



<b>Title</b>	Structuring Special Purpose Vehicles for Financing Renewable Generators on a Blockchain Marketplace
<b>Authors(s)</b>	Alao, Olakunle, Cuffe, Paul
<b>Publication date</b>	2022-03
<b>Publication information</b>	Alao, Olakunle, and Paul Cuffe. "Structuring Special Purpose Vehicles for Financing Renewable Generators on a Blockchain Marketplace." IEEE, March 2022. <a href="https://doi.org/10.1109/tia.2021.3135252">https://doi.org/10.1109/tia.2021.3135252</a> .
<b>Publisher</b>	IEEE
<b>Item record/more information</b>	<a href="http://hdl.handle.net/10197/25716">http://hdl.handle.net/10197/25716</a>
<b>Publisher's version (DOI)</b>	10.1109/tia.2021.3135252

Downloaded 2026-05-02 00:26:13

The UCD community has made this article openly available. Please share how this access benefits you. Your story matters! (@ucd\_oa)



© Some rights reserved. For more information

# Structuring Special Purpose Vehicles for Financing Renewable Generators on a Blockchain Marketplace

Olakunle Alao, *Member, IEEE* and Paul Cuffe, *Member, IEEE*

**Abstract**—Eighteen percent of the world’s population does not have access to electricity, impeding economic, social, and human development. The electricity access challenge can be attributed to the significant investment gap needed to finance new power projects, requiring new and innovative financing options. Independent Power Projects, funded, built, owned, and operated by the private sector and constituted via a Special Purpose Vehicle – a legal entity whose sole purpose is implementing a power project – have become one of the fastest-growing sources of investment in the electricity sector. The limitations of traditional finance sources, including high credit, liquidity, margining, third-party, legal, and process risks, means that funds for these projects are expensive and raised only after a long and arduous process. The present manuscript addresses these challenges by describing a novel decentralized autonomous organization, a blockchain-agnostic special purpose vehicle underpinned by a trio of autonomous mechanisms – *mobilization, collateralization and settlement*. These mechanisms enable seamless finance mobilization for the special purpose vehicle from a location-independent crowd, revenue collection from the electricity buyer in a risk-mitigated manner, and disbursal of eventual project revenues to investors.

## I. INTRODUCTION

WITH US\$1 trillion of renewable electricity investment needed to meet the United Nation’s Sustainable Development Goals (UN SDGs) for secure, clean, and affordable energy, the main challenge posed to the electricity industry is the significant investment gap required to finance new renewable power projects [1]. New and innovative finance sources are necessary to bridge this investment gap. *Independent power projects*, funded, built, owned, and operated by the private sector and constituted via a *Special Purpose Vehicle (SPV)* – a legal entity whose sole purpose is implementing a power project [2] – have become one of the fastest-growing sources of investment in the electricity sector [3]. They have recently eased the burden on the public sector of financing large power projects. With these generators, particularly the renewable ones, offering record-low electricity generation prices, it is evident that they represent one of the quickest means of achieving cheap renewable electricity [4]. However, the limitations of traditional finance sources, including high credit, liquidity, margining, third-party, legal, and process risks, means that funds for these projects are expensive and raised only after a long and arduous process [2], [5].

This publication has been funded by the Sustainable Energy Authority of Ireland under the SEAI Research, Development & Demonstration Funding Programme 2018, grant number 18/RDD/373 and additional funding provided by the UCD Energy Institute.

O. Alao (olakunle.alao@ucdconnect.ie) and P. Cuffe (paul.cuffe@ucd.ie) are with the School of Electrical and Electronic Engineering, University College Dublin.

Interests disclosure: the authors hold cryptographic assets.

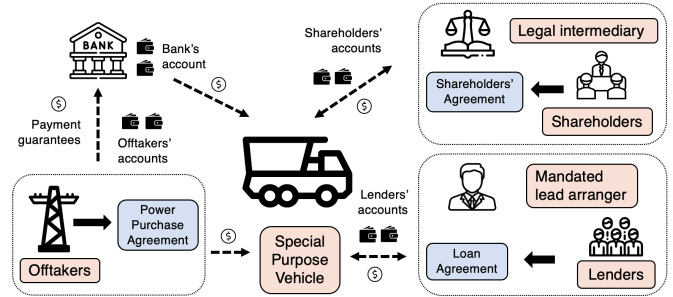


Fig. 1. Structure of a typical traditional renewable generator special purpose vehicle

The ideal scenario for renewable generator SPVs is that project owners have access to funding from multiple location-independent investors operating autonomously with different risk appetites and disposable funds. On the other hand, investors demand the fractionalization of such capital-intensive assets, enabling them contribute any amount of investment in the project and easily trade those investments later to interested parties in an open market. They also want to be guaranteed a share of future revenues in the project. Lastly, the electricity buyers from the SPV require a payment structure that reduces their direct and indirect electricity costs. Overall, these parties intend to achieve their objectives frictionlessly, seamlessly, and reliably. The inherent characteristics of blockchains, including decentralization, tokenization, and immutability, as well as smart contracts that are self-executing and persisting, could allow a new SPV arrangement that enables these parties to realize their ambitions. Therefore, this research aims to design the mechanisms that would underpin such an arrangement.

### A. Special Purpose Vehicles

An SPV is a commercial venture created by one or more organizations to undertake a specific purpose, such as implementing a renewable electricity project. SPVs have legal status as an independent entity, usually with their own assets and liabilities separate from their parent organizations [2]. The structure of a typical traditional renewable generator SPV is shown in Fig 1, while its life cycle is shown in Fig 2.

The three key parties of the SPV from an investment perspective are the shareholders, lenders, and off-takers. The *shareholders* are the legal owners of the generator’s physical assets, providing initial equity for the project in return for an ownership stake in the SPV. They are constituted at the project’s inception through a traditional shareholder’s agreement, usually underwritten by mutually contracted legal intermediaries [2]. The structure of this traditional shareholder’s arrangement

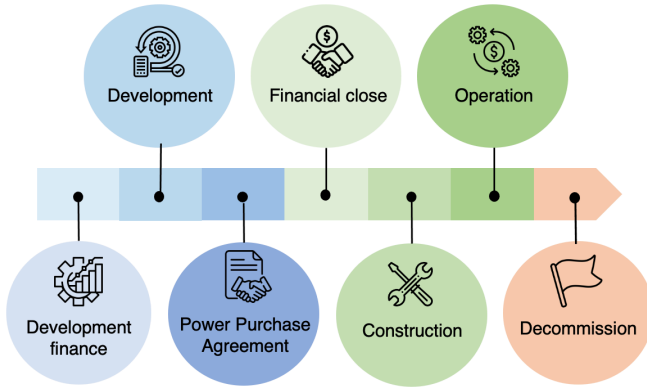


Fig. 2. Life cycle of a typical power project Special Purpose Vehicle

exposes the SPV to third-party, legal, and process risks. *Legal risks* arises due to the possible costs that can be incurred from long and grueling arbitration processes resulting from contractual and ownership disputes between shareholders [6]. The contracted legal intermediary can be fraudulent or partial, subtly favoring certain shareholders over others, leading to *third-party risk*. A hidden cost also persists due to *process risks*, the possibility that shareholders could suffer financial losses because of the bureaucratic traditional contracting regime resulting in operational inefficiencies. Losses could also be incurred due to the manual processes of the error-susceptible and slow-moving legal intermediary, resulting in operational unreliability [7].

Once the shareholders have been constituted and initial funds provided, the project commences the earliest phase of the SPV life cycle – *development finance*. This phase involves undertaking the *development* of the power project, including technical and financial feasibility assessments and detailed environmental and social impact studies [8]. Projects that succeed in the development stage proceed to secure their revenue streams by signing a bilateral *power purchase agreement* with the designated electricity buyer(s), otherwise known as *offtakers*. However, this bilateral arrangement is liable to counterparty credit, third-party, legal, and process risks.

*Credit risk* is the eventuality that the SPV's revenues will be negatively impacted because of payment defaults by the off-takers [8]. The traditional strategy for hedging SPV credit risk is by delegating an intermediary, usually a commercial bank, to hold cash collateral for the off-taker. Alternatively, a letter of credit, serving as a payment default insurance cover, can be purchased by off-takers from a commercial bank to perform the same purpose [9]. In that way, if an off-taker defaults on its payment obligation to the SPV, the delegated bank settles the deficit [6]. Traditional credit risk hedging strategies are expensive and expose the SPV to third-party risks, the eventuality that the intermediary managing collaterals can become fraudulent or bankrupt [6], [9]. They are liable to legal risks due to the possible costs from mediating processes or resulting from disputed payments or payment defaults between the SPV and off-takers [6]. They also suffer from process risks due to the error-susceptible and slow-moving bureaucratic intermediary managing the payment guarantees.

After signing the power purchase agreement, SPVs strive to reach financial close, securing all the funds needed for project *construction*. To raise debt finance or loan for the project to reach financial close, the SPV usually obtains funds from *lenders*, which are typically development finance institutions or commercial banks [9]. The limited pool of finance from these handful of traditional sources makes this process onerous and expensive [5], [9]. As only a few investors participate in funding such capital-intensive projects, investments have inherent *liquidity risk* since investors are unable to quickly exit their investment positions in the project at any time. In simple terms, liquidity implies that investors can contribute any amount of investment in the project and easily trade those investments later to interested parties in an open market [7]. Further, in the finance mobilization stage, a *mandated lead arranger* usually acts as the facilitator and coordinator of finance from several financial institutions, leading to third-party risk exposure for investors. The inherent administrative inefficiencies of traditional financial institutions slow the finance mobilization process for SPVs, leading to high process risk [9]. Again, legal risks could surface because of the possible costs that can be incurred from arbitration processes due to contractual disputes amongst lenders [6].

Following financial close and construction, the SPV aims to sustainably *operate* the power project to provide returns for its investors. Returns emanate from receipt of revenues from the off-takers. However, electricity payments in traditional SPVs are usually non-frequent, leading to accumulated settlement payments, and exposing off-takers to high *margining risks*. Non-frequent settlement times imposes the need for off-takers to reserve higher cash collaterals or purchase letter of credits at exorbitant costs to match the amount of insured cash flow, introducing the risk of high margin payments [10]. Margining risks decreases electricity off-take appetite and result in increased electricity costs for end-users.

Finally, the power project gets *decommissioned* after the duration of the power purchase agreement, usually tallying with the project's operational life [5]. Notably, the aforementioned challenges and limitations make it difficult for traditional SPVs to obtain the required funds for project implementation. And even if they do so, they achieve this at a high cost and only after a long and exhausting process.

## B. Decentralized Autonomous Organizations

Decentralized Autonomous Organizations (DAOs) are emerging as a game-changing concept enabling new ways of governance, ownership, consensus, and asset management [11]. DAOs are organizations established and represented on a blockchain, a decentralized and immutable digital ledger, enabling transparent and secure interactions between anonymous participants [12]. The rules of these organizations are underwritten by interconnected programmable smart contracts, algorithmic protocols that self-execute based on pre-defined terms and conditions [13], [14]. DAOs typically combine decentralized governance and finance principles to enforce specific actions amongst members of a network who do not have to trust or know each other and without the need for oversight from a central intermediary [11]. For instance, DAO rules embodied in smart contracts can enable autonomous disbursement of dividends

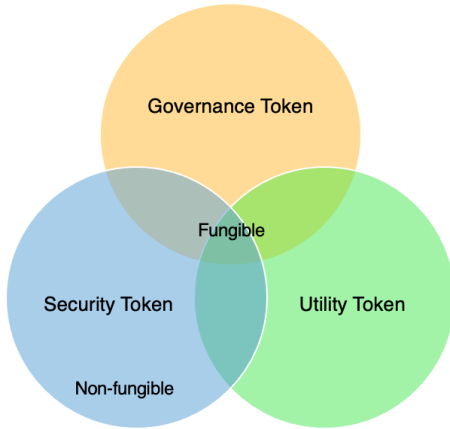


Fig. 3. The main categories of tokens underpinning DAO ecosystems

from a venture to certain organization members, supposing, for example, 50% or more of them consent to this decision. Today (as of November 2021), the market capitalization of DAO tokens sit at more than US\$ 44 billion, with a daily trading volume of about US\$ 4 billion [15].

Generally, DAOs are designed based on their founding members' vision and mission, and as such, have no canonical structure [16]. They could be fully decentralized (on-chain) or blended (i.e., having on- and off-chain components), with either arrangement having their weaknesses and strengths [17]. Their governance and ownership structure could be established at the inception of the project, or dependent on held utility, security, or governance tokens [18]. *Utility tokens* are often referred to as user tokens, serving as the medium of exchange in DAO platforms. They usually act as an access point into a DAO, and without them, users are unable to enjoy the available services or products. These tokens are fungible; identical tokens that can be easily exchanged and traded by holders on a public blockchain marketplace [19], and might be earned over time as a reward for contributing to the network or sold through an initial coin offering program. These programs are a mechanism for raising funds for a blockchain project, where investors are assigned tokens granting them certain rights and privileges, such as financial returns, voting rights, etc. [16]. Initial coin offering programs are reputed to have raised more money through crowdfunding than any other sector. Some examples of DAOs that have sold tokens worth over US\$ 1 trillion through initial coin offerings to fund their projects, includes EOS, telegram open network, and BITFINEX [20].

*Security tokens* are tokens that represent ownership of an external tradeable asset, such as real estate, collectibles, etc. They can be fungible or non-fungible, unique tokens used to prove asset ownership [19], [21]. Through security token offerings, companies can publicly sell equity of their projects represented as security tokens on the blockchain, granting holders an ownership interest, right to share of earnings, etc. Notably, unlike initial coin offerings, security token offerings could be regulated by Federal laws that govern security, such as the United States Securities and Exchange Commission [22].

*Governance tokens* are fungible tokens that usually double as utility or security tokens; however, they can be minted separately. Each token type, as shown in Fig. 3, provides specific features based on the DAO ecosystem. However, these groups are not mutually exclusive, as a token can fit into more than one category [18].

Today, DAOs are built on the three main categories of tokens, which can be fungible, non-fungible, or both. An illustrative example of a DAO that is based on fungible tokens is the MakerDAO, whose core service is the support of the fungible DAI stablecoin cryptocurrency, closely pegged to the fiat US\$ via decentralized incentive structures [23]. Therefore, users can hold DAI, without the prospect of price volatility normally associated with other cryptocurrencies. A community of MakerDAO governance fungible token holders oversee the Maker Protocol, the interconnected smart contracts that power DAI [18]. With such decentralized governance arrangements, changing the strategic direction of the community simply requires a majority vote from the *governors*, permitting the *developers* to upgrade the system's source code [18].

While most DAOs have been solely built on fungible tokens, DAOs based on non-fungible tokens are starting to see the light of the day, especially in the creative industries, such as collectibles, music, gaming, etc. [21]. The outputs from these industries (e.g., an art work) are well suited for non-fungible tokens representation since they are usually unique and invaluable. However, non-fungible tokens are illiquid given that again they are unique and can not be easily exchanged and traded [24]. A number of DAOs based on non-fungible-backed tokens have been proposed recently, one of which will be described as follows. In May 2021, JENNY DAO raised US\$ 7 million through the sale of its social fungible utility token for shared non-fungible token ownership. The DAO will be responsible for acquiring non-fungible tokens and adding them to a secured smart contract-controlled vault. These non-fungible tokens can be auctioned to prospective sellers if consenting token holders reach a certain threshold and instruct the smart contract to unlock the vault [25].

Overall, DAO use cases suggest that they can potentially improve the transparency of governance and financial transactions, enhance prompt settlement payments, reduce administrative and transaction costs, hedge third-party risk exposures, etc. DAOs introduce new risks to organization members including *volatility risk* of the native currency of the blockchain [11], *security risks* due to poorly tested smart contracts or new attack vectors and interactions with other blockchain applications [26], *design risks* resulting from faultily designed smart contracts [5], and *account risks* because of user smart contract account management-related errors [27]. Many of these risks can now be explicitly hedged. Moreover, the potential benefits of DAOs currently necessitate continuous research and development regarding the extent of value they can offer for diverse industries. Even governments such as the US [28] and UK [29] are evaluating and adopting sub-functionalities of DAOs such as decentralized finance to improve transparency, efficiency, and trust in financial management. Still, private companies continue to lead the research and development of DAOs globally.

One of the main proposed applications of DAO principles in the electricity industry is in renewable electricity tokens and

investment [30]. Here, fungible tokens are used to represent ownership of renewable generators because such tokens can be liquidly traded on a public blockchain marketplace [5], [11], [30]–[32]. Non-fungible tokens might be unsuitable for representing renewable generators since these assets can be formally valued and quantified [2]. Moreover, the representation of these assets with non-fungible tokens could result in valuation surges, leading to high electricity costs for end-users, and as such, negating the impact of renewable generators in contributing to the UN SDGs for secure and affordable energy. Hence, the rest of this paper considers the use of fungible tokens for renewable electricity investment.

Although there are no definitive and explicit government policies or rules and regulations for DAO in the renewable electricity or overall electricity sector, private companies are leading the innovation and charting the course for employing DAOs in accelerating renewable generation. Several renewable electricity infrastructure companies now utilize decentralized governance and finance principles to accelerate renewable electricity investments and asset co-ownership [5], [11], [30]–[32]. These projects crowdsell small and capital-intensive renewable projects to potential investors, using blockchains to trace and track ownership and revenues transparently and securely. Smart contracts are used to autonomously invoke payments from these generators to investors, as electricity is produced and metered in real-time [30].

Some illustrative examples of these projects are described as follows. In 2018, a Gibraltar-based startup raised US\$ 40 million through the sale of its utility tokens WPR to allow renewable generators such as solar or wind farms to mobilize capital by selling future energy production upfront to potential investors, in the form of security tokens [32]. A South African-based company also crowdsells solar PVs to potential investors. These solar assets are subsequently leased to end-users in developing countries, usually schools and small businesses. This company has funded a number of renewable electricity projects with the most recent a 0.5MW (US\$ 1.4 million) solar plus battery storage farm in Zimbabwe, which reached financial close in March 2021 [31]. An Israeli-based startup mobilizes finance for solar farms in Israel, Portugal, Kazakhstan, and Ukraine, through its native utility tokens SDAO that have already delivered about US\$ 450,000 from crowdsales [30]. Lastly, another venture based in the US develops decentralized platforms for financing renewable generators in communities that lack electricity access, through the sale of its security tokens MPAQ to prospective investors. It also allows its users to transact with its utility tokens NRG to purchase electricity to meet their energy demand [30].

The use of DAOs for renewable electricity investments has minimized some of the risks of traditional arrangements such as liquidity, third-party, legal, and process risks, which is discussed in better detail in subsequent sections. However, none of the state-of-the-art DAOs explicitly hedge counterparty credit risk, the core and fundamental risk of a renewable electricity infrastructure venture [2]. As all these solutions are industry-based and -focused, the concrete theoretical mechanisms facilitating and underpinning their operations are *black-boxed*. They also do not objectively consider the limitations and new risks introduced by DAOs. Excluding a precursor study

in [5], there is yet to be any rigorous academic research around the financing of renewable generators on a blockchain-agnostic marketplace, which is inappropriate for the equitable and just advancement of this novel field in the context of the general renewable electricity industry. These gaps, therefore, motivate this research study.

### C. Novel Contribution

The novel contribution of the present work is a functional description of a blockchain-agnostic smart contract that operates as a mediator between key parties of an SPV. Hence, the specificities of smart contract chain code development are abstracted in this work. Such smart contract scripting details have already been investigated earlier, such as in [10]. The proposed structural framework addresses the following research questions:

- How can a DAO be developed to mirror the technical, legal, and commercial functionalities of traditional SPVs, while limiting some of the new risks it introduces?
- How can a DAO be developed to overcome the limitations and hedge the underlying risk exposures of existing SPV structures?

The core functionalities of traditional SPVs are maintained in the proposed blockchain SPV through the trio of autonomous mechanisms – mobilization, collateralization, and settlement. In this way, design risks are minimized. These autonomous mechanisms streamline finance mobilization for the SPV from a location-independent crowd, revenue collection from the electricity buyer, and disbursement of eventual project revenues to investors. Notably, in traditional project finance, relatively stable fiat currencies such as the US\$ are used as the medium of exchange. However, the native currencies of blockchains are highly volatile [11], exposing the SPV to the possibility of incurring financial losses, such as the state-of-the-art renewable electricity DAOs [30]–[32]. Volatility risk can be mitigated by incorporating a stablecoin cryptocurrency into the smart contract. However, this interaction with another blockchain application introduces security risks. Hence, a mature stablecoin cryptocurrency, operating on decentralized governance and finance principles, such as [23], can be chosen as the proposed DAO’s utility token.

The trio of autonomous mechanisms is also employed to hedge the underlying risk exposures of traditional SPVs: credit, liquidity, margining, third-party, legal, and process. The autonomous mobilization mechanism governed by the smart contract, such as employed in [31], [32], opens up a whole world of location-independent investors to fund renewable generators with any amount, in exchange for the DAO’s native security token, and be guaranteed a share of future revenues in the project by redeeming such token. This vast funding pool means quicker and more available capital for renewable generators. The mobilization mechanism hedges liquidity risk, as investors can easily trade their investments in the project. Credit risk inherent in traditional SPVs are addressed via the autonomous collateralization mechanism, incentivizing off-takers to fulfill their payment obligations to the renewable generator. Off-takers are shielded from margining risks due to the autonomous settlement mechanism that enables prompt settlement payment to the investors.

All these actions, as well as those of other arrangements within the SPV, such as the shareholder's agreement, are enforced by the smart contract without the oversight of a human third-party intermediary. Legal risks of traditional SPVs are hedged by the autonomous smart contract enabling enduring and irrefutable arrangements. Process risks are minimized as a result of the process automation introduced by the same self-executing, persisting, and immutable smart contracts that operate based on only the prespecified conditions embedded in them [30]. Importantly, the objective of this research is not to develop a definitive renewable generator DAO structure but instead to showcase the fundamental mechanics that should exist in such arrangements and to determine their effectiveness in overcoming the limitations of traditional instruments.

## II. METHODOLOGY

This section describes the design of the blockchain SPV structured as a DAO. Designing DAOs can be challenging because the blockchain smart contract that governs their operation must maintain the equivalent legal, financial, and technical functionalities of the traditional contract they are representing [27]. This emphasizes the significance of the *business logic*, the terms and conditions of the smart contract, enabling asset-handling and incentivizing rational actions amongst parties that do not have to trust or know each other [33]. Critical to the business logic of the blockchain SPV is a trio of autonomous mechanisms; mobilization, collateralization, and settlement. The rest of this section will demonstrate how these mechanisms embedded in the smart contract can enable a renewable generator to overcome the challenges of existing SPV structures.

There are many potential ways of harnessing the power of smart contracts to establish a DAO. For illustration, a particular DAO structure, suitable for financing renewable generators, is outlined. Again, the aim of this research is not to develop a definitive renewable generator DAO structure but rather to propose the key mechanics that should exist in such arrangements and to determine what sort of value can be derived from them in minimizing the underlying risk exposures of existing instruments. The proposed structure, embodied in Fig. 4, is implemented as a smart contract, immutably handling assets existing on a suitable blockchain network and complemented by traditional legal contracts. The cryptocurrency volatility risk inherent in state-of-the-art renewable electricity DAOs [31], [32] are hedged using a mature stablecoin, operating on decentralized governance and finance principles, such as [23]. Hence, throughout the rest of this paper, the blockchain stablecoin cryptocurrency is equivalent to the US\$ off-chain fiat currency and is the proposed DAO's medium of exchange or utility token.

The three key parties of the blockchain SPV are the shareholders, decentralized lenders, and off-takers. The actions and inactions of these players are governed and motivated by the smart contract, minimizing third-party, legal, and process risks. As a result, they have no need of directly interacting with one another. Rather, they function in alignment with the pre-specified agreements encoded in the smart contract's business logic. The *shareholders* are the legal owners of the generator's physical assets, providing initial funds for the project in return

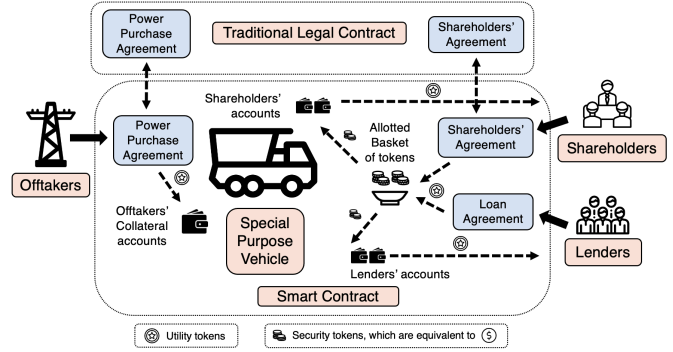


Fig. 4. Structure of the proposed blockchain-agnostic renewable generator special purpose vehicle

for an ownership stake in the SPV. They are constituted off-chain at the project's inception via a traditional shareholder's agreement. Each shareholder's stake, represented in this traditional agreement, is thereafter immutably written into the smart contract. To construct the power project, the shareholders require the bulk of project funding from external sources. However, the limited finance from traditional finance sources makes this process onerous and expensive [5]. To address this issue, we propose that the shareholders use the smart contract's autonomous mobilization mechanism to secure debt finance for the SPV from decentralized lenders, situated anywhere globally.

Shareholders obtain these funds through a security token offering scheme, whose terms and conditions are set in a traditional loan agreement. In such a program, they determine the number of tokens and price per token, whose product equals the project's total investment cost. Afterward, they allocate some of the tokens between themselves, representing the off-chain equity they provided at the SPV's inception. Finally, they sell the remaining tokens through the mobilization mechanism of the blockchain SPV platform. The sold tokens are designed to match the amount of debt finance they intend to secure to implement the project. *Decentralized lenders* are incentivized to buy these security tokens because owning them grants them access to future revenue streams, in the form of utility tokens, in a way fully governed by the smart contract. Before the security token offering program, the shareholders must secure the revenue stream, serving as the basis of loan repayment to the decentralized lenders [3]. The revenue stream is derived from the *offtakers*, the buyers of the electricity produced by the renewable generator. A traditional power purchase agreement between the shareholders and the off-takers guarantees the project's revenue stream. This agreement is initially negotiated off-chain, after which the key terms are immutably written into the smart contract.

Once the project commences operation, shareholders and decentralized lenders receive revenue streams from the off-takers through the smart contract. A blockchain-enabled smart meter serves as a *hardware oracle*, recording off-takers electricity consumption data and feeding it to the smart contract for settlement purposes. A new challenge arises in this decentralized and trustless arrangement: what if the off-takers do not have the funds or willingness to make the payments for the

electricity they have consumed? To this end, an autonomous collateralization mechanism is proposed to mitigate this credit risk posed by the offtakers. The smart contract collateral mechanism autonomously manages collaterals for offtakers to incentivize them to fulfill their payment obligations to the spv. Holding such collaterals can result in margining risk. However, margining risk is addressed by the autonomous settlement mechanism, which enforces prompt smart contract settlement as electricity is consumed and metered in real-time. This mechanism essentially reduces the credit exposure of the offtaker to the spv at every instance, and hence, the margining risk. The rest of this section presents a more in-depth design of the proposed illustrative business logic.

#### A. Mobilization Mechanism

The shareholders mobilize finance for the generator once the revenue stream is guaranteed. Project revenues emanate from the offtakers, the buyers of the electricity produced by the generator. An off-chain negotiated power purchase agreement between the offtakers and shareholders is used to secure the project's revenue stream, after which the key agreed terms are immutably written into the smart contract. The finance  $F$  for the project is obtained from two distinct types of investors: shareholders and decentralized lenders, and is represented as a gearing ratio, the ratio of debt to equity contributions in the project. Equity funds  $E$  are provided off-chain by  $i^{th}$  shareholders at the project's inception. The shareholders are the project's legal owners and provide initial funds with the expectation of earning a return on their investment throughout the project's power purchase agreement. In contrast, debt  $D$  for the project, in utility tokens, is obtained from  $j^{th}$  decentralized lenders on the blockchain spv platform at a later stage, in return for security tokens. The composition of the total finance cost for the project is as in (1).

$$F = \sum_{i=1}^I E_i + \sum_{j=1}^J D_j \quad (1)$$

1) *Token Distribution*: Shareholders provide off-chain equity funds at the project's inception. In return, they receive an ownership stake in the spv. These initial funds provided by the shareholders might, for instance, be utilized to complete development studies for the project [5]. For the project to proceed to construction, financial close must be achieved by the spv, which is when all the project finance for construction has been fully secured. A security token offering scheme is proposed to raise these funds. Here, the shareholders assign tokens  $\beta$  at a price  $p$ , equivalent to the project's finance cost as in (2).

$$F = \beta \times p \quad (2)$$

Afterward, they allocate tokens to themselves, representing their stake in the project. Specifically,  $i^{th}$  shareholders receive tokens  $\beta_i$  as in (3). Finally, they sell the remaining tokens on the blockchain spv platform through a security token offering program. The decentralized lenders purchase these security tokens to provide the project's debt finance in exchange for the DAO's utility token. They are motivated to hold these security

---

#### Algorithm 1 : Mobilization Mechanism

---

```

1:  $\forall E_i$  and  $A_i$  is the contribution and address, respectively
   of  $i^{th}$  shareholder.
Input:  $F, E, E_i, A_i$ 
(A) Shareholders contribution :
2:  $\forall$  Derive required debt  $D$ 
   let  $D = F - E$ 
3:  $\forall$  Assign security tokens to shareholder based on its
   contribution
4:  $\mathbb{M}(i): \beta_i \rightarrow A_i$ 
Output:  $\mathbb{M}(i)$ 
5:  $\forall D_j$  and  $A_j$  is the utility tokens contribution and address,
   respectively of  $j^{th}$  decentralized lender.
Input:  $D_j, A_j$ 
(B) Decentralized lenders contribution :
6:  $\forall$  Check if the mobilized debt  $D^*$  is less than the required
   debt and if the contributed debt by the decentralized lender
   is not greater than the difference between the required and
   mobilized debt.
7: if ( $D^* < D$ ), ( $D_j \leq D - D^*$ ) then
8:    $\forall$  Assign security tokens to decentralized lender based
   on its contribution
9:    $\mathbb{M}(j): \beta_j \rightarrow A_j$ 
10:   $\forall$  Top-up  $D^*$  with the decentralized lender contribution
   let  $D^* = D^* + D_j$ 
11: else
12:    $\forall$  Revert transaction to the initial state
13: end if
Output:  $\mathbb{M}(j), D^*$ 

```

---

tokens because owning them guarantees them access to future revenue streams, in the form of utility tokens, comprising their initial investment and interest, in a way fully governed by the smart contract. This smart contract arrangement is immune to tampering and cannot be subsequently rescinded by the shareholders [30]. The tokens  $\beta_j$  received by  $j^{th}$  decentralized lenders is as in (4). Algorithm 1 showcases the sequence of execution of the autonomous mobilization mechanism.

$$\beta_i = \frac{E_i}{E} \times \frac{E}{E + D} \times \beta \quad (3)$$

$$\beta_j = \frac{D_j}{D} \times \frac{D}{E + D} \times \beta \quad (4)$$

In practice, the employed renewable generator tokenization will result in the fractionalization of an otherwise capital-intensive project, increasing the pool of potential investors and liquidity since smaller investors can participate in the asset's financing process, and ensuring that loans are secured quickly and competitively on the DAO platform.

2) *Expected Returns*: We propose that the smart contract allows investors to periodically initiate withdrawals in utility tokens corresponding to their due returns. The total debt  $L$  due to the decentralized lenders in the project is as in (5), where  $r$  is the interest rate,  $y$  is the debt principal (i.e., the actual debt provided), and  $q$  is the number of payment period. The total annual debt service  $W_n$  paid by the smart contract to the decentralized lenders to gradually offset the total debt

is as in (6).  $d$  is the Debt Service Coverage Ratio (DSCR), the ratio of the periodic revenues to the debt required to be repaid, specified in the blockchain loan agreement between the shareholders and the decentralized lenders.  $f$  is the duration (in years) of the power purchase agreement. Equation (6) implies that the decentralized lenders will receive total annual payments according to the project's DSCR until the entire debt has been fully serviced.

$$L = \left( \frac{r \times y}{1 - (1 + r)^{-q}} \right) \times q \quad (5)$$

$$W_n = \begin{cases} \frac{\delta_t}{d} & \sum_{n=1}^{N=f} W_n \leq L, \\ 0 & \sum_{n=1}^{N=f} W_n > L \end{cases} \quad (6)$$

The principal  $y$  and interest  $l$  components of the debt service vary, with the interest payments declining over time. The interest component of the total annual debt service throughout the loan tenure is shown in (7). In (7),  $B$  represents the beginning balance of the total debt yet to be serviced, and  $q^*$  is the number of remaining payment periods.

$$l = B \times \frac{r}{q^*} \quad (7)$$

In parallel to debt servicing, the shareholders also receive total annual payments proportional to their stake in the SPV. The total annual payments disbursed to shareholders  $G$  by the smart contract over the operational life of the project is as in (8). Equation (8) implies that before the total debt is completely paid, the shareholders earn the remainder of the total annual revenue less the debt service amount. However, once the total debt has been completely serviced, the shareholders earn all the revenues from the project until it is decommissioned.

$$G_n = \begin{cases} \delta_t - W_n & \sum_{n=1}^{N=f} G_n \leq L, \\ \delta_t & \sum_{n=1}^{N=f} G_n > L \end{cases} \quad (8)$$

### B. Collateralization & Settlement Mechanisms

This section outlines how the blockchain SPV smart contract collects the revenue in utility tokens from the designated off-takers, the buyers of the electricity and the principal source of revenue for the project, and disburses it to the respective investors. Revenue collection and disbursement in the SPV is governed by novel collateralization and settlement mechanisms that compel parties who do not have to trust or know each other to uphold the underlying arrangements of the SPV.

Off-taker credit risk is one of the main underlying risks of a renewable generator SPV, making debt finance mobilization onerous and expensive. Credit risk is high in traditional arrangements because off-takers having power purchase agreements with SPVs may simply not have the funds or willingness to follow through on their payment obligations for electricity consumed. The traditional mechanism for minimizing credit risk is by purchasing a letter of credit from or depositing cash collateral in a financial institution. However, these mechanisms are expensive and expose the SPV to third-party, legal, and process risks, already described in previous sections. To mitigate

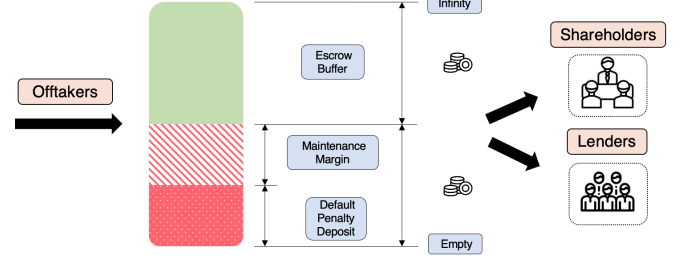


Fig. 5. Management levels of collateral to be maintained by off-takers in the smart contract.

this risk exposure on-chain and in a fully autonomous way, a collateralization mechanism is employed.

The collateral account  $R_t$  maintained by the off-takers, constitutes maintenance margin  $M_t$  and default penalty deposit  $H^*$  as in (9) and as visually shown in Fig. 5. The maintenance margin of an off-taker mirrors its credit exposure to the SPV at every trading period. To ensure that off-takers have adequate funds in their collateral account to make settlement payments in utility tokens due to the SPV, the minimum reserved maintenance margin  $M_{min,t}$  must be greater than the expected payment to be made by the off-taker in a future date as in (10). For instance, if based on the power purchase agreement, cash collection by the smart contract is specified to be made weekly, then  $M_{min,t}$  must be greater than the expected electricity payment for the next week.

$$R_t = M_t + H^* \quad (9)$$

$$M_{min,t} \geq \max(\delta_t^{k \rightarrow i,j}) \quad (10)$$

The default penalty  $H$  is used to penalize defaulting off-takers in the smart contract whose maintenance margin falls below the minimum requirement, as conveyed in Algorithm 2. A default on the maintenance margin leads to a default penalty deduction from the default penalty deposit. Once the default penalty deposit is depleted, the off-taker's blockchain-enabled meter becomes notified, and thereafter, ceases to allow electricity supply to the off-taker. In practice, the proposed collateralization mechanism results in zero off-taker credit risk for SPVs, since they are incentivized by the smart contract to fulfill their payment obligations. Such autonomous action minimizes the new risks that traditional credit risk hedging strategies would have otherwise introduced, enabling SPVs secure financing at more advantageous terms. However, the SPVs could still incur unexpected financial losses during the period before it finds a replacement off-taker. Hence, it is critical that the default penalty payment can compensate the SPV for this power purchase agreement replacement risk or that it is sufficient to disincentivize off-takers from defaulting on their maintenance margin requirement and consequently exiting the power purchase agreement [27].

Off-takers could be exposed to high margining risk, a financial risk that future revenues are lower as a result of maintenance margin payments. This risk generally results due to the infrequent settlement cycle of traditional revenue collection mechanisms. Settlement payments in the UK wholesale

**Algorithm 2** : Collateralization Mechanism

---

```

1: \\  $A_k$  is the address of the offtaker
Input:  $A_k$ 
2: \\ For all offtakers  $A_k$  do the following:
3: for  $k \leftarrow 1$  to  $A_k$  do
4:   \\ Check if offtaker's maintenance margin falls below
   the minimum requirement
5:   if ( $M_k < M_{min}$ ) then
6:     \\ Deduct default penalty  $H$  from the default penalty
     deposit  $H_k^*$  of the offtaker
     let  $H_k^* = H_k^* - H$ 
7:   end if
8:   \\ Check if the default penalty deposit of the offtaker
   is lower than the default penalty payment
9:   if ( $H_k^* < H$ ) then
10:    \\ Empty collateral account  $R_k$  of offtaker
    let  $R_k = 0$  (i.e.,  $M_k = 0$ ,  $H_k^* = 0$ )
11:    \\ Record offtaker as expelled  $X_k$  from the smart
    contract
12:     $\mathbb{M}(k): A_k \rightarrow X_k$ 
13:   else
14:     \\ Revert transaction to the initial state
15:   end if
16: end for
Output:  $\mathbb{M}(k)$ ,  $R_k$ 

```

---

electricity market, for example, can take from a few months to up to 2 years to conclude [30]. Therefore, an autonomous settlement mechanism is employed to promptly and irrefutably collect revenues from offtakers as electricity is consumed and metered in real-time, and periodically settle investors. This implies that in practice, offtakers can reduce their margining risk by the factor expressed in (11), where  $\tau_d$  is the average settlement time for traditional arrangements and  $\tau_b$  for the proposed DAO. This reduced margining risk will result in higher electricity connections and a lower cost of electricity for end-users.

$$\frac{\tau_d}{\tau_b}, \tau_d \gg \tau_b \quad (11)$$

Notably, The smart contract is naturally unaware of the real-time electricity consumption by the offtakers. Therefore, the blockchain spv requires an *oracle* to feed the smart contract with this external data. A blockchain-enabled smart meter, such as in [34], is employed to undertake this metering and billing function for the spv. The meter records the electricity consumed by the offtakers and relays it to the smart contract. The sequence of execution of the autonomous settlement mechanism is demonstrated in Algorithm 3.

### III. RESULTS AND DISCUSSION

This section showcases the workings and value of the autonomous mechanisms of the blockchain spv. The case study forming the basis of analysis in this paper are notional estimates derived from similar power projects in the case study region as in [3]. The MATLAB scripts utilized for simulating the case study and results can be found in a persistent online repository at [35].

**Algorithm 3** : Settlement Mechanism

---

```

1: \\ For all investors  $A_{i,j}$  do the following:
2: for  $i, j \leftarrow 1$  to  $A_{i,j}$  do
3:   \\ Check if the settlement function has not been invoked
   within a prespecified period  $I'$ , where  $I$  and  $I^*$  are the
   current and last invoke time, respectively.
4:   if ( $I \geq I^* + I'$ ) then
5:     \\ Top-up shareholder account  $R_i$  with due revenue
     let  $R_i = R_i + \beta_i \times \delta_t$ 
6:     \\ Top-up decentralized lender account  $R_j$  with due
     revenue
     let  $R_j = R_j + \beta_j \times \delta_t$ 
7:   else
8:     \\ Revert transaction to the initial state
9:   end if
10: end for
Output:  $R_i$ ,  $R_j$ 

```

---

#### A. Case Study

A 10MW solar pv independent power project in Tororo, Uganda, is considered in this study. The revenue  $\delta_t$  (in utility tokens or in this case us\$) of such generator as in (12), is a product of the price  $P$  (in us\$/kwh) agreed between the generator and offtaker(s), and the volume  $V_t$  (in kwh) consumed by the offtaker, where  $\forall t \in T$  is the day(s) considered.

$$\delta_t = \int_t^T (PV_t) dt \quad (12)$$

The electricity volume produced daily by the solar generator is shown in (13). In (13),  $N_t$  is the daily solar radiation (in kwh/m<sup>2</sup>/day),  $a$ ,  $h$ , and  $\phi$  indicates the area, yield, and performance ratio of the solar panel, respectively [36]. The idea of *degradation* and *curtailment* is also introduced, to make this analysis more realistic. Solar panels degrade annually, represented as the degradation factor of the solar generator  $\omega_1$  [37]. Likewise, these generators can be compelled to supply power below their installed capacity, represented as the constraint & curtailment factor of the generator  $\omega_2$  [38]. While these assumptions are crucial in the estimation of the solar generator's cash flows, we note that they do not impact the actual operational mechanics of the proposed DAO.

$$V_t = N_t a h \phi (1 - \omega_1) (1 - \omega_2) \quad (13)$$

Several daily solar radiation models have been proposed and substantiated with actual data, e.g., in [39]. For simulation purposes, the model suggested in [39] is used as in (14). In (14),  $S_t$  is the average daily extraterrestrial radiation, that is, the radiation at the top of the earth's atmosphere. The sky clearness index is represented as  $C_t$ , the average temperature (in °C) as  $U_t$ , while  $\lambda_1$ ,  $\lambda_2$ , and  $\lambda_3$  are location-conditional parameters.

$$N_t = S_t \sqrt{C_t} (\lambda_1 + \lambda_2 U_t) + \lambda_3 \quad (14)$$

The generation profile of the solar plant using the aforementioned model becomes as in Fig. 6. The downward trend in Fig.

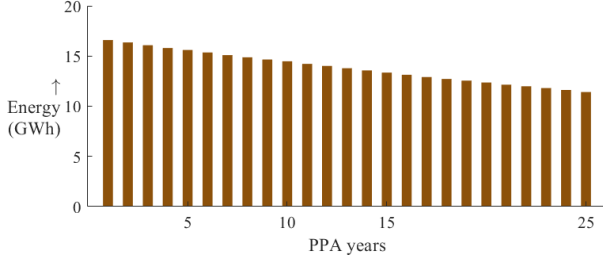


Fig. 6. Predicted generation profile of the 10MW solar generator based in Tororo, Uganda over its operational life.

6 is due to the solar panel degradation assumption employed in this analysis. The generation profile determination occurs at the project development stage, costing us\$0.2 million and funded off-chain by the shareholders at project inception. Further, from project development analysis, construction is billed to cost us\$8.9 million, with an annual operational cost of us\$50,000. The total project cost amounts to us\$10.35 million. With a 70:30 gearing ratio, the equity funds required to be mobilized by the shareholders for project implementation amounts to us\$3.1 million (including project development cost), while debt amounts to us\$7.2 million.

Thereafter, a 25-year, build-own-operate and take-or-pay power purchase agreement at a tariff of us\$60/MWh is negotiated and signed off-chain between the independent power project and several offtakers, including manufacturing industries, large co-ops, homes, etc. While a fixed price has been employed for this analysis as in regulated electricity markets such as the case study region, a similar predictable price will also hold in deregulated electricity markets. Today, several bilateral contracts are available in deregulated electricity markets that enable solar generators to sell their electricity at a guaranteed fixed price for a short- or long-term [40]. One example of such arrangement is a contract-for-difference between a renewable generator and a counterparty offtaker, buying electricity from the same pool that the generator is selling into [10]. These parties are incentivized to enter this contract because it is mutually beneficial for them to hedge their exposure to the deregulated electricity market's spot price volatility since high prices are good for the generator but bad for the offtaker and vice versa.

Table I outlines the details of the notional project's specifications, power purchase agreement, and loan agreement. Excluding the loan interest rate selected as 3%, considerably much lower than the rates offered by most commercial banks for such projects as in [41], all other data points are mere assumptions. Essentially, the finance cost is representative of the interest rate, which is dependent on the liquidity of the market, associated administrative cost for mobilizing funds for the SPV, and the SPV's risk such as credit, margining, etc. [9]. And as already established, the DAO platform addresses the underlying risks of SPVs that result in high finance cost, as will be substantiated in the following analysis and discussions.

TABLE I.  
SPECIFICATIONS AND KEY AGREEMENTS OF TORORO CASE STUDY

Project Specifications	Input
Power technology	solar PV
Location	Tororo, Uganda
Installed capacity	10MW
Annual degradation	1.5%
Constraint and curtailment	8%
Development cost	us\$0.2 million
Construction cost	us\$8.9 million
Annual operational cost	us\$50,000
Total cost	us\$10.35 million
<b>Power Purchase Agreement</b>	
Duration	25 years
Delivery mechanism	build-own-operate
Supply agreement	take-or-pay
Tariff	us\$60/MWh
<b>Loan Agreement</b>	
Gearing ratio	70:30
Allotted tokens	1.035 billion
Token price	us\$cent1
Loan tenure	16 years
Interest rate	3%
Frequency of investor payments	Annually
Debt Service Coverage Ratio	1.35x

## B. Results

1) *Mobilization Mechanism*: After signing the power purchase agreement, the shareholders raise funds required for the project to reach financial close. Therefore, they initiate a security token offering program on the blockchain SPV, allotting 1.035 billion security tokens at a rate of us\$cent1 per token. At this price, the total value of the tokens is us\$10.35 million, matching the total investment cost of the project. Of these, the shareholders hold 0.31 billion tokens (us\$3.1 million) as per their off-chain equity share in the SPV. Thereafter, they sell the remaining 0.72 billion tokens (us\$7.2 million) to the public via the blockchain SPV platform. For simulation purposes, it is assumed that three aggregated classes of decentralized lenders; i.e., A, B, and C; purchase these tokens at a ratio of 50:20:30. The distribution of the tokens amongst the investors becomes as in Fig. 7. With these security tokens, they can directly redeem a share of the project's future revenues, in utility tokens by interacting with the blockchain smart contract.

The smart contract autonomously collates the revenue payments of the offtakers and allocates the earnings due to each investor. The investors' revenue distribution depends on the number of security tokens held by them in the smart contract. Therefore, investors can periodically invoke a withdrawal of their earnings from their smart contract accounts. The us\$ cash flow of the investors – shareholders and decentralized lenders – are simulated with the outcome presented in Fig. 8. It is apparent that revenue disbursement to the investors is made as per the loan agreement in the smart contract, which prioritizes payment to the decentralized lenders based on the DSCR, which in this case is 1.35x. The us\$ total payments made to the investors over the project's useful operational life is shown

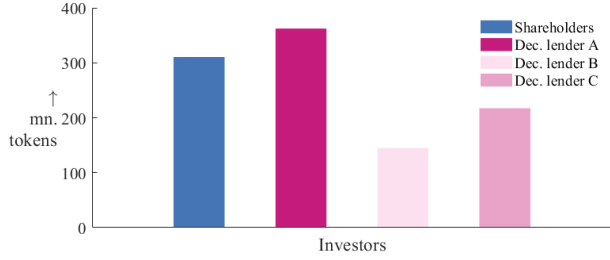


Fig. 7. Distribution of tokens amongst project investors, amounting to the total required investment in us\$

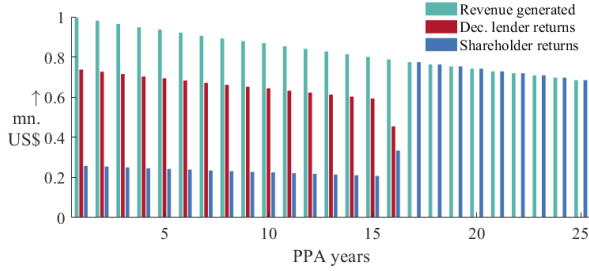


Fig. 8. Outcome of project finance via the blockchain-agnostic special purpose vehicle.

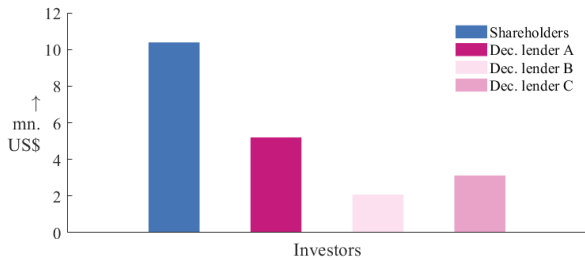


Fig. 9. Returns for investors over the project's 25-year operational life.

in Fig. 9. The total payments due to the shareholders are higher than the decentralized lenders because of the shorter time taken to repay the decentralized lenders compared to the shareholders. Further, the shareholders take on the risk that the project might not function up to its specified operational life or any other associated risk exposures that the project faces before decommissioning. These assumptions follow the traditional practice as in [9].

2) *Collateralization & Settlement Mechanisms*: To showcase the collateralization and settlement mechanisms, the collateral accounts (in utility tokens or this case us\$) of three different offtakers buying electricity from the spv during three different periods of the first operational year of the power project are examined. We assume that the smart contract agreement between the shareholders and the offtakers includes a daily payment frequency, a maintenance margin equalling 150% of the subsequent week's payment, and a us\$500 default penalty deposit.

The first offtaker, purchasing 5% of the electricity generated by the plant, commences the trading period with a default penalty deposit of us\$2700. It maintains this amount all

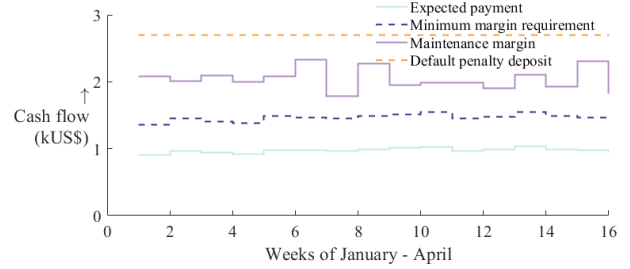


Fig. 10. Collateral mechanism of non-defaulting offtaker.

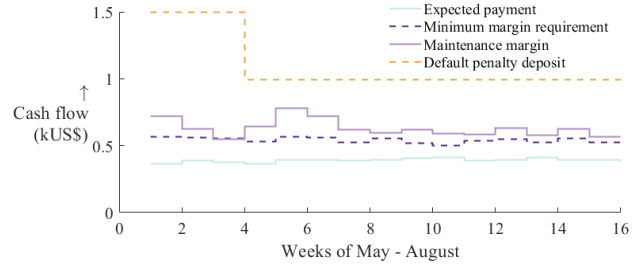


Fig. 11. Collateral mechanism of partially-defaulting offtaker.

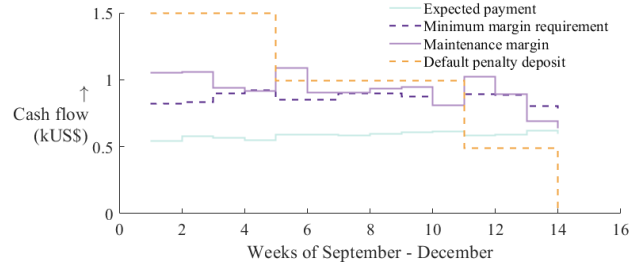


Fig. 12. Collateral mechanism of total-defaulting offtaker.

through the trading period because it abides by the collateral account management rules of the smart contract as in Fig. 10. The second offtaker, purchasing 2% of the electricity generated by the plant, begins the trading period under examination in Fig. 11 with a default penalty deposit of us\$1500. In the third week, it defaults on its minimum maintenance margin requirement and consequently pays a default penalty. It has a sufficient default penalty deposit to fund this payment, and as such, remains in the power purchase agreement. Finally, we assess the collateral account of the third offtaker, purchasing 3% of the electricity generated by the plant, and commencing the trading period under study with a default penalty deposit of us\$1500. The offtaker at multiple times defaults on its minimum maintenance margin requirement until its default penalty deposit is depleted. The offtaker is terminated from the agreement on week 14 as in Fig. 12.

### C. Discussion

The results have demonstrated that a renewable generator spv structured as a DAO could minimize the underlying risk exposures of traditional spvs while maintaining the conventional core structures. Again, we note that the general focus of

this paper is on the smart contract autonomous mechanisms enabled by a DAO in reducing renewable generator’s finance cost, reflected in the low-interest rates for these projects. Therefore, any project finance structure and assumptions or renewable electricity technology can leverage the proposed trio of autonomous smart contract mechanisms to achieve similar outcomes. The rest of this section reinforces the benefits of the blockchain SPV and some of the barriers to mainstream adoption of such novel technology.

By opening up a world of location-independent potential investors and by fractionalizing renewable assets through tokenization to attract smaller investors, loans are secured quickly and competitively on the DAO platform. Intuitively, the investment risks are reduced since these risks are distributed amongst thousands or millions of people rather than a few financial institutions. Liquidity risk is also mitigated because investors can quickly enter or exit their investment positions in the asset as there will be parties willing to take either position on the open and public blockchain marketplace.

Transactions are frictionless and margining risks are minimized in the SPV because the smart contract autonomously, seamlessly, and promptly settles transactions on behalf of parties. The results indicate that margining risk can be reduced by 4 to up to 96 times in the worst-case scenario (calculated using Equation 11), compared to traditional arrangements, such as in [30]. Offtaker credit risk is also driven to zero as offtakers must fulfill their payment obligations, enforced by the smart contract autonomous mechanism. However, the SPVs could still incur unexpected financial losses because, at any instance, an offtaker can decide to cease making payments for electricity consumed to the smart contract. In such a situation, the offtaker only forfeits its collateral in the smart contract to the SPV. The onus then lies on the SPV to secure a replacement power purchase agreement with another offtaker before the collateral funds diminish.

While there are many potential risks of DAOS, such as currency volatility, security, design, and account, briefly discussed in earlier sections; security risk is the main threat of the proposed DAO structure. Once the DAO smart contract is deployed on the blockchain, it becomes immutable. Hence, any programming error in the smart contract code can expose the DAO to security attacks, resulting in financial losses. A prime example is The DAO attack, where US\$70 million was stolen by a malicious smart contract using a flaw present in a single line of the DAO code [17]. By hedging cryptocurrency volatility risks in the DAO, using a stablecoin service, the SPV becomes vulnerable to security risks inherent in the integrated service. The hardware oracle (in this case, the blockchain-enabled smart meter), relaying offtakers, electricity consumption data to the smart contract, also exposes the DAO to security risks due to possible tampering and manipulation. Although the stablecoin and oracle services are maturing technologies supporting live blockchain applications [18], the risk they pose still remain.

While many of the aforementioned risks can be potentially hedged, the unfamiliarity of these risks continues to limit DAO’s mainstream adoption. This concern is not helped by the fact that DAOS’ development has been solely championed by the profit-driven private sector, who do not explicitly showcase the exact mechanics and associated risks and limitations of their

TABLE II. RISK PROFILE OF TRADITIONAL VERSUS BLOCKCHAIN SPV

Risk	Traditional SPV	Blockchain SPV
Liquidity	High	Low
Credit	High	Low
Margining	High	Low
Third-party	High	Low
Legal	High	Low
Process	High	Low
Account	Low	High
Volatility	Low	Low
Design	Low	Low
Security	Low	High

products. To improve social understanding and adoption and government’s acceptance, more objective academic research on DAOS must be promoted and motivated.

In summary, the risk profile of both traditional and blockchain SPVs are summarized in Table II, with the color green indicating low risk; and red, high risk. This work has attempted to quantify the impact of the blockchain SPV in addressing some of the risks of traditional SPVs, such as credit and margining risks. However, the other risks will undoubtedly be more challenging to evaluate explicitly without implementing or deploying the DAO on a live blockchain network. Therefore, future research work could consider this gap.

#### IV. CONCLUSION

This work has shown that employing a blockchain special purpose vehicle can enable seamless funds mobilization, and revenue collection and disbursement amongst SPV stakeholders. The proposed structure could reduce renewable generators reliance on traditional financial institutions, leading to electricity sustainability, affordability, and security. The proposed instrument is merely illustrative of the kind of autonomous mechanisms that can be enabled by a blockchain marketplace. Hence, any project finance structure or renewable electricity technology can employ the proposed trio of autonomous smart contract mechanisms to realize similar development outcomes.

#### REFERENCES

- [1] F. Mark and C. Reid, “Investing in the Clean Trillion: Closing the clean energy investment gap,” Ceres, Tech. Rep. January, 2014.
- [2] A. N. Chowdhury, P.-H. Chen, and R. L. K. Tiong, “Establishing SPV for Power Projects in Asia: An Analysis of Critical Financial and Legal Factors,” *Business Economics and Management*, vol. 13, no. 3, pp. 546–566, 2012. doi: 10.3846/16111699.2011.643446.
- [3] A. Eberhard, K. Gratwick, E. Morella, and P. Antmann, “Independent Power Projects in Sub-Saharan Africa: Investment trends and policy lessons,” *Energy Policy*, vol. 108, pp. 390–424, 2017, ISSN: 03014215. doi: 10.1016/j.enpol.2017.05.023.
- [4] W. Kruger, A. Eberhard, and K. Swartz, “Renewable Energy Auctions: A Global Overview Renewable Energy Auctions : A Global Overview,” Tech. Rep., 2018.
- [5] O. A. and P. Cuffe, “Towards a blockchain special purpose vehicle for financing independent renewable electricity projects in sub-saharan africa,” in *2020 6th IEEE International Energy Conference (ENERGYCon)*, 2020, pp. 1041–1046. doi: 10.1109/ENERGYCon48941.2020.9236599.

- [6] J. Hull, *Options, Futures and Other Derivatives*. 2012, ISBN: 0135009944. doi: 10.1007/978-1-4419-9230-7\_2.
- [7] O. Alao and P. Cuffe, "Towards a Blockchain Weather Derivative Financial Instrument for Hedging Volumetric Risks of Solar Power Producers," in *2021 IEEE PowerTech*, 2021, pp. 1–6.
- [8] World Bank Group, *Risk Allocation Bankability and Mitigation in Project Financed Transactions*, 2021. [Online]. Available: <https://ppp.worldbank.org/public-private-partnership/financing/risk-allocation-mitigation>.
- [9] Dentons, "A Guide to Project Finance," Tech. Rep., 2018.
- [10] O. Alao and P. Cuffe, "Structuring Contract-for-Difference Instruments for Hedging Electricity Price Risks on a Blockchain-based Marketplace," in *IEEE TechRxiv*, 2021, pp. 1–12.
- [11] A. de Villiers and P. Cuffe, "A three-tier framework for understanding disruption trajectories for blockchain in the electricity industry," *IEEE Access*, vol. 8, pp. 65 670–65 682, 2020.
- [12] B. Wang, M. Dabbaghjamesh, A. Kavousi-Fard, and S. Mehraeen, "Cybersecurity enhancement of power trading within the networked microgrids based on blockchain and directed acyclic graph approach," *IEEE Transactions on Industry Applications*, vol. 55, no. 6, pp. 7300–7309, 2019. doi: 10.1109/TIA.2019.2919820.
- [13] J. Chen, J. Wu, H. Liang, S. Mumtaz, J. Li, K. Konstantin, A. K. Bashir, and R. Nawaz, "Collaborative trust blockchain based unbiased control transfer mechanism for industrial automation," *IEEE Transactions on Industry Applications*, vol. 56, no. 4, pp. 4478–4488, 2020. doi: 10.1109/TIA.2019.2959550.
- [14] K. Christidis and M. Devetsikiotis, "Blockchains and Smart Contracts for the Internet of Things," *IEEE Access*, vol. 4, pp. 2292–2303, 2016, ISSN: 21693536. doi: 10.1109/ACCESS.2016.2566339.
- [15] CoinMarketCap, *Top DAO Tokens by Market Capitalization*, 2021. [Online]. Available: <https://coinmarketcap.com/view/dao/>.
- [16] S. Wang, W. Ding, J. Li, Y. Yuan, L. Ouyang, and F.-Y. Wang, "Decentralized autonomous organizations: Concept, model, and applications," *IEEE Transactions on Computational Social Systems*, vol. 6, no. 5, pp. 870–878, 2019. doi: 10.1109/TCSS.2019.2938190.
- [17] L. Liu, S. Zhou, H. Huang, and Z. Zheng, "From technology to society: An overview of blockchain-based dao," *IEEE Open Journal of the Computer Society*, vol. 2, pp. 204–215, 2021. doi: 10.1109/OJCS.2021.3072661.
- [18] Maker Team, "The Maker Protocol," Tech. Rep., 2020. [Online]. Available: <https://docs.makerdao.com/getting-started/maker-protocol-101>.
- [19] D. Musan, "NFT.finance: Leveraging Non-Fungible Tokens," Ph.D. dissertation, Imperial College London, 2020.
- [20] ICOBench, *ICO Rating Platform*, 2021. [Online]. Available: <https://icobench.com/>.
- [21] Ethereum, *Non-Fungible Tokens (NFT)*, 2021. [Online]. Available: <https://ethereum.org/en/nft/>.
- [22] M. d. Angelo and G. Salzer, "Towards the identification of security tokens on ethereum," in *2021 11th IFIP International Conference on New Technologies, Mobility and Security (NTMS)*, 2021, pp. 1–5. doi: 10.1109/NTMS49979.2021.9432663.
- [23] Maker Team, "The Dai Stablecoin System," Tech. Rep., 2017.
- [24] Q. Wang, R. Li, Q. Wang, and S. Chen, "Non-Fungible Token (NFT): Overview, Evaluation, Opportunities and Challenges," Tech. Rep., 2021.
- [25] Jenny, *The first metaverse DAO and social token on Unicy*, 2021. [Online]. Available: <https://jennynft.io/>.
- [26] Y. Huang, Y. Bian, R. Li, J. L. Zhao, and P. Shi, "Smart contract security: A software lifecycle perspective," *IEEE Access*, vol. 7, pp. 150 184–150 202, 2019.
- [27] C. P. Fries and P. Kohl-landgraf, "Smart Derivative Contracts: Detaching Transactions from Counterparty Credit Risk," pp. 1–22, 2018.
- [28] US Government, *Blockchain Community*, 2021. [Online]. Available: <https://digital.gov/communities/blockchain/>.
- [29] The UK Government Office for Science, "Distributed Ledger Technology: beyond blockchain," Tech. Rep., 2020.
- [30] M. Andoni et al., "Blockchain technology in the energy sector: A systematic review of challenges and opportunities," *Renewable and Sustainable Energy Reviews*, vol. 100, pp. 143–174, 2019, ISSN: 18790690. doi: 10.1016/j.rser.2018.10.014.
- [31] Sun Exchange, *The Sun Exchange*. [Online]. Available: <https://thesunexchange.com/>.
- [32] WePower, *Platform connecting energy suppliers, corporate buyers and energy producers for easy, direct green energy transactions*. [Online]. Available: <https://wepower.com/>.
- [33] S. Wang, L. Ouyang, Y. Yuan, X. Ni, X. Han, and F. Wang, "Blockchain-enabled smart contracts: Architecture, applications, and future trends," *IEEE Transactions on Systems, Man, and Cybernetics: Systems*, vol. 49, no. 11, pp. 2266–2277, 2019.
- [34] E. Mengelkamp, J. Gartner, K. Rock, S. Kessler, L. Orsini, and C. Weinhardt, "Designing microgrid energy markets: A case study: The Brooklyn Microgrid," *Applied Energy*, vol. 210, pp. 870–880, 2018, ISSN: 03062619. doi: 10.1016/j.apenergy.2017.06.054.
- [35] O. Alao and P. Cuffe, *Raw data and scripts from "Structuring Special Purpose Vehicles for Financing Solar Generators on a Blockchain Marketplace"*, 2021. [Online]. Available: <https://figshare.com/s/5ed95a41c494246a467b>.
- [36] S. Bhattacharya and A. Owusu, "Cross hedging strategies for solar energy production using weather derivatives," *SSRN*, no. 1408333, pp. 1190–1195, 2015. doi: 10.2139/ssrn.2642685.
- [37] R. A. Kharait, P. Stiles, J. Carriere, and L. McClung, "Impact of Degradation Rates on Solar PV Financing for Projects Located in the United States," in *2017 IEEE 44th Photovoltaic Specialist Conference (PVSC)*, 2017, pp. 2833–2835. doi: 10.1109/PVSC.2017.8366032.
- [38] M. Martin Almenta, D. J. Morrow, R. J. Best, B. Fox, and A. M. Foley, "An Analysis of Wind Curtailment and Constraint at a Nodal Level," *IEEE Transactions on Sustainable Energy*, vol. 8, no. 2, pp. 488–495, 2017. doi: 10.1109/TSTE.2016.2607799.
- [39] H. Li, F. Cao, X. Wang, and W. Ma, "A temperature-based model for estimating monthly average daily global solar radiation," *The Scientific World Journal*, vol. 2014, 2014, ISSN: 1537744X. doi: 10.1155/2014/128754.
- [40] S. J. Deng and S. S. Oren, "Electricity derivatives and risk management," *Energy*, vol. 31, no. 6-7, pp. 940–953, 2006, ISSN: 03605442. doi: 10.1016/j.energy.2005.02.015.
- [41] B. Steffen, "Estimating the cost of capital for renewable energy projects," *Energy Economics*, vol. 88, p. 104 783, 2020, ISSN: 0140-9883. doi: <https://doi.org/10.1016/j.eneco.2020.104783>.