace

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Abstract—The vulnerability of solar power producers to sunshine fluctuations exposes them to the volumetric risk that future electricity generation may deviate from predicted generation. Weather derivatives have recently emerged as a tool for hedging the volumetric risks of these power producers. However, the state-of-the-art instruments have several shortcomings, contributing to their limited application in the industry. Therefore, novel solar radiation-based weather derivative smart contract arrangements on a blockchain marketplace are proposed to address some of the main limitations of traditional instruments. In this regard, the cash flow of solar generators is modelled to assess the weather elements causing its stochasticity. Using this information, novel smart contract arrangements on a blockchain marketplace with solar radiation days as the underlying weather index are developed and analytically valued. Thereafter, a suite of novel smart contract autonomous mechanisms compelling contracting parties to behave rationally and maintain an enduring arrangement is presented. Finally, a trading strategy based on the developed smart contract arrangements is proposed to minimize the power producers' volatility risk. Results emanating from notional simulations indicate that the proposed approach could be more suitable for hedging the volumetric risks of solar power producers than traditional instruments.

Keywords—Electricity market, renewable electricity, electricity derivatives, decentralized finance, blockchain

I. INTRODUCTION

SOLAR Power Producers (SPPs) trading in electricity markets are usually exposed to cash flow volatility risks stemming from price and volume. First, the unique physical characteristics of electricity systems requiring that generation always match demand cause the spot prices in the physical electricity market to differ from period to period [1]. Hence, SPPs could be susceptible to the risk of prolonged low prices. Further, the weather-dependent characteristics of SPPs mean their output is stochastic, and as such, make them susceptible to underperform predictions for hours, days, weeks, months, or years [2]. Overall, these cash flow volatility risks could make it challenging for SPPs to secure finance at favorable rates and advantageous terms from traditionally risk-averse financial institutions [3].

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In practice, SPPs while trading in the physical electricity market, concurrently participate in the financial market to mitigate their cash flow volatility exposures using several available price and volumetric risk hedging instruments [4]. Price risk hedging instruments are straightforward and have now been well studied and understood [5]. Today, several traditional bilateral contracts exist in electricity markets, such as in [3], [4], [6]–[8], allowing SPPs to sell their power at a fixed price for a short- or long-term. One typical example of such arrangement is a contract-for-difference between a renewable generator and a counterparty electricity supplier, buying power from the same pool that the generator is selling into [3]. These parties are incentivized to enter this contract because it is mutually beneficial to minimize their exposure to spot price volatility since low prices are bad for the generator but good for the supplier, and vice versa.

SPPs remain exposed to the volumetric risk that actual electricity generation may deviate from forecasted generation. Imbalance risk, resulting from supply deviations at the delivery period, has also now been well studied and understood with several available hedging strategies, such as in [9]–[15], used in practice to minimize SPP's exposure to such risk. The nature of global climate variability and changes mean that the volumetric risks resulting from supply deviations in the order of weeks, months, and years could present significant cash flow volatility exposures for diverse companies [16], including SPPs [17]. However, this risk has received the least attention of the elements causing the cash flow volatility of SPPs. These long-term volumetric risks could influence an SPPs' ability to attract finance at favorable rates and advantageous terms since investment decisions for generators are made based on several years to decades of cash flow expectations [18]. Hence, the more predictable these cash flows are, the more creditworthy SPPs become, and the more seamless it is for them to mobilize competitive finance for project implementation [16].

Weather derivatives have recently emerged as a tool for minimizing long-term supply risks in several sectors whose cash flows are dependent on weather, such as agriculture, tourism and travel, construction, energy, and entertainment [5]. Yet, only a handful of weather derivative mechanisms, such as in [8], [9], [19]–[21], have been proposed to hedge the long-term volumetric risks of SPPs. Therefore, the focus of this work is on exploring weather derivatives for minimizing the cash flow volatility risk of SPPs.

A. Weather Derivatives

Weather derivatives are relatively new financial contracts

whose payoffs are contingent on the movement of an underlying meteorological index such as rainfall, temperature, snowfall, sunshine, wind speed, etc. [5]. The weather derivatives market opened in 1997, with a handful of private transactions in the United States involving the transfer of weather risk between counterparties. Since then, the market has developed along two lines [22]. First, *exchange-traded* markets, which are public, standardised, and regulated platforms enabling multi-lateral transactions between several parties [23]. The Chicago Mercantile Exchange (CME) was the first established market of such nature [15]. The European weather derivatives market has developed along the other line, *over-the-counter* (OTC) markets, involving customized contracts that are bilaterally traded [22].

Options are the commonly traded contracts on OTC platforms. The buyer of a *call option* on an underlying weather index receives a payoff if the weather index is greater than the pre-agreed strike value at the contract's maturity date. The buyer of a *put option* receives a payoff if the weather index is lower than the pre-agreed strike value. The payoff of these contracts is usually variable, with the amount increasing linearly with respect to the deviation of the weather index from its strike value [5]. Futures and options on futures contracts are available on weather exchanges. *Futures* are agreements to buy or sell the value of an underlying weather index at a particular future date. A *call option on futures* gives the buyer the right, but not the obligation, to buy one futures contract at a specific strike price and date. Conversely, *put option on futures* gives the buyer the right, but not the obligation, to sell one futures contract [5].

Weather derivative markets have yet to truly take off since their creation two decades ago due to several shortcomings, contributing to their limited application in diverse industries [15], [22]. The few weather derivative mechanisms employed to hedge the volumetric risks of SPPs, such as in [8], [9], [15], [19]–[21], also suffer the same fate as legacy weather derivative instruments. These evident shortcomings, explicitly discussed in the rest of this paper, could discourage SPPs from trading weather derivatives, especially as their volumetric profile are not as volatile as other renewable power producers, such as wind generators [24]. Indeed, they can assume their volumetric risks, known as risk retention [25]. Essentially, the risks introduced by the derivative must be less than that of bearing the volumetric uncertainties for the employed hedging instrument to be viable [23]. Nevertheless, global climate variability and changes indicate that volumetric risk could increasingly become more significant for the bankability of weather-reliant companies [8], [16].

Although the following limitations of weather derivatives for hedging volumetric risks of SPPs are not purely technical but relate to other broader market issues, such as business models, regulatory requirements, etc. [26], this paper will focus on the shortcomings from the perspective of the hedging instrument itself. To better understand how some of these issues arise, it will be useful to describe the typical trade cycle for market participants in traditional arrangements. There are three key processes in a derivative transaction: *Execution*, *Clearing*, and *Settlement*, as shown in Fig. 1 [26]–[28].

Execution refers to when the buyer and seller of the contract

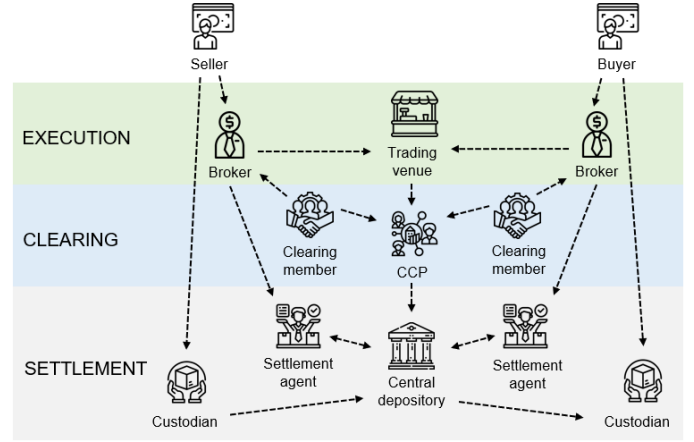


Fig. 1. Typical simplified trade cycle for market participants in traditional derivative arrangements. Adapted from the European Central Bank [27].

instruct their respective brokers as to their willingness to trade. An order is filled to enable the matching of these parties. Compatible counterparties may then execute the trade by entering into a legally binding arrangement [28]. Say the arrangement is a call option and the underlying index is greater than the pre-agreed strike value at the contract's maturity date, then the buyer is due a payoff [5]. The details of such payoff are usually sent for *clearing* to a central counterparty clearing house (CCP) that reconciles orders, netting them with other unconcluded transactions [27]. The CCP is the market maker, otherwise known as the liquidity provider, the buyer to all sellers and the seller to all buyers. The CCP is made up of several clearing members, excluding the exchange, which is usually an independent legal entity [29]. Thereafter, the clearing members notify their respective brokers of their requirements, and the brokers instruct their settlement agents [27]. Notably, these members are also responsible for managing collaterals and measuring counterparty exposures on behalf of the contracting parties to minimize defaults [23]. In the *settlement* process, the settlement agent of the seller's broker receives the payoff from the seller's custodian through a central depository into its account and credits it to the CCP. The CCP then issues an instruction for the payoff to be credited to the account of the buyer's settlement agent, who credits the buyer's custodian, again through the central depository [27]. While the description of the above trade cycle mostly refers to exchanges, most OTC market participants are now mandated to delegate intermediary clearing houses, which are typically members of the CCP [28].

Since the default of Lehman Brothers in 2008, worth tens of billions of US\$, derivative markets have grappled under the weight of counterparty credit risks [26]. *Credit risk*, the possibility of a party incurring financial losses because its opposite party in the contract fails to fulfil its payment obligations [30], is the greatest source of concern for market participants. It is also one of the most difficult risk to hedge since it is innate in every derivative transaction [28]. All the proposed weather derivative arrangements for hedging the volumetric risk of SPPs, including in [8], [9], [15], [19]–[21], are liable to

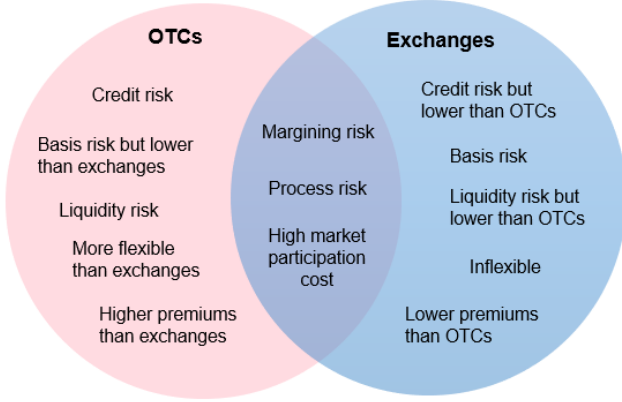


Fig. 2. Limitations of traditional weather derivative arrangements from the perspective of the hedging instrument.

this risk (refer to Fig. 2). OTC contracts naturally have higher credit risks since they are traded bilaterally and are not always cleared centrally [28]. Credit risks are lower in exchanges since this risk is transferred to a trusted CCP, delegated to manage collaterals and measure counterparty exposures on behalf of contracting parties [26]. Still, exchanges possess credit risk due to misalignment between parties' exposure and their reserved collateral, occurring because collateral settlements happen days after exposure measurement [6], [26], [31]. Credit risk is even more severe in electricity markets compared to the financial industry, given that clearing and settlement could take from a few months to up to two years to conclude [32].

Basis risk is another important issue that has limited the demand for weather derivatives [33], including SPPs [9], [19], [21]. This risk results when the underlying index of the contract is from a different area other than the location that the hedger wishes to cover [5], [30] or the index does not sufficiently correlate with the hedged quantity [5], [19], (e.g., using temperature to hedge solar power). Basis risk concern exchange-traded and OTC weather derivative contracts but for different reasons: *flexibility* issues in exchanges and liquidity issues in OTCs (refer to Fig. 2 and 3). In exchanges, basis risk arises because these contracts are standardised [33] and cover a few locations [30]. For example, the underlying index (mainly temperature) for weather derivatives hosted on one of the biggest exchanges in the world, CME, only covers 30 large cities, mainly in the United States [15]. This implies that SPPs outside these cities intending to hedge their volumetric risk face basis risk from the choice and location of the underlying index.

OTCs are theoretically immune to basis risk due to their flexibility compared to exchanges [30]. However, basis risk could still exist in reality due to the illiquidity of OTCs, evident in [8], [19], [21]. And in derivatives, liquidity is vital since, for every party taking one side, there must be a willing counterparty taking the opposite side [23]. Liquidity risks in OTCs weather derivatives are severe given the inherent liquidity issues from the underlying index, discussed in the following paragraph [5], [34]. To this end, the proposed OTC contracts for hedging SPP volumetric risk, such as in [8], [19], [21], remain temperature-

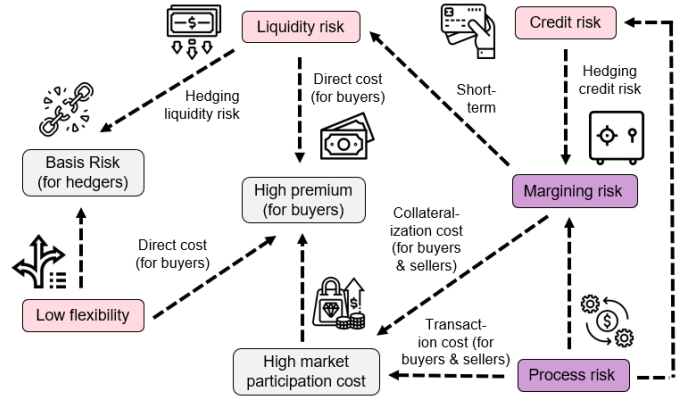


Fig. 3. Interconnectedness of the limitations of traditional weather derivative arrangements from the perspective of the hedging instrument

based since there is an existing large pool of players impacted by temperature variations compared to any other weather index [5]. Overall, basis risk is challenging to hedge since existing instruments are unable to at the same time realise flexibility and liquidity [30].

Liquidity risk, the risk that there will be no counterparty to take the opposite side of a contract, which is necessary for a derivative agreement to occur, also has a significant impact on the derivative's price (premium) [22]. While liquidity risks concern mainly OTCs [30], exchanges could suffer from this problem due to the inherent liquidity issues from the typically location-specific underlying index, unlike in financial derivatives or traditional commodity markets, dealing with say, a specific grade of crude oil [34]. This issue is coupled with the fact that since the inception of weather derivatives, there have been little or no additional players (i.e., participants that do not classify as hedgers or insurers) [22], evident from the listings in two of the most popular exchanges in America and Europe, CME [15] and EEX [35], respectively. And according to a survey carried out on market participants, the limited number of counterparties in the weather derivatives space makes current arrangements expensive [22]. Low liquidity also results in inadequate high-quality market data needed to price weather derivatives accurately [5]. Hence, there tends to be a high bonus to compensate for the challenging valuation exercise [36], thus making such arrangements less attractive for buyers [22]. Overall, there is a positive connectedness cycle between liquidity and premium. An increase in liquidity lowers premiums [5] and lower premiums results in more liquidity, particularly for buyers [22].

Liquidity risk also refers to the lack of liquid assets or cash. *Margining risks* is a form of short-term liquidity risk where future cash flows of market participants are smaller than expected due to high collateral requirements [27]. This risk is high in weather derivative arrangements, especially for electricity participants, such as in [8], [9], [15], [19]–[21] since clearing and settlements could take several months to conclude [32]. This infrequent clearing and settlement times results in accumulated settlement obligations, requiring parties to maintain high margins to mirror the volume of cash flows to be protected against credit risk [26] (refer to Fig. 3).

Alternatively, a letter of credit, serving as a payment default insurance, can be purchased by market participants from a commercial bank to achieve the same requirement. However, such collateralization costs are exorbitant and contribute to the market participation cost [37]. The following example shows that margining risks are significant in the electricity industry. In 2021/22, skyrocketing electricity prices and volatility in the European market resulted in exchanges requiring additional margin payments in billions of Euros from energy companies to cover credit risk. This increased collateral requirement due to higher margin calls has left some of these companies on the verge of bankruptcy [38].

Process risk is the most interconnected risk of traditional weather derivative arrangements (refer to Fig. 3). It arises from the likelihood of market participants experiencing financial losses because the process underpinning the arrangement, from the execution to the settlement phase (see Fig. 2), lacks operational efficiency and reliability [26], [28], [29]. Traditional derivative arrangements are operationally inefficient and thus have high market participation costs, including transaction fees, because of the presence of several redundant intermediaries in the trade cycle value chain [27]. Moreover, these entities employ their own unique set of representations for events and processes, requiring continual data reconciliation to ensure uniformity of information amongst market participants [39]. In addition to increased transaction fees, the bureaucracy of current arrangements results in infrequent and slow clearing and settlement times that contribute to margining and credit risks, also impacting market participation costs [27]. Losses due to operational unreliability can result from manual errors or insolvent actors [29]. Such potential vulnerability is also worsened since current arrangements are mainly enabled by centralised entities (e.g., the CCP), having a single point of failure [28].

Overall, it is presently challenging for market participants to realise the upsides of OTCs and exchanges in the same transaction, given that most of the pros of these platforms are generally mutually exclusive (refer to Fig. 2) [23]. Therefore, the rest of this paper will explore how Decentralized Finance (DeFi) instruments could hybridise the benefits and minimize the shortcomings of these existing traditional instruments.

B. Decentralized Finance

DeFi instruments are financial services residing on a public *blockchain*, a distributed and immutable digital ledger, enabling seamless, secure, and transparent transactions between disparate parties [40]. These instruments are underwritten by interconnected *smart contracts*, computer scripts that self-execute based on pre-specified criteria [41]. For instance, a smart contract can autonomously control cryptographic assets based on certain conditions. And when the appropriate conditions are met, funds are autonomously disbursed to the rightful participant(s). DeFi instruments effectively allow parties to take certain financial positions and behave rationally without oversight from a central intermediary. Today (as of April 2022), the market capitalization of DeFi instruments sit at more than US\$ 140 billion, with a daily trading volume of about US\$ 7 billion [42].

DeFi presents compelling opportunities in derivative markets, beset by numerous intermediaries [28] handling deterministic functionalities [29]. DeFi derivative instruments have been mainly explored in the financial industry, with several benefits identified compared to traditional arrangements. Ref. [28], [32], [43] analyzed their role in traditional arrangements and concluded that the process improvements from introducing DeFi results in operational efficiencies that significantly reduce market participation cost. Ref. [26], [27], [29], [31], [32] noted that these operational efficiencies also results in faster and more frequent clearing and settlement cycles that reduce credit and margining (another form of liquidity) risks, and further diminishes participation fees. A case study highlighted in [28] to substantiate this point is an industry analysis that indicated that implementing DeFi in derivative markets can save financial institutions more than US\$12 billion annually. Ref. [29] reported that liquidity based on the number of available counterparties could be improved using DeFi derivatives due to lower entry barriers and flexible options. Ref. [43] supports this notion with a qualitative analysis of more than 122 existing DeFi companies, including derivatives.

The electricity sector has recently seen a few proposals of DeFi derivatives, motivated by the identified benefits of these products in the financial industry. These studies have mainly focused on meshing DeFi with existing electricity market structures and describing how they might reduce some of the underlying risks of traditional electricity derivative instruments, just as in the financial industry. In [44], a contract-for-difference was structured on a blockchain marketplace to hedge the price risk of renewable electricity generators. In [10], a blockchain prediction marketplace was proposed to hedge the imbalance risks of wind generators, leveraging the *wisdom of the crowd*. Similarly, [21] introduced the idea of developing weather derivatives on a DeFi marketplace for hedging the volumetric risks of SPPs. While this project showed promise in using DeFi-hosted weather derivatives, a temperature index was used as the underlying weather index, potentially exposing SPPs to basis risk. Ref. [45] has recently shown that DeFi can minimize such basis risk since the market payoffs are more flexible and liquid than traditional instruments. The same study noted that flexibility comes from the fact that these instruments can be defined directly by the local generation, while liquidity is due to it being accessible to participants from all locations, unlike traditional arrangements that are only available in a few countries.

Although DeFi presents several benefits for market participants compared to traditional arrangements, they introduce new risks. These risks include *volatility risk* of the blockchain's native currency [46], *security risks* due to poorly vetted smart contract codes or new attack vectors and interactions with other DeFi applications [47], *account risks* from user errors and *design risks* from defectively designed smart contracts [31]. Some of these risks can now be explicitly hedged, as seen in the following sections.

C. Novel Contributions

Considering the limitations of traditional weather derivatives and the potential issues of implementing a DeFi solution, occasions the following research questions:

- How can a DeFi derivative instrument be developed to mirror the functionalities of traditional arrangements for hedging the volumetric risks of SPPs, while minimizing some of the new risks it introduces?
- How can a DeFi derivative instrument be developed to overcome the shortcomings of traditional arrangements for hedging the volumetric risks of SPPs?

The core functionalities of traditional weather derivatives are maintained in the proposed instrument through a suite of autonomous smart contract mechanisms: settlement, collateralization, and authentication (see Fig. 4). In this way, design risks inherent in DeFi instruments are minimized. The native currency of the DeFi marketplace may be volatile, exposing participants to the likelihood of incurring financial losses [46]. Therefore, a stablecoin based on DeFi principles is incorporated into the marketplace to mitigate this volatility risk, as in [48]. Similarly, the decentralized marketplace requires an off-chain entity that will provide the varying underlying weather index, serving as the payoff to contracting parties. An oracle based on decentralized governance principle, such as in [49], accomplishes this task for the network.

The suite of autonomous mechanisms enhances process efficiency by streamlining the trade cycle for market participants and reducing the numerous intermediaries in traditional arrangements, as in [26]–[29], [31]. This improved process contributes to a reduced market participation cost (lower transaction and collateralization fees) and minimizes credit and margining risks, as in [28], [32], [43]. While transaction costs are also inherent in DeFi, newer and more operationally efficient blockchains mean that such costs are trivial. For example, one of the earliest blockchains costs 0.001% of the native currency in transaction costs for cross-border transactions compared to traditional financial institutions charging anything between 5 to 10% [50]. Costs due to the incorporated DeFi are also negligible and can be socialised across the network. The integration of the stable coin is costless [48], while one of the most popular oracles presently charges an average of around US\$ 1 for providing decentralized off-chain information, following a competitive tender [51]. Such fees are also set to reduce as the network grows in liquidity.

The authentication mechanism manages the execution process of traditional arrangements without human intermediaries. The collateralization and settlement mechanisms also remove the need for numerous human intermediaries, albeit having two new intermediaries, but functioning on decentralized finance and governance principles. Together, these mechanisms result in faster and more frequent clearing and settlement times, ameliorating credit and margining exposures. These faster and more frequent clearing and settlement times are enabled by the improved data reconciliation process in the shared ledger [39], unlike in traditional arrangements where each intermediary employs its own unique set of representations for events and processes [27]. They are also facilitated by the smart contract's ability to transfer liquidity instantly and round-the-clock, including weekends and public holidays when traditional banks are usually nonfunctional [50]. Particularly, the collateralization mechanism ensures that collateral requirements are updated in real-time once settlement has been completed, thus eliminating the exposure-collateral misalignment in traditional

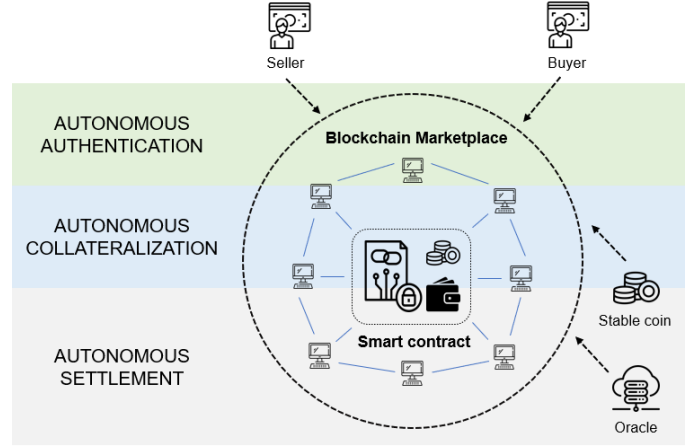


Fig. 4. Trade cycle for market participants in the proposed blockchain marketplace.

arrangements [26]. Likewise, the settlement mechanism ensures that the payoffs are prompt and frequent [28], reducing market participants' collateral requirements [27].

The autonomous mechanisms also enhance operational reliability in two ways. First, the self-executing, persisting, and immutable smart contracts underpinning the autonomous mechanism, function solely on the pre-specified conditions embedded in them [52], and as such, are void of manual errors. The counterparty exposure due to insolvent actors is also eliminated since these smart contracts assume the role of human intermediaries, with firm rules regarding defaults and termination [31]. Secondly, the autonomous mechanisms reduce the effects of the issues mentioned above. Even if they occur, their impacts would be less severe since the concentration of risks to centralised entities, with a single point of failure, is socialized on the decentralized network. For instance, in traditional arrangements, the CCP takes on the credit risk of all market participants [28]. However, in the proposed structure, the smart contract hosts several independent arrangements, all with their unique default management rules: termination penalties and margining requirements, etc., as in [26], [29], [31].

The flexibility in structuring DeFi arrangements, as in [29], [45], allows the development and pricing of tailor-made arrangements to meet the specific requirements of SPPs. In practice, the same flexibility can be achieved to hedge basis risks using traditional OTC contracts, as in [3], [53], etc. Again, OTCs have severe liquidity issues emanating from the trading platform [30] and underlying weather index [22], [34]. DeFi instruments could retain flexible arrangements while potentially enhancing liquidity, ensuring that the traded smart contract arrangements are likely to be practically available for purchase in the marketplace. We note that well-designed derivatives can be successful centrally or decentrally, on a blockchain. However, this work focuses on how the characteristics of the underlying blockchain technology could make existing arrangements more attractive for buyers and sellers, for the following reasons.

Traditional hedging arrangements are only available in a

few countries, and mainly to a few large principal actors (i.e., hedgers and insurers) [15], [35]. However, DeFi fosters a marketplace accessible to participants from all locations, with a range of budget, risk appetite, and trading strategies, as in [45], [49]. Moreover, weather derivative markets are generally illiquid and with the existing participants are forecasted to remain so, as in [22], [34]. As such, additional participants, including speculators, arbitrageurs, etc., not naturally connected to the underlying index are crucial for the industry to take off [22]. These market participants, including the minute-sized ones, could be incentivized to trade in the marketplace because of the lower participation cost of DeFi, which reduces their “barrier to entry.” Reduced participation costs are critical for the attractiveness of hedging instruments considering that listing on standard exchanges is considered expensive, time-consuming, and outside the financial capabilities of most smaller companies [5], [23], [27].

Further, as these participants are not linked to the underlying, they are likely to trade multiple fractions of the arrangement over several maturity dates, furthering the liquidity of the marketplace. An illustrative example of a DeFi marketplace aggregating these additional players is the Augur prediction platform, with a current market capitalization of about US\$ 200 million and an average daily trading volume totaling over US\$ 45 million [49]. The use of a universal fungible currency that can be seamlessly exchanged cross-border, as reported in [50], could also make the proposed hedging instrument more attractive. Such native currencies, along with the interoperability of DeFi marketplaces, can result in a liquid shared economy, as in [48], where other global market participants from different blockchain ecosystems can easily plug into the proposed marketplace [43]. Overall, improved liquidity lowers premiums [22], further attracting new market participants, particularly buyers.

The combined features of flexibility and liquidity enable the mitigation of basis risks through the development and analytical valuation of solar radiation-based derivative smart contract arrangements that absolutely correlate with solar power. The potency of these arrangements is underpinned by a concrete assessment of the underlying weather elements causing solar radiation stochasticity. Moreover, no study is yet to undertake such explicit investigation to develop a robust derivative instrument for SPPs. These combined features also enable the development of a *self-financing* and *implied volatility-matching* portfolio. This portfolio is realized from the combination of several smart contract arrangements, whereby the premiums obtained from selling specific arrangements, covering the implied cash flow volatility exposure of the power producers, are used to fund the purchase of other arrangements. This resulting portfolio further drives down the hedging cost incurred by the SPPs to almost zero while remaining effective in hedging their cash flow volatility risks. Overall, the minimized risks of weather derivatives, including the realization of a virtually costless hedge, could incentivize SPPs to explicitly ameliorate their long-term exposures rather than assuming this risk. This assertion is valid because, for instance, the employed derivative would not be viable for SPPs if the hedging cost is higher than the potential financial losses from cash flow volatilities caused by their volumetric risk. However, by reducing such hedging

fees, the proposed instrument becomes inevitably more usable for these generators. Combining the proposed solutions gives rise to a novel weather derivative instrument that addresses some of the main limitations of traditional instruments.

II. METHODOLOGY

This section aims to methodically showcase the proposed derivative smart contract’s design written on solar radiation days (i.e., the measure of daily solar radiation deviation) and traded on a blockchain marketplace. To this end, the cash flow of SPPs is explicitly modelled to determine the underlying weather elements causing their stochasticity. With this information, novel smart contract arrangements written on solar radiation days are developed and analytically valued for blockchain deployment. Thereafter, the smart contract structure enabling autonomous settlement, collateralization, and authentication amongst contracting parties are presented. Lastly, a trading strategy using the developed smart contract arrangements is proposed to minimize the power producer’s cash flow volatility risk.

A. Physical Market Model

1) *Assumptions*: The following assumptions are made to model the SPP’s cash flow:

- The volatile electricity prices p_t of the physical market have been explicitly hedged (i.e., p_t equals a guaranteed price P). Again, price risk hedging instruments are straightforward and have now been well studied and understood [5], with existing bilateral contracts, such as in [3], [6], [7], allowing SPPs to sell their power at a guaranteed price for a pre-agreed term.
- The imbalance risk of the SPPs has been hedged using one of the existing hedging products, as in [9]–[13].
- The physical market accepts the entire offered electricity volume of the SPP at every trading period. Barring grid constraints, renewable generators have grid priority access in virtually all electricity markets due to their zero marginal cost and low-carbon footprint.

2) *Cash flow model*: The cash flow δ_t of the SPP (in US\$) is firstly modelled, as in (1), to determine the elements that causes its volatility risk, where $\forall t \in T$ is the day(s) considered. While the electricity price P (in US\$/kWh) is fixed, the quantity of electricity V_t (in kwh) generated is stochastic. Therefore, the δ_t of the SPP is also stochastic.

$$\delta_t = \int_t^T (PV_t) dt \quad (1)$$

The quantity of electricity generated daily by an SPP is shown in (2). While R_t the daily solar radiation (in kwh/m²/day) is stochastic; a (in m²), y , and ϕ are known parameters representing the area, yield, and performance ratio of the solar panel, respectively [9]. From (2), V_t is directly proportional to R_t (i.e., $V_t = f(R_t)$, $f : \mathbb{R}^+ \rightarrow \mathbb{R}^+$). Hence, it is possible to develop hedging strategies for the SPP using solar radiation as the underlying weather index.

$$V_t = aR_t\phi y \quad (2)$$

3) *Underlying weather models*: Since derivatives are instruments that obtain their value from some underlying index, a sense of a weather-linked derivative requires a grasp of the underlying weather index. Therefore, an understanding of solar radiation's evolution will be critical in developing a robust derivative smart contract that effectively hedges SPPs against the vagaries of sunshine. Several daily solar radiation models have been proposed and validated with real-world data in [54], [55], etc. In this work, the daily solar radiation model suggested in [54] is used as in (3). E_t is the average daily *extraterrestrial radiation*, the radiation at the top of the earth's atmosphere; C_t the sky clearness index; M_t the average temperature (in °C); and λ_1 , λ_2 , and λ_3 location-dependent parameters. From (3), it can be observed that solar radiation depends on extraterrestrial radiation, sky clearness, and average temperature. Hence, it will be valuable to understand the evolution of these meteorological phenomena.

$$R_t = E_t \sqrt{C_t} (\lambda_1 + \lambda_2 M_t) + \lambda_3 \quad (3)$$

Extraterrestrial radiation can be modelled as in (4) [56]. In (4), ν_1 and ν_2 are known solar constants. ν_3 and ν_6 , are pre-calculated parameters representing inverse relative distance and solar declination angle, respectively. Lastly, ν_4 and ν_5 , indicates the location-dependent sunset hour angle and latitude, respectively. From (4), we note that extraterrestrial radiation is deterministic with negligible error.

$$E_t = \nu_1 \nu_2 \nu_3 \left(\nu_4 \sin(\nu_5) \sin(\nu_6) + \cos(\nu_5) \cos(\nu_6) \sin(\nu_4) \right) \quad (4)$$

The day's sky clearness C_t is generally an unobserved meteorological phenomenon [55]. A common proxy for the location-dependent expected sky clearness, given *filtration* \mathcal{F}_t (i.e., information until time t) $\mathbb{E}[C_t | \mathcal{F}_t]$, is the *diurnal temperature variation* [54], since it indicates the fraction of extraterrestrial radiation that reaches the earth's surface [55]. C_t is modelled as in (5), where the deviation from the expected sky clearness σ_{C_t} is a standard Brownian motion W_t , with a location-dependent volatility coefficient σ_t (i.e., $\sigma_{C_t} = \sigma_t dW_t$). The solution to the stochastic differential equation in (5) is shown in (6). The first term of (6) is deterministic, while the second term is stochastic.

$$dC_t = \mathbb{E}[C_t | \mathcal{F}_t] + \sigma_{C_t} \quad (5)$$

$$C_t = \mathbb{E}[C_t | \mathcal{F}_t] + \int_t^T \sigma_t e^{-g(t-u)} dW_u \quad (6)$$

Average temperature can be expressed as an additive time series with unique trend, seasonal and random constituents, as in (7) [9]. N_t represents the temperature trend of the year [9], S_t the annually sinusoidal seasonal temperature component [19], and σ_{M_t} the deviation from the expected temperature. The expected average temperature given filtration $\mathbb{E}[M_t | \mathcal{F}_t]$, is the sum of the trend N_t and seasonal S_t components of temperature. The expanded version of $\mathbb{E}[M_t | \mathcal{F}_t]$ is shown in (8), where χ_1 , χ_2 , χ_3 , and θ are location-dependent parameters,

and ω and t are known constants [57].

$$M_t = \underbrace{N_t + S_t}_{\mathbb{E}[M_t | \mathcal{F}_t]} + \sigma_{M_t} \quad (7)$$

$$\mathbb{E}[M_t | \mathcal{F}_t] = \underbrace{\chi_1 + \chi_{2,t}}_{N_t} + \underbrace{\chi_3 \sin(\omega t + \theta)}_{S_t}, \quad (8)$$

Average temperature is modeled as a Geometric Ornstein-Uhlenbeck process that comprises two independent processes: Brownian motion and a compound mean-reverting process as in (9) [57]. In (9), η and σ_t represents the location-dependent drift and volatility coefficients, respectively. The solution to the stochastic differential equation in (9) is shown in (10). The first and second terms of (10) are deterministic, while the third term is stochastic.

$$dM_t = \left(\frac{d\mathbb{E}[M_t | \mathcal{F}_t]}{dt} + \eta (\mathbb{E}[M_t | \mathcal{F}_t] - M_t) \right) dt + \sigma_t dW_t \quad (9)$$

$$M_t = \mathbb{E}[M_t | \mathcal{F}_t] + \left(\mathbb{E}[M_0 | \mathcal{F}_t] - M_0 \right) e^{-kt} + \int_t^T \sigma_t e^{-k(t-s)} dW_s \quad (10)$$

In summary, the cash flow profile of an SPP can be determined from the analysis of the evolution of solar radiation. From the chosen models, it can also be ascertained that the stochasticity of sky clearness σ_{C_t} and average temperature σ_{M_t} are the elements that result in SPP's cash flow volatility. Therefore, the understanding of the variations in these two phenomena will be crucial in developing appropriate hedging strategies for the SPP in the blockchain marketplace. Besides, the literature investigating these relationships is sparse, reinforcing the importance of this modeling exercise.

B. Blockchain Marketplace Model

In this section, we develop flexible weather derivative smart contract arrangements on a blockchain marketplace that power producers can use to minimize their cash flow volatility risk, as shown in Fig. 5. In practice, this novel marketplace would reside in the financial market, operating concurrently with the physical market and available to SPPs along with other electricity derivatives.

1) *Assumptions*: The following assumptions are made to develop the blockchain marketplace:

- The native currency of the blockchain marketplace may be volatile, exposing participants to the possibility of incurring financial losses. Therefore, a collateral-backed stablecoin has been incorporated into the smart contract. Collateral-backed stablecoins achieve their pegging with fiat currencies via overcollateralization of a basket of crypto-assets locked in smart contracts. They maintain a 1:1 pegging with fiat currencies, the usually denominated currencies of the pool market's clearing price [46]. Hence, we maintain that 1 stablecoin equals US\$1. The stablecoin service introduces an attack vector and thus exposes the smart contract to security risks. We note that such stablecoin services are a mature technology, operating on decentralized governance and finance principles,

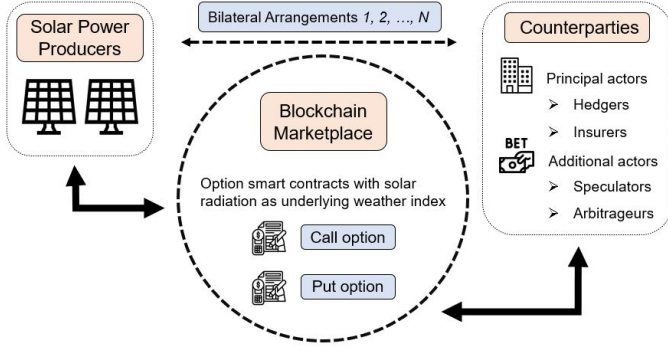


Fig. 5. Ecosystem of blockchain weather derivative marketplace with solar radiation as underlying weather index

and presently underpinning several DeFi applications, such as in [49].

- The marketplace requires an off-chain entity that will provide it the varying underlying weather index, serving as the payoff to contracting parties. An oracle accomplishes this task for the marketplace. While the smart contract can read and react to the data fed by the oracle, a malicious party could manipulate this data stream to game the operation of the smart contract [58]. Hence, the oracle introduces a possible attack vector and thus could expose the smart contract to security risks. Again, we note that several oracles are mature, operate on decentralized governance and finance principles, and now support several DeFi applications, such as in [48].

2) *Contracting parties*: The proposed blockchain marketplace constitutes SPPs whose goal is to hedge their cash flow volatility risks (see Fig. 5). Traditional counterparties of the SPPs known as principal actors in the hedging arrangement also exist and include insurers and other hedgers. These insurers mainly comprise insurance and reinsurance companies, energy trading firms, and large banks, aiming to diversify their investment portfolio [30], [34], [36]. Hedgers comprise natural counterparties whose cash flows might be affected by temperature or sunshine and inherently have an opposite volumetric risk profile to SPPs, such as energy consumers, beverage producers, construction companies, agricultural companies, ski resorts, etc. [30], [36]. An example of such a transaction could be between an SPP and a tea manufacturing or retailing company since sunshine might lead to warmer temperatures which might be bad for the tea company (i.e., lowering sales volume) but good for the SPP (i.e., increasing power production), and vice-versa. This type of hedging strategy for beverage companies is said to be common in England [30]. By reducing market participation costs, smaller-sized principal actors are also motivated to participate in the marketplace.

For the same reason, the marketplace could attract other additional actors, including speculators, arbitrageurs, etc. Speculators, such as independent commodity traders or private investors, would bet on the outcomes of the underlying index to make profits [26], [45]. Arbitrageurs, such as independent commodity traders or hedge funds, would also trade smart contract arrangements based on multiple market dynamics to make risk-free profits [34]. Hedge funds are funds pooled

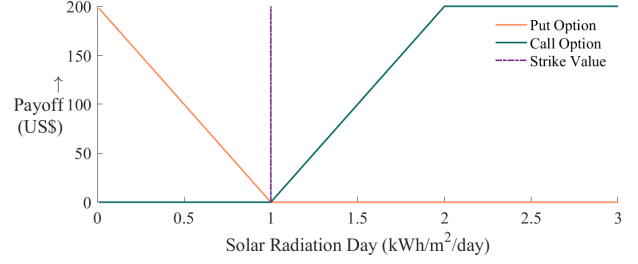


Fig. 6. Notional put and call options payoff on solar radiation days

by a group of investors to engage in speculative investments in volatile markets [23]. Arbitrage opportunities could exist as [36] notes that there is an inherent arbitrage advantage relative to energy and agricultural commodities. Notably, all the outlined contracting parties can be buyers or sellers of the smart contract arrangement depending on their trading strategy since either position could result in a net positive payoff [5]. For instance, while insurers mainly act as sellers [22], they can act as buyers to reduce their existing exposures [36].

3) *Smart contract payoff structure*: To hedge the volumetric risk of SPPs in the physical market, two smart contract arrangements with solar radiation days as the underlying weather index are developed on the blockchain marketplace – a put option with a payoff as in (11) and a call option with a payoff as in (12). K is the pre-specified strike value, and γ is the tick price, a US\$ amount associated with a solar radiation day since solar radiation is not itself tradable. A payment cap ζ that equals K is included in the call option payoff because while the put option payoff is capped by the difference between K and $R_t = 0$, the call option payoff is theoretically boundless as R_t can become arbitrarily higher than forecasted due to abnormal weather conditions. The visual representation of the payoff of these contracts is shown in Fig. 6.

$$\Phi_p = \gamma \max(K - R_t, 0) \quad (11)$$

$$\Phi_c = \gamma \min(\max(R_t - K, 0), \zeta) \quad (12)$$

The fair strike value of the smart contract arrangements (i.e., the strike that results in a zero net present value) is the expected daily solar radiation given filtration $\mathbb{E}[R_t | \mathcal{F}_t]$, mathematically represented as in (13).

$$\mathbb{E}[R_t | \mathcal{F}_t] = E_t \sqrt{\mathbb{E}[C_t | \mathcal{F}_t]} (\lambda_1 + \lambda_2 \mathbb{E}[M_t | \mathcal{F}_t]) + \lambda_3 \quad (13)$$

4) *Valuation of smart contract arrangements*: The arbitrage-free price F of the weather derivative smart contract arrangements in the blockchain marketplace at time t and with payoff $\Phi_{p,c}$ at time $T > t$, is the discounted value $e^{-r(T-t)}$ of the conditional expected payoff given filtration $\mathbb{E}_{\mathbb{Q}}[\Phi_{p,c} | \mathcal{F}_t]$, as shown in (14). In (14), $r \geq 0$ is the risk-free interest rate. The equivalent risk-neutral measure \mathbb{Q} can be ascertained for derivatives written on tradable assets such as stocks, etc. [5]. This measure cannot be determined for solar radiation since it is not tradable, implying that the proposed marketplace is incomplete. Hence, the no-arbitrage condition cannot be

applied to determine the options' price on solar radiation days.

$$F_{p,c;t} = e^{-r(T-t)} \left(\mathbb{E}_{\mathbb{Q}}[\Phi_{p,c} | \mathcal{F}_t] \right) \quad (14)$$

However, the notional price (or premium) of the smart contract arrangements, as in (15), can be derived as the discounted value of the conditional expected payoff under the real-world probability measure \mathbb{P} , given \mathcal{F}_t and considering a time-dependent risk loading τ_t . Other considerations include the implied volatility of payoffs $\sigma_{\Phi_{p,c}}$ and blockchain transaction costs b_t . The risk loading τ accounts for the exposures of sellers of smart contract arrangements to payoff volatilities [59]. This element is time-dependent, increasing with respect to the duration of the agreement, as proposed in (16), where q is the time-value decay rate. The implied volatility of the smart contract payoffs $\sigma_{\Phi_{p,c}}$ in US\$, as in (17), is derived analytically by considering the combined stochasticity of sky clearness (i.e., the second term of Equation 6) and average temperature (i.e., the third term of Equation 10). Once the marketplace becomes established and functional, the benefit of filtration will improve the volatility estimation due to the incorporation of historical volatility information.

$$F_{p,c;t} = e^{-r(T-t)} \left(\mathbb{E}_{\mathbb{P}}[\Phi_{p,c} | \mathcal{F}_t] + (\tau_t \times \sigma_{\Phi_{p,c}}) \right) + b_t \quad (15)$$

$$\tau_t = \tau e^{q(T-t)} \quad (16)$$

$$\sigma_{\Phi_{p,c};t} = \gamma \left(E_t \sqrt{\int_t^T \sigma_t e^{-g(t-u)} dW_u} \right. \\ \left. \left(\lambda_1 + \lambda_2 \int_t^T \sigma_t e^{-k(t-s)} dW_s \right) \right) \quad (17)$$

Further, blockchain marketplaces entail certain variable costs per transaction, taking the form: $b_t \sim \mathcal{N}(\mu_{b_t}, \sigma_{b_t}^2)$. Notably, b_t is incurred by both the buyer and seller of the smart contract arrangement, and the actual premium payable to the seller excludes b_t . Overall, the proposed weather derivative instrument's value primarily depends on the implied volatility, strike value, and time-dependent risk loading. The higher the implied volatility, the more expensive the arrangement becomes. The same relationship holds as the agreement duration becomes longer or the deviation of the pre-specified strike value from the expected solar radiation becomes wider.

5) *Smart contract governing mechanisms*: Structuring DeFi instruments can be challenging because the smart contract representing their operation must maintain the technical, financial, and legal functionalities of the traditional instrument that they are substituting [31]. This reality demonstrates the significance of the *business logic*, the brain of the smart contract, where all asset-handling and incentive mechanisms, compelling rational actions are embedded [60]. Principal to the smart contract's business logic for the proposed weather derivative DeFi instrument is a suite of novel autonomous mechanisms – settlement, collateralization, and authentication. These mechanisms, described in the following sections, enhances process efficiency by streamlining the trade cycle for market participants and reducing the numerous intermediaries in traditional arrangements.

Algorithm 1 : Autonomous Settlement Mechanism

Input: R_t

```

1: \ For all pairs of enrolled contracting parties  $A_{i,j}$  ( $i$  is the
   buyer of the smart contract arrangement and  $j$  the seller)
2: for  $i, j \leftarrow 1$  to  $A_{i,j}$  do
3:   \ Check if  $A_i$  is mapped  $M(i)$  to  $\Phi_p$  arrangement and
      $R_t < K$ 
4:   if  $(\mathbb{M}(i) : A_i \rightarrow \Phi_p); (R_t < K)$  then
5:     \ Update collateral account  $H_{i,j}$  of  $A_{i,j}$ 
     let  $H_i = H_i + \Phi_p; H_j = H_j - \Phi_p$ 
6:     \ Check if  $A_i$  is mapped  $M(i)$  to  $\Phi_c$  arrangement
       and  $R_t > K$ 
7:   else if  $(\mathbb{M}(i) : A_i \rightarrow \Phi_c); (R_t > K)$  then
8:     \ Update collateral account  $H_{i,j}$  of  $A_{i,j}$ 
     let  $H_i = H_i + \Phi_p; H_j = H_j - \Phi_p$ 
9:   else
10:    \ Revert transaction to the initial state
11:  end if
12: end for

```

Output: H_i, H_j

a) Autonomous settlement mechanism: We describe a novel autonomous settlement mechanism to remove the need for numerous clearing and settlement human intermediaries and enforce real-time settlement payments to hedge margining risks. This mechanism computes the payoff $\Phi_{p,c}$ of enrolled smart contract parties $A_{i,j}$ and autonomously updates their collateral accounts $H_{i,j}$, as the daily solar radiation index R_t are observed in real-time. This prompt and autonomous action makes settlement swifter and reliable, and minimizes margining risks. In practice, this implies that market participants can ameliorate their margining risk by the factor shown in (18), where τ_d is the average settlement time for traditional arrangements and τ_b for the proposed instrument.

$$\frac{\tau_d}{\tau_b}, \tau_d \gg \tau_b \quad (18)$$

While the strike value and tick price of the arrangement are immutably pre-written into the smart contract during enrollment of bilateral contracting parties, the smart contract is naturally unaware of the fluctuating daily solar radiation. Therefore, the marketplace employs an oracle, such as in [49], to provide this external data to the smart contract. Summarily, three actions are implemented sequentially when the settlement mechanism is invoked. The day's solar radiation index is obtained from the oracle. Thereafter, the payoff is calculated within the smart contract. Finally, the contracting parties' collateral accounts are autonomously updated with the computed payoff. The sequence of execution of the autonomous settlement mechanism is shown in Algorithm 1. This chaincode irrefutably executes once the smart contract is deployed on the blockchain.

b) Autonomous collateralization mechanism: Credit risk is one of the main risks of contracting parties in a derivative transaction [28]. To hedge credit risk on-chain and autonomously to streamline the clearing process, a novel collateralization mechanism is described. These mechanism ensures that collateral requirements are updated in real-time

once settlement has been completed, thus eliminating the exposure-collateral misalignment in traditional arrangements. These collaterals must be adequate to compel contracting parties to act rationally, and as such, maintain an enduring arrangement. Therefore, developing an appropriate collateralization mechanism is one of the central design problems for such a blockchain-based derivative instrument [31]. Principal to collateral management is the idea of maintenance margins and termination penalties [23], [31]. Maintenance margins are funds maintained by a contracting party in a collateral account to reflect its credit exposure to its counterparty in real-time. Termination penalties are deposits reserved in a collateral account, serving as a sanction for parties that default on the maintenance margin requirement or exit the smart contract before the end of the agreement's duration [23], [31].

To ensure that sellers of the smart contract arrangement have adequate funds in their collateral accounts to make settlement payments to their bilateral counterparty over the agreement duration, their minimum maintenance margin B_t^{min} must equal the sum of their expected daily payoff for the remaining days of the agreement z_1 . Since the daily payoff is stochastic, the premium $F_{p,c}$ at z_1 can serve as a proxy, as in (19). This requirement is imposed because the settlement mechanism ensures autonomous daily payoffs due to buyers of the smart contract arrangement, which limits their credit exposure to a single day. In practice, buyers can propose a suitable margining requirement, however, this value must satisfy the minimum requirement in (19). Notably, buyers have zero margin requirements because they do not make settlement payments.

$$B_t^{min} = \sum_{t=0}^{T=z_1} e^{-r(T-t)} \left(\mathbb{E}_{\mathbb{P}}[\Phi_{p,c} \mid \mathcal{F}_t] + (\tau_t \times \sigma_{\Phi_{p,c}}) \right) + b_t \quad (19)$$

Contracting parties can terminate the smart contract arrangement prematurely, that is, before the conclusion of the agreement. They can do so actively or by neglecting their minimum collateral requirement L_t^{min} , in the case of sellers of the arrangement. A termination penalty Υ , equivalent to (19) is proposed to discourage such actions, where z_1 is substituted for z_2 , the days it takes to replace the smart contract arrangement. This relationship implies that Υ must be sufficient to minimize the exposure of a non-exiting or non-defaulting contracting party until it secures a replacement arrangement that covers the initial position it took before its counterparty terminated the agreement. Contracting parties can propose a suitable termination penalty, but this value must satisfy the minimum requirement. Therefore, the minimum collateral requirement L_t^{min} that the contracting parties must maintain is the sum of their maintenance margin B_t^{min} and termination penalty Υ , as in (20).

$$L_t^{min} = B_t^{min} + \Upsilon \quad (20)$$

Parties are motivated to observe the collateral accounts of their bilateral counterparties in real-time and enforce a *default call* if these collaterals fall short of the minimum collateral requirement. In this way, contracting parties are incentivized to maintain their collaterals above the minimum requirement

Algorithm 2 : Autonomous Collateralization Mechanism

Input: $A_{i,j}$
Default on L_t^{min} :
1: $\backslash\backslash$ Check if collateral is below the minimum requirement
2: **if** $(H_{i,j} < L_t^{min})$ **then**
3: $\backslash\backslash$ Transfer termination penalty Υ^* of defaulting party $A_{i,j}^*$ from $H_{i,j}^*$ into $H_{i,j}'$ of non-defaulting party $A_{i,j}'$. Liquidate $H_{i,j}^*$ and $H_{i,j}'$.
4: **let** $H_{i,j}' = H_{i,j}' + \Upsilon^*$; $H_{i,j}^* = H_{i,j}^* - \Upsilon^*$
5: $\backslash\backslash$ Record $A_{i,j}^*$, $A_{i,j}'$ as evicted $G_{i,j}$ from the smart contract. $\mathbb{M}(i,j)$ maps $A_{i,j}^*$, $A_{i,j}'$ to $G_{i,j}$.
6: $\mathbb{M}(i,j): A_{i,j}^*, A_{i,j}' \longrightarrow G_{i,j}$
7: **else**
8: $\backslash\backslash$ Revert transaction to the initial state
9: **end if**
Output: $G_{i,j}$
Active exit :
10: $\backslash\backslash$ Transfer termination penalty Υ^* of exiting party $A_{i,j}^*$ from $H_{i,j}^*$ into $H_{i,j}'$ of non-exiting party $A_{i,j}'$. Liquidate $H_{i,j}^*$ and $H_{i,j}'$.
11: **let** $H_{i,j}' = H_{i,j}' + \Upsilon^*$; $H_{i,j}^* = H_{i,j}^* - \Upsilon^*$;
12: $\backslash\backslash$ Record $A_{i,j}^*$, $A_{i,j}'$ as evicted $G_{i,j}$ from the smart contract. $\mathbb{M}(i,j)$ maps $A_{i,j}^*$, $A_{i,j}'$ to $G_{i,j}$.
13: $\mathbb{M}(i,j): A_{i,j}^*, A_{i,j}' \longrightarrow G_{i,j}$
Output: $G_{i,j}$

to avoid liquidating their accounts in the smart contract. Still, contracting parties can decide to terminate the smart contract arrangement in exchange for their termination penalty deposit. The sequence of implementation of the autonomous collateralization mechanism is detailed in Algorithm 2.

c) Autonomous authentication mechanism: The authentication mechanism manages the execution process of the arrangement, without the need for human intermediaries, described as follows. First, contracting parties must signal their intention to enrol in the smart contract by defining their position $Z_{i,j}$ as a buyer i or seller j of a put Φ_p or a call Φ_c option. Thereafter, parties on either side of the arrangement propose suitable terms to the marketplace: a strike value K , tick price γ , risk-free interest rate r , time-dependent risk loading τ_t , implied payoff volatility $\sigma_{\Phi_{p,c}}$, contract duration $T-t$, and termination penalty Υ . The placement of an *intent* deposit Q is imposed on parties to incentivize true enrolments. The intent deposit for sellers of the smart contract arrangement Q_j , is as in (21), while that of the buyers Q_i , is as in (22). Contracting parties can commence observing the smart contract's events to ascertain if and when a counterparty with common terms places an intent deposit for enrolment in the smart contract. The ability to watch such events is programmable in most blockchains [60].

$$Q_j \geq \Upsilon \quad (21)$$

$$Q_i \geq \Upsilon + F_{p,c} \quad (22)$$

When and if contracting parties discover a counterparty that shares common terms with them, they enrol themselves and that counterparty into the smart contract arrangement as a pair $A_{i,j}$, using the next available sequential ID pair

Algorithm 3 : Autonomous Authentication Mechanism

```

1:  $\backslash\backslash$   $Z_{i,j}$  is the position of the enrolling contracting parties.
Input:  $Z_{i,j}, K_{i,j}, \gamma_{i,j}, r_{i,j}, \tau_{t;i,j}, \sigma_{\Phi_{p,c;i,j}}, T - t_{i,j}, \Upsilon_{i,j}$ 
   Positioning, Offering, and Staking :
2:  $\backslash\backslash$  Check if  $Q$  meets enrolment requirement
3: if  $(Q_j \geq \Upsilon), (Q_i \geq \Upsilon + F_{p,c})$  then
4:    $\backslash\backslash$  Record terms offered by contracting party
5:    $\mathbb{M}(i,j): (K_{i,j}, \gamma_{i,j}, r_{i,j}, \tau_{t;i,j}, \sigma_{\Phi_{p,c;i,j}},$ 
      $T - t_{i,j}, \Upsilon_{i,j}) \rightarrow Z_{i,j}$ 
6: else
7:    $\backslash\backslash$  Revert transaction to the initial state
8: end if
   Enrolling :
9:  $\backslash\backslash$  Check that terms of the contracting parties correspond.
10: if  $(K_i = K_j), (\gamma_i = \gamma_j), (r_i = r_j), (\tau_{t;i} = \tau_{t;j}),$ 
      $(\sigma_{\Phi_{p,c;i}} = \sigma_{\Phi_{p,c;j}}), (T - t_i = T - t_j), (\Upsilon_i = \Upsilon_j)$  then
11:    $\backslash\backslash$  Pay  $Q$  into  $H_{i,j}$  of the now enrolled  $A_{i,j}$ . Thereafter,
     liquidate the  $Q$  account of the now enrolled  $A_{i,j}$ .
12:   let  $(H_j = \Upsilon + F_{p,c}); (H_i = \Upsilon); (Q_{i,j} = 0)$ 
13:    $\backslash\backslash$  Record enrolling  $Z_{i,j}$  as a common pair of enrolled
     contracting parties  $A_{i,j}$ .  $\mathbb{M}(i,j)$  maps  $Z_{i,j}$  to  $A_{i,j}$ .
14:    $\mathbb{M}(i,j): Z_{i,j} \rightarrow A_{i,j}$ 
15:   let  $A_{i,j} = A_{i,j} + 1$ 
16: else
17:    $\backslash\backslash$  Revert transaction to the initial state
18: end if
Output:  $A_{i,j}$ 

```

count $(A_{i,j} + 1)$. Otherwise, they wait until a counterparty with equivalent terms enrolls them into the arrangement as a pair. This buyer i – seller j pair requirement is enforced by Algorithm 3 because the marketplace is effectively a bilateral agreement that requires that the terms of the buyer and seller of a particular smart contract arrangement correspond. Following enrolment, the intent deposit $Q_{i,j}$ of contracting parties are transferred to their collateral account $H_{i,j}$, less $F_{p,c}$, the premium which is autonomously deducted from the buyer's account and sent to the seller. The collateral account of these parties after enrolment, therefore, becomes $H_j = \Upsilon + F_{p,c}$ for the seller and $H_i = \Upsilon$ for the buyer. Afterwards, the seller of the smart contract arrangement is mandated to maintain the minimum collateral requirement L_t^{min} as its collateral account becomes depleted due to potential daily payoffs to the buyer.

C. Trading in the physical and blockchain marketplaces

In this section, the metric used to measure the volumetric volatility risk of an SPP is presented and a trading strategy to adequately hedge this risk using weather derivative smart contracts in the blockchain marketplace, is proposed.

1) *Risk metric:* Cash flow certainty is critical for renewable electricity generators to attract finance at favorable rates and advantageous terms from traditionally risk-averse financial institutions [3] as well as manage risks during their operational phase [45]. Therefore, the dilemma of an SPP is minimizing its implied cash flow volatility σ_{δ_t} , as in (23), derived by considering the combined stochasticity of sky clearness and average temperature. In practice, the benefit of filtration will

improve the volatility estimation due to the incorporation of historical volatility information in the calculation. The realized cash flow volatility of the SPP is evaluated using the root mean square deviation D of the expected cash flows given filtration $\mathbb{E}[\delta_t | \mathcal{F}_t]$ from the actual cash flows, as in (24).

$$\sigma_{\delta_t} = \text{Pa}\phi y \int_t^T \left(E_t \sqrt{\int_t^T \sigma_t e^{-g(t-u)} dW_u} \right. \\ \left. \left(\lambda_1 + \lambda_2 \int_t^T \sigma_t e^{-k(t-s)} dW_s \right) \right) \quad (23)$$

$$D = \sqrt{\frac{1}{T} \sum_{t=1}^T (\mathbb{E}[\delta_t | \mathcal{F}_t] - \delta_t)^2} \quad (24)$$

2) *Proposed trading strategy:* The long-term hedging strategy of a rational SPP is not seeking arbitrage opportunities or speculative profits but rather hedging its cash flow volatility risk at the lowest possible cost. To achieve this, the SPP observes the following procedure. The SPP estimates its implied cash flow volatility, as in (23), for the period it is selling power to the physical electricity market. It is practically unlikely for the SPP to hedge its entire implied cash flow volatility exposure; even so, will result in super-hedging. Therefore, it scales its implied cash flow volatility $\sigma_{\delta_t}^*$ using the time-dependent risk loading τ_t attribute of the marketplace as a proxy, as in (25). The risk loading characteristics of sellers of smart contract arrangements in a liquid market, such as the blockchain network, should correlate with the implied cash flow volatility of the SPP since they both depend on the same underlying weather elements.

$$\sigma_{\delta_t}^* = \sigma_{\delta_t} \times \tau_t \quad (25)$$

Thereafter, the SPP sells units n of call options with combined premium $F_{c;n,t}$, corresponding to its scaled implied cash flow volatility (SCIV) $\sigma_{\delta_t}^*$, as in (26). It is important to note that the relationship in (26) is a soft equality, as the SCIV is itself only an estimate. However, the SPP takes this position because if the sold call options are triggered on a nominated day (i.e., overproduction periods: when solar radiation is higher than the strike value), it has more funds than anticipated to pay its counterparty to the extent of the deviation. It uses the received call options payment to purchase units n of put options that also correspond with its SCIV, as in (27). It takes this position because if the purchased put options are triggered on a nominated day (i.e., underproduction periods: when solar radiation is lower than the strike value), it is compensated with cash flows from its counterparty to the extent of the deviation.

$$\sum_{t=0}^T \sum_{n=1}^N F_{c;n,t} \hat{=} \sigma_{\delta_t}^* \quad (26)$$

$$\sum_{t=0}^T \sum_{n=1}^N F_{c;n,t} \approx \sum_{t=0}^T \sum_{n=1}^N \Phi_{p;n,t} \quad (27)$$

The *sell call* and *buy put* self-financing arrangement is a replicating portfolio of a *costless swap* [5]. However, the proposed portfolio could result in some hedging cost ψ as in

(28) due to the varying average daily SCIV for the period of the available traded smart contract arrangements and the seller's time-dependent risk loading assumptions. This schema is posited rather than a direct swap because, in practice, it is unlikely that the SPP will find an opposite party willing to enter such a direct agreement with solar radiation as the underlying weather index.

$$\psi = \sum_{t=0}^T \sum_{n=1}^N F_{c;n,t} - \sum_{t=0}^T \sum_{n=1}^N F_{p;n,t} \quad (28)$$

In summary, the return matrix of the SPP's resulting portfolio is as in (29).

$$\pi = \begin{pmatrix} -F_{p,n} & \Phi_{p,n} - F_{p,n} \\ \vdots & \vdots \\ -F_{p,N} & \Phi_{p,N} - F_{p,N} \\ F_{c,n} - \Phi_{c,n} & F_{c,n} \\ \vdots & \vdots \\ F_{c,N} - \Phi_{c,N} & F_{c,N} \end{pmatrix} \cdot \begin{pmatrix} p_1 \\ p_2 \end{pmatrix} \quad (29)$$

In (29), $\mathbb{P} = (p_1, p_2) \in \mathbb{R}^N$ is a probability vector (i.e., $p_{1,2} \geq 0$ and $p_1 + p_2 = 1$), where p_1 indicates the likelihood of a column 1 outcome, which is when the solar radiation index is higher than the strike value. p_2 is the possibility of a column 2 outcome, when the solar radiation index is lower than the strike value.

III. RESULTS AND DISCUSSION

This section demonstrates the value of trading in the physical electricity market and employing the proposed trading strategy using solar radiation-based derivative smart contract arrangements in the blockchain marketplace. The MATLAB scripts used to simulate the case study and results are available in a persistent online repository at [61].

A. Case study

The case study serving as the basis of analysis in this work are fair notional estimates from several sources. Electricity price and installed capacity data are determined using information from existing electricity markets¹, solar panel data are obtained from data sheets². Radiation, latitude, sky clearness, and temperature information are estimated from meteorological databases^{3,4,5} [54]. These data points employed for scenario analysis are generally chosen to be sufficiently wide for the generalization of the proposed approach.

Two separate SPPs selling power to a physical electricity market in a calendar year are considered in this case study. The first generator is based in one of the world's cloudiest cities, Oslo, while the other is based in one of the world's sunniest cities, Windhoek, Namibia. The assumed physical market parameters for both SPPs are shown in Table I. The

TABLE I.
NOTIONAL PHYSICAL MARKET PARAMETERS FOR THE SOLAR POWER PRODUCER IN OSLO (NORWAY) AND WINDHOEK (NAMIBIA)

Parameters	Oslo	Windhoek
Electricity price (US\$/kWh)	0.065	0.05
Installed capacity (kW)	120,000	120,000
Solar panel [$a(m^2)$, ϕ , y]	75000, 0.17, 0.73	75000, 0.19, 0.75
Solar radiation ($\lambda_{1,2,3}$)	0.089, -0.0001, 0.19	0.189, -0.00003, 0.29
Latitude (rad.)	1.034	- 0.39
Expected sky clearness	4.5, 1, 1	12, 3, 1
($\mathbb{E}[C_t]$, σ_t , k)		
Actual sky clearness	6, 3, 1	10.5, 4, 1
(C_t , σ_t , k)		
Mean temperature	5, 1, 10, 54.5	13, 7, 5, -55
[$\chi_{1,2,3}$, $\theta(^{\circ})$]		
Expected temperature [σ_t ($^{\circ}\text{C}$)]	5	5
Actual temperature [σ_t ($^{\circ}\text{C}$)]	6	6

TABLE II.
COMMON BLOCKCHAIN MARKETPLACE PARAMETERS

Parameters	Oslo	Windhoek
Tick price (us\$)	10	10
Risk-free interest rate (%)	0.6	1
Time-dependent risk loading (%; τ , q)	25, 31	10, 9.8
Blockchain transaction cost (us\$; μ_{b_t} , $\sigma_{b_t}^2$)	60, 30	60, 30

actual values for the production scenarios for the SPPs in the calendar year under review are chosen to follow two different paths. The SPP in Oslo is assumed to experience overproduction from its generation plant all year compared to its long-term forecast, in the order of several years. Conversely, the SPP in Windhoek encountered underproduction in its plant compared to its long-term forecast.

B. Results for the authentication mechanism

Before the calendar year under review, both SPPs resolved to hedge their long-term volumetric risks by enrolling in the proposed solar radiation-based derivative smart contract. They enrol seamlessly into this smart contract by adhering to Algorithm 3, requiring them to choose a trading position and propose suitable contractual terms, such as in Tables II - IV, in search of a bilateral counterparty. In practice, an SPP will unlikely find a single counterparty willing to take its opposite trading position, covering its entire implied cash volatility exposure for a calendar year. To achieve an adequately hedged position, in reality, these SPPs will trade several smart contract arrangements based on the proposed trading strategy in Section II-C2 and described as follows.

First, they assess the notional common terms of the available smart contract arrangements in the marketplace, as in Table II. Thereafter, they consider the available arrangements' strike value deviations from expected solar radiation given filtration (i.e., $\mathbb{E}[R_t|\mathcal{F}_t] \pm$ a deviation value), as in Table III and IV. Moreover, for a smart contract arrangement to possess inherent worth, it must have a strike value K that deviates from $\mathbb{E}[R_t|\mathcal{F}_t]$. Call options take negative deviation values, meaning that they are *in the money* at the time of the agreement's purchase and, therefore, have an intrinsic worth. Similarly, put options take positive deviation values to be *in the money* and, hence, have an intrinsic worth.

¹<https://www.iea.org/data-and-statistics>

²<https://photovoltaic-software.com/principle-ressources/how-calculate-solar-energy-power-pv-systems>

³<https://simplemaps.com/data/af-cities>

⁴<https://globalsolaratlas.info/map?c=11.609193,8.4375,3>

⁵<https://weather-and-climate.com/>

TABLE III.
TRADING PORTFOLIO OF THE SPP IN OSLO TO ACHIEVE AN ADEQUATELY
HEDGED POSITION

Option	Position	Strike (kwh/m ² /day)	Premium (us\$/day)	SCIV (us\$/day)	Unit	Duration
Call	Sell	- 0.3	284	187	87	Jan 1 - Mar 4
Call	Sell	- 0.3	328	536	87	Mar 4 - Mar 31
Put	Buy	+ 0.3	297	295	87	Jan 1 - Mar 31
Call	Sell	- 0.4	1143	1165	203	Apr 1 - Jul 6
Call	Sell	- 0.4	1150	1176	203	Jul 7 - Aug 31
Put	Buy	+ 0.4	1150	1205	203	Apr 1 - Aug 31
Put	Buy	+ 0.25	388	637	114	Sep 1 - Oct 16
Put	Buy	+ 0.25	311	170	114	Oct 17 - Dec 31
Call	Sell	- 0.25	340	362	114	Sep 1 - Dec 31

TABLE IV.
TRADING PORTFOLIO OF THE SPP IN WINDHOEK TO ACHIEVE AN ADEQUATELY
HEDGED POSITION

Option	Position	Strike (kwh/m ² /day)	Premium (us\$/day)	SCIV (us\$/day)	Unit	Duration
Call	Sell	- 0.16	1069	1080	273	Jan 1 - Feb 28
Call	Sell	- 0.16	945	872	273	Mar 1 - Apr 30
Put	Buy	+ 0.16	1015	990	273	Jan 1 - Apr 30
Call	Sell	- 0.12	605	635	242	May 1 - Jun 30
Call	Sell	- 0.12	692	776	242	Jul 1 - Oct 31
Put	Buy	+ 0.12	668	830	242	May 1 - Oct 31
Call	Sell	- 0.19	1175	1105	289	Nov 1 - Dec 31
Put	Buy	+ 0.19	1095	1171	289	Nov 1 - Dec 15
Put	Buy	+ 0.19	1177	1107	289	Dec 16 - Dec 31

Given these strike values, SPPs can trade units of the smart contract arrangement according to the proposed trading strategy, equating to an average daily premium that corresponds to their average daily SCIV for that period. The SPP must be careful not to super-hedge a position while attempting to achieve this proportionality. For instance, in Jan 1 - Mar 31 in the Oslo portfolio, the SPP resolved to trade a position between Mar 4 - Mar 31 that did not fully correspond with the SCIV for that period. However, enforcing the proposed trading strategy's proportionality of premiums and SCIV while achieving a self-financing position will result in super-hedging of the Jan 1 - Mar 4 period.

Likewise, available smart contract arrangements are unlikely to cover the entire calendar year, so an SPP must trade other arrangements to protect its cash flows for the rest of the year. For instance, the first three rows of the Oslo portfolio indicate that the SPP could costlessly hedge its SCIV with the available arrangements from Jan 1 - Mar 31. However, it had to trade other smart contract arrangements from Mar 31 to cover its cash flow volatility exposure for the rest of the year, as seen in rows 4 - 9. Notably, the traded smart contract arrangements are only illustrative of how an adequately hedged position using the proposed approach can be realized as other combinations could result in a similar outcome. For example, an arrangement with a higher strike value deviation than 0.3, as in rows 1 - 3 of the Oslo portfolio, will require the SPP to trade fewer than the 87 units of options to achieve an adequately hedged position for the same period.

C. Results for the settlement mechanism

The autonomous settlement mechanism ensures that due buyers of smart contract arrangements receive their payoff

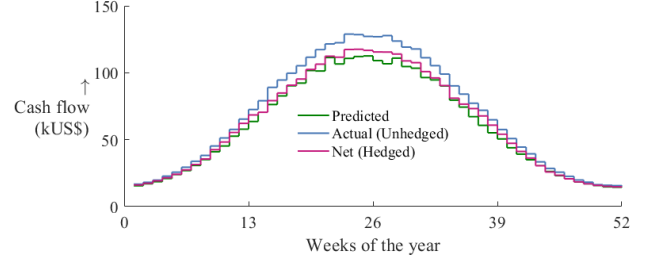


Fig. 7. Weekly predicted, actual (unhedged), and net (adequately hedged) cash flows of the SPP in a calendar year in Oslo, Norway

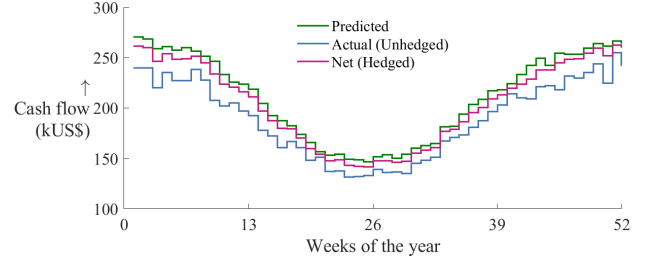


Fig. 8. Weekly predicted, actual (unhedged), and net (adequately hedged) cash flows of the SPP in a calendar year in Windhoek, Namibia

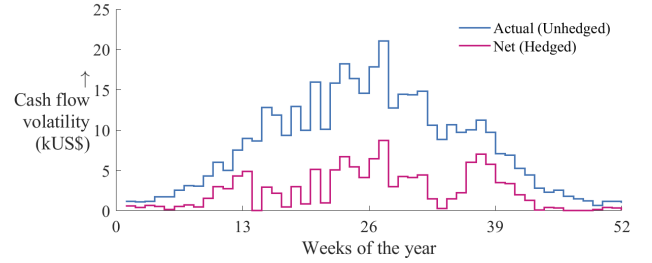


Fig. 9. Weekly actual (unhedged) and net (adequately hedged) cash flow volatility of the SPP in a calendar year in Oslo, Norway

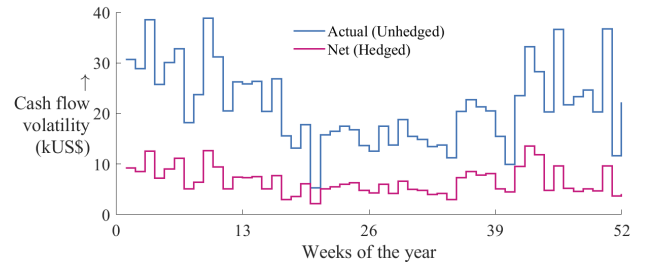


Fig. 10. Weekly actual (unhedged) and net (adequately hedged) cash flow volatility of the SPP in a calendar year in Windhoek, Namibia

immediately after the day's solar radiation index has been observed. The following results demonstrate how these payoffs minimize the cash flow volatility risk of the SPP in a virtually costless manner. From the overproduction case in Fig. 7 and underproduction case in Fig. 8, the weekly net (adequately hedged) cash flows of the SPPs are much more closer to the predicted value than the actual (unhedged) cash flows. This

TABLE V.
HEDGING OF WEEKLY CASH FLOW VOLATILITY OF THE SPPs

Oslo, Norway	Actual (unhedged)	Net (hedged)
Mean volatility (kUS\$)	7.90	2.40
Maximum volatility (kUS\$)	21.07	8.75
Windhoek, Namibia		
Mean volatility (kUS\$)	21.55	6.61
Maximum volatility (kUS\$)	38.85	13.57

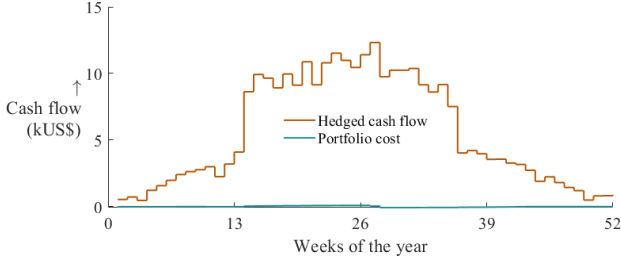


Fig. 11. Weekly hedged cash flow vs portfolio cost of the SPP in a calendar year in Oslo, Norway

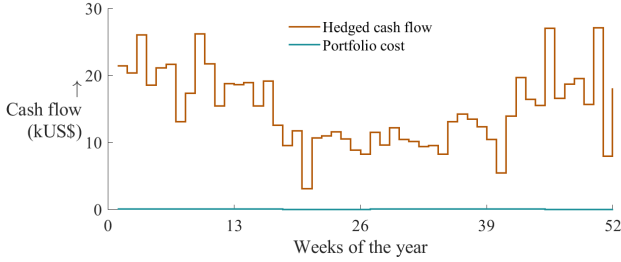


Fig. 12. Weekly hedged cash flow vs portfolio cost of the SPP in a calendar year in Windhoek, Namibia

cash flow predictability is crucial for solar generators to attract finance at favorable rates. Indeed, the SPP loses cash flows over the calendar year in the adequately hedged case of the overproduction scenario in Fig. 7. However, the SPP has instead chosen cash flow predictability over speculative profits. Contrarily, in the adequately hedged case of the underproduction scenario in Fig. 8, the cash flow losses of the SPP are reduced due to smart contract payoffs.

The cash flow volatility exposures of both production scenarios are assessed using the root mean square deviation metric, as in Fig. 9, for the overproduction case in Oslo, and as in Fig. 10, for the underproduction case in Windhoek. Fig. 9 and 10 illustrate the potency of cash flow hedging using the proposed trading strategy. From the summarized results in Table V, the employed trading strategy effectively mitigates the cash flow volatility exposures of the SPPs. Fig. 11 and 12 shows the weekly hedged cash flow compared to the portfolio hedging cost incurred by the SPPs in Oslo and Windhoek. The results indicate that the proposed trading strategy effectively hedges the cash flow volatility risk of the SPPs at virtually no cost.

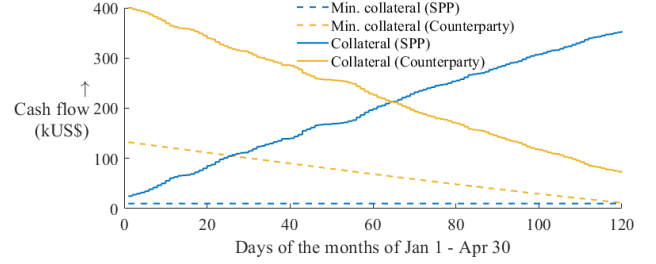


Fig. 13. Smart contract collateralization mechanism for non-defaulting or non-exiting contracting parties

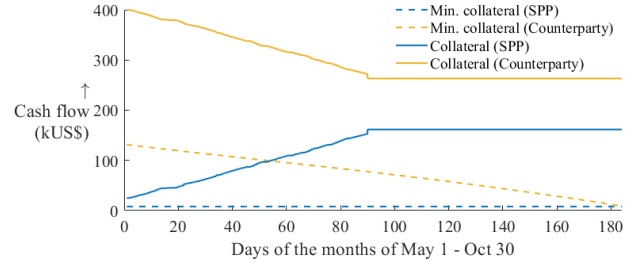


Fig. 14. Smart contract collateralization mechanism for an exiting contracting party

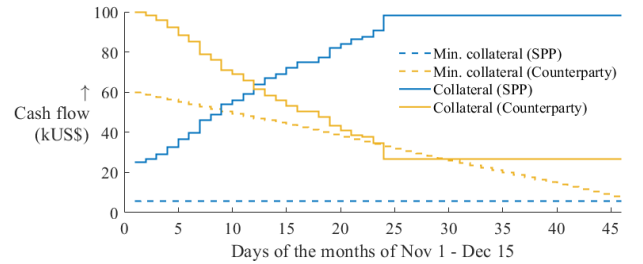


Fig. 15. Smart contract collateralization mechanism for a defaulting contracting party

D. Results for the collateralization mechanism

In this section, we demonstrate the actions taken by the autonomous collateralization mechanism to compel contracting parties to maintain an enduring arrangement. We also show how real-time collateral requirement updates once settlement is received eliminates exposure-collateral misalignments and results in zero credit risk for market participants. The collateral accounts of the Windhoek SPP and three separate bilateral counterparties from whom the generator purchased put options are examined. The minimum collateral requirement is estimated using Equations 18 and 19, where the replacement days for a terminated smart contract arrangement are chosen to align with the agreement's duration since longer-term arrangements expose parties to higher counterparty risks. In all scenarios, we assume that the premium paid by the SPP at the inception of the arrangement constitutes part of the starting collateral account balance of the bilateral counterparties.

In the Jan 1 - Apr 30 arrangement (i.e., row 3 of the Windhoek portfolio), both contracting parties agree to a replacement days value of 10. So their minimum collateral

requirement (Min. collateral) is computed as shown in Fig. 13. Both contracting parties remain in the smart contract over the agreement duration and appropriately maintain their collaterals. In the May 1 - Oct 31 arrangement (i.e., row 6 of the Windhoek portfolio), both contracting parties agree to a replacement days value of 12. So their minimum collateral requirement is computed as in Fig. 14. Here, the contracting parties appropriately maintain their collaterals until trading day 90 when the seller of the smart contract arrangement (i.e., the SPP's counterparty) exits the agreement. The SPP also becomes evicted from the smart contract, but before then, it receives a termination penalty compensation of US\$ 8,026 from the seller. In the Nov 1 - Dec 15 arrangement (i.e., row 8 of the Windhoek portfolio), both contracting parties agree to a replacement days value of 5. So their minimum collateral requirement is estimated as in Fig. 15. Here, the contracting parties appropriately maintain their collaterals until trading day 24, when the seller defaults on the minimum requirement. A default call is immediately invoked by the SPP. Both contracting parties' collateral accounts become liquidated from the smart contract. Again, the seller forfeits its termination penalty deposit of US\$ 5,856 to the SPP.

E. Discussion

The results from this study have demonstrated that the proposed DeFi marketplace as well as the self-financing and implied volatility-matching trading strategy can address some of the main shortcomings of traditional instruments in hedging the volumetric risks of SPPs. While these limitations are not solely technical but relate to other broader market issues, as seconded in [26], this paper focused on the issues from the perspective of the hedging instrument itself. The rest of this section notes the caveats in interpreting the realized outcomes and their potential consequence in the broader renewable electricity industry.

1) *DeFi marketplace*: This work has attempted to quantify the impacts of the proposed marketplace in addressing some of the risks of traditional arrangements, described as follows. Process risk is low, resulting in depressed margining and credit exposures. Margining risk can be reduced by 30 to up to 730 times in the worst-case scenario, calculated using (18), compared to traditional arrangements, as reported in [32]. Credit risk is driven to zero (also observed in [31]), as real-time collateral requirement updates are made once settlement is received, eliminating exposure-collateral misalignments. However, the SPP or other hedgers could still incur financial losses if the termination penalty payment becomes insufficient to cover its volumetric risk before securing a replacement contract that represents its initial hedged position. The same issue also exists in traditional credit risk hedging mechanisms. Flexibility is retained as in OTC arrangements while liquidity could be potentially enhanced, allowing selecting an underlying weather index (i.e., solar radiation) that absolutely correlates with solar power, hedging basis risk. The degree of minimization of liquidity risks is more challenging to evaluate explicitly without implementing or deploying the DeFi instrument on a live blockchain network. Future research could consider this gap.

There are other risks that the DeFi marketplace hedges in traditional arrangements that are not discussed in this paper. This stance is taken because these risks still exist in the proposed instrument. Ref. [26], [27], [29], [31], [43] noted the role played by DeFi in minimizing systemic risk due to the concentration of risks to a centralised counterparty with a single point of failure. However, Ref. [28] showed that while blockchain can reduce the systemic risk posed by these parties, this exposure transpires in another form in the decentralized market structure due to a heavy reliance on digital trading infrastructure which may be vulnerable to technological failures. While the proposed arrangement also reduces third-party risks due to human intermediaries in the trade cycle [27], it introduces a few new intermediaries, albeit based on decentralized finance and governance principles [48], [49]. These new actors themselves could pose security risks [58]. Legal risks are another exposure that falls into this category, but such non-technical issues are beyond the scope of this work.

The risks inherent in the DeFi instrument itself that is challenging to hedge include security and account risks. Once the DeFi smart contract is committed to the blockchain, it becomes immutable [46]. Therefore, programming flaws in the smart contract code can expose market participants to security attacks, resulting in financial losses [32]. The integrated DeFi smart contracts, stable coin and oracle, also expose market participants to security risks [58]. The DeFi instrument is also liable to account risks due to the possible loss of private keys and accidental funds transfer to the wrong or an invalid address. Account risks are noteworthy in the blockchain ecosystem because asset ownership is held in digital keys, and if they get missing, funds associated with them become irretrievable. Similarly, accidental fund transfer to a wrong or invalid address means eternal loss of funds [60].

2) *Trading strategy*: The proposed self-financing and implied volatility-matching trading strategy has proven effective and economical in hedging the cash flow volatility risk of SPPs. However, there are a few notable caveats. First, solar power is seasonal and not flat throughout the calendar year. As such, the SCIV for more extended smart contract arrangements will be less accurate than shorter periods. Hence, shorter arrangements will produce more precise results than the portfolios employed in our case. Moreover, the proposed trading strategy is only a demonstration of how an adequately hedged position can be achieved over a calendar year. It is also important to note that both components of the SCIV, time-dependent risk loading and implied cash flow volatility, are mere notional estimates and may significantly deviate from the actual values in reality. In practice, once actual trading commences on the blockchain marketplace, traders will have better information about these parameters.

Secondly, while the proposed trading strategy is expected to be self-financing, we have ascertained that, in reality, the combination of several smart contract arrangements over different accumulated duration will result in net positive or negative premiums. These differences in premiums result from the varying average daily SCIV for the period of the available traded smart contract arrangements and the seller's time-dependent risk loading attributes, which increases in line with

the agreement's duration. Nonetheless, realizing the proposed trading strategy will typically result in a much lower hedging cost than the amount of cash flow protected.

Other revenue risks of SPPs, including price and imbalance risks, were isolated to investigate the efficacy of the proposed trading strategy. While both of these revenue risks are short-term-based [7], considering them could impact the trading strategy and its outcome. The negligence of this effect could be reckoned a limitation of this work and considered for future research. Again, we note that these assumptions relate to constructing trading strategies and have no effect on the mechanics of the DeFi platform, whose main benefit is minimizing the risks inherent in traditional platforms.

IV. CONCLUSION

This work has shown that the proposed approach can address some of the main limitations inhibiting the take-off of traditional weather derivatives, including for SPPs. The DeFi marketplace introduces new risks that need to be better assessed and understood before they can become mainstream in the renewable energy industry. However, compared to traditional arrangements that have been around for more than two decades, blockchains are only burgeoning and have a chance to address these underlying risks and enable the sector to gain traction. From the perspective of the employed trading strategy, the realized stable cash flows could minimize the finance cost of constructing new solar generators. The virtually costless hedge could further incentivize SPPs to explicitly hedge their long-term volumetric risks using the proposed approach, rather than assuming this risk due to the expensive premiums of traditional contracts. The proposed instrument is merely illustrative of the kind of flexible hedging arrangements that the blockchain marketplace can underpin. Any other weather index or trading strategy could easily and usefully be employed to hedge other renewable generators. It suffices to note that the selected weather index should sufficiently correlate with the generator's stochastic output and that the trading strategy should align with the generator's hedging objectives.

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