Sustainable Energy Authority of Ireland

National Energy Research, Development & Demonstration Funding Programme

FINAL REPORT TEMPLATE

SECTION 1: PROJECT DETAILS – FOR PUBLICATION

Project Title	Using Blockchains to Facilitate Renewable Power Generation
Lead Grantee (Organisation)	UCD
Lead Grantee (Name)	Asst. Prof. Paul Cuffe
Final Report Prepared By	Paul Cuffe
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	Name	**Organisation**
Project Partner(s)		
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Project Summary (max 500 words)
This project examined how blockchain technologies might facilitate the integration of renewable energy sources into Ireland's electricity system. Prediction markets were proposed to offer renewable generators and system operators enhanced foresight into future power output levels and other relevant variables. Known for their effective information aggregation in other business contexts, the deployment of prediction markets for aiding renewables integration appeared overdue. This project demonstrated prediction markets for probabilistic forecasting of renewable energy source output. The use of prediction markets to hedge against imbalance costs in the day-ahead electricity market for wind power was also explored.

In addition to studying how to predict uncertainties, the project also articulated how blockchains could be used to hedge against volatility. Leveraging the flexible functionality of smart contracts, the project explored how revenue flows from energy projects could be trustlessly and autonomously controlled. This approach uncovered untapped potential for new smart contract instruments that allow for dynamic hedging of electricity price and resource risks for renewable generators. The project also explored tokenized, peer-to-peer electricity trading schemes. By critically deconstructing many of the claims made about this technology, this project identified conceptual problems with many proposed peer-to-peer electricity trading schemes. Building from this sceptical base, a new, more appropriate use case for blockchain was identified: enabling revenue sharing and fractional ownership of wind turbines and solar panels.

Keywords (min 3 and max 10)	Blockchain, forecasting, smart contracts, energy communities, prediction markets, hedging, transactive energy, energy communities

NB – Both Section 1 and Section 2 of this Final Report will be made publicly available in a Final Technical Report uploaded online to the National Energy Research Database.

In the following Section, please provide a clear overview of your project, including details of the key findings, outcomes and recommendations. The section headings below are provided as a guide, please update or add to these as best suits your project.

By submitting this project report to SEAI, you confirm you are happy for Section 1 and Section 2 of this report to be made publicly available. If you wish to request edits to this section in advance of publication, please contact SEAI at EnergyResearch@seai.ie.

SECTION 2: FINAL TECHNICAL REPORT – FOR PUBLICATION (max 10 pages)

2.1 Executive Summary

This project sought to explore how modern blockchains, such as Ethereum, could host exotic financial arrangements that help renewable energy developers to better manage their exposure to uncertainties and risks. This could make renewable energy a more competitive source of electrical energy, and that this would spur an increased roll-out of wind and solar farms.

Three strands were explored: how to *tokenise* electricity to permit direct-to-consumer electricity sales; how to embody bespoke financial hedging instruments as *smart contracts*, which self-execute on the blockchain in a frictionless way beyond human interference; and how to structure blockchain-hosted predictions marketplaces to crowdsource accurate forecasts of e.g future wind power outputs.

The project team was led by Dr. Paul Cuffe at UCD, supervising three PhD students, each examining one of these strands. All three students published multiple papers during their studies and graduated on time and are now active in the Irish energy industry.

2.2 Introduction to Project

Prediction markets for forecasting in highly renewable power systems (Work Package 1)

Anticipating a surge in the integration of renewable energy resources, driven by global decarbonization efforts, power systems are faced with new challenges and opportunities. Renewable sources are becoming increasingly cost-competitive with traditional power plants, and as a result, they are expected to adhere to similar market regulations. This puts pressure on them to help mitigate the intrinsic volatility and uncertainty associated with their weather-dependent outputs. To manage this, the work package explored the utilization of *prediction markets*, which have shown the ability to offer accurate forecasting signals. These markets, especially when hosted on blockchain platforms, offer decentralized access to large, varied data sets; they operate to crowdsource predictions from many stakeholders.

The primary focus of the work package was to leverage prediction markets to forecast renewable energy outputs, using the market price as an informational metric. A range of use cases were identified and analyzed.

In the first application considered, this work package showed that binary prediction markets could produce useful probabilistic forecasts for renewable energy. By involving multiple forecasting methods as trading agents, the work package revealed that the market equilibrium price could be used to derive a full cumulative distribution function for possible renewable outputs. This approach was tested on three onshore wind farms in Australia, showing a reduction in market imbalance costs and outperforming individual models.

The second application evaluated how prediction markets could act as a hedge for renewable energy producers against imbalance costs in the day-ahead electricity market. By trading in both markets, wind power producers could offset potential financial losses. An optimal trading strategy was formulated, minimizing maximum possible financial loss and setting share prices based on an indifference utility condition. This method demonstrated improved risk measures and constrained financial losses.

The third application expanded the hedging concept by acknowledging the volume risk in renewable energy revenues, usually attributed to variable weather conditions. It proposed that a sufficiently liquid binary prediction market could mimic the function of weather/power derivatives to stabilize the financial profile of renewable sources. Different risk-preference models were considered for determining the size and price of contracts in the market. The method was deemed viable even under guaranteed-tariff mechanisms like power purchase agreements.

Lastly, the work package investigated the role of conditional prediction markets in aiding policy decisions for renewable energy promotion. In this setup, market participants speculated on the likelihood of achieving policy objectives such as renewable generation targets or carbon emission levels, based on different policy alternatives. The alternative with the highest market price was considered the most favourable. A case study comparing feed-in-tariff and renewable portfolio standards demonstrated the utility of this approach.

In summary, the work package provided valuable insights into using prediction markets for renewable energy forecasting, risk management, and policy decision support, showcasing their potential advantages over existing approaches.

Smart contract hedging instruments for risk management in volatile electricity Markets (Work Package 2)

Addressing global emission reduction targets necessitates a significant scaling-up of renewable electricity funding. Traditional financing for renewable energy assets often faces hurdles due to various core revenue risks, including financing, volume, and price risks. Traditional risk-hedging methods, although commonly employed, suffer from operational inefficiencies and reliance on multiple intermediaries. To tackle these challenges, this work package, for the first time, investigated the application of blockchain smart contracts as alternative financial and risk management tools for renewable electricity firms.

The work package began by conceptualizing and structuring a financing framework that utilized blockchain smart contracts. Case studies, focusing on the financial and operational risks of renewable energy generators, were deployed to evaluate whether these blockchain-based financial instruments outperformed their traditional counterparts. Subsequent studies in the work package developed new smart contract-based hedging arrangements aimed at minimizing volume and price risks. These arrangements were analytically valued and implemented on a blockchain network.

The findings from these case studies suggested that blockchain smart contracts have the potential to mitigate the limitations and risks inherent in traditional financing and hedging mechanisms. However, they also introduce new types of risks that must be thoroughly evaluated before mainstream adoption. To address this, the work package concluded with the formulation of a risk taxonomy specifically targeted at understanding the challenges and risks of applying blockchain smart contracts in renewable electricity transactions.

The work package advocated for cross-sector collaboration involving developers, researchers, renewable energy companies, and governments to collectively address and understand the risks associated with blockchain smart contracts. In summary, while traditional financial and risk-hedging mechanisms have been established for decades, blockchain smart contracts are emerging as promising alternatives that, once their associated risks are addressed, could significantly advance the renewable energy sector.

Electricity tokenisation and peer-to-peer trading of renewable energy (Work Package 3)

The concept of electricity consumption rights is inherently intangible; proposals have recently emerged for such rights to be (somehow) symbolized through digital tokens. Blockchain technology shows promise in this arena, particularly for peer-to-peer electricity trades, and has frequently been proposed for this use case. The term "tokenized energy" appears to require that a digital token somehow represents a specific quantum of electrical power. Despite its academic and industry attention, primarily around encouraging renewable energy production and removing the need for traditional electricity authorities, reservations and confusions about the meaningfulness of tokenized energy remain.

This work package began as a deep dive into the field of tokenized energy. It undertook a comprehensive review of existing literature to uncover the multiple facets that this term encapsulates, while identifying the current knowledge gaps. An early conclusion was that early excitement around blockchain and cryptocurrencies led to the premature conclusion that energy could be as easily tokenized as financial assets. From this, a richer perspective on tokenized energy was developed, defining these tokens as *"validators of consumption,"* which are contingent upon specific legal and regulatory foundations that implicitly support their application.

This new perspective was then used to explore how tokenized energy platforms could still offer advantageous prospects for regulators and electricity providers. For instance, it might enable the development of innovative business models that inherently encourage both socially and electrically advantageous practices.

The work package also re-evaluated the potential for tokens to act as a signal for prioritized electricity supply during grid failures, offering a fresh mechanism to balance consumer-operator interactions within the electrical network.

Expanding on this broader view of tokenization, the work package introduced the notion of tokenized revenue streams, designed to split the consistent income flows of electrical generation companies. These specialized tokens enable holders to claim their portion of shared cash flows directly. In this system, an electricity market operator would remit cryptocurrency payments for delivered energy to a smart contract, which in turn disburses the funds according to token ownership. This work then went further, to suggest new business models that could thrive in such tokenized revenue ecosystems, thereby mitigating risk exposures. This concept of tokenized revenue streams proves to be a viable application in the electrical industry, avoiding the conceptual and theoretical pitfalls associated with tokenized energy.

This work package also articulated the argument that the unresolved issues in existing blockchain proposals for the energy sector often arise from the complex interplay between the physical and digital worlds, essentially illustrating a variant of the *"Oracle"* problem. Originally designed as a financial transaction medium, the extension of blockchain to physical assets like electricity often results in complications. Hence, confining blockchain's utility to financial transactions may offer a more practical application in the electricity sector. In this regard, the tokenized revenue stream model serves as the central technical contribution of this work package.

2.3 Project Objectives

Prediction Markets (WP1)

This work package aimed to validate the operational utility of blockchain-hosted prediction markets for renewable electricity generators. It also sought to demonstrate that these markets could forecast a broad spectrum of uncertainties, ranging from power outputs and market conditions to long-term policy changes. Additionally, the package aimed to juxtapose the accessibility of using blockchain prediction markets against the complexity of implementing numerical forecasting models. Rooted in both theoretical and empirical evidence, the objective was to substantiate that decentralized prediction markets offer more reliable forecasts pertinent to the renewable energy sector, thereby facilitating the integration of volatile renewables like wind and solar. Overall, the goal was to build a compelling case for the adoption of prediction markets in the energy sector.

The work package crystallised around the following four key research objectives:

I. Probabilistic Forecasting for Renewable Energy

The first objective focused on applying prediction markets for probabilistic forecasting of renewable energy output. The methodology and problem formulation were developed, and the effectiveness of the proposed approach was validated using real-world wind power plant data.

II. Hedging Against Imbalance Costs

The second objective was to investigate the use of prediction markets for hedging against imbalance costs for wind power in the day-ahead electricity market. Specific trading strategies and problem formulations were developed, demonstrated through worked examples.

III. Weather Derivatives for Renewable Energy

The third objective was to explore how prediction markets could serve as weather derivatives, offering a hedging instrument against the volumetric risks associated with fluctuating weather conditions affecting renewable energy.

IV. Decision Support for Renewable Energy Policies

The fourth objective was to evaluate the potential of prediction markets as decision-support tools in shaping policies that promote renewable energy. This aspect looked at how market participants could speculate on the success of different policy alternatives.

By aligning with emerging trends in blockchain technology, this work package was the first to indicate the potential of decentralized prediction markets in improving renewable energy forecasting and risk management.

Hedging (WP2)

This work package aimed to demonstrate the viability of implementing financial instruments as smart contracts for hedging against risks related to renewable energy fluctuations. It also sought to establish that these smart contract-based hedging instruments could be cost-effective and more flexible than traditional financial products. By mitigating the uncertainty in power outputs from renewable projects, the goal was to offer generators and suppliers hedging solutions that are frictionless, rapid, devoid of counter-party risk, and low in operational overheads. This approach aimed to enhance profitability in the renewable energy sector, thereby encouraging greater industry participation.

This work package had the following five central research questions as its key research themes:

I. Evaluate Risk Mitigation through Blockchain Smart Contracts

The project demonstrated that blockchain smart contracts can minimize various risk exposures inherent in traditional renewable electricity transactions, such as liquidity, credit, and legal risks. However, new risks tied to digital infrastructure were also identified.

II. Replicate Core Functionalities of Traditional Arrangements with Smart Contracts

The research confirmed that smart contracts could be customized to maintain the technical, financial, and legal functionalities of traditional arrangements, offering a viable alternative for renewable energy project financing.

III. Customize Smart Contracts for Renewable Generators

Bespoke smart contracts were successfully designed and deployed on blockchain networks, specifically catering to the needs of renewable generators for hedging volumetric risks.

IV. Examine Smart Contracts for Long-Term Operational Viability

The project implemented a smart contract for minimizing electricity price risks in Wind Power Plants (WPPs), outlining the features that are necessary for enduring functionality.

V. Identify and Assess New Risks Introduced by Smart Contracts

While blockchain smart contracts mitigated many traditional risks, they introduced new forms of risk, such as security and design risks. The project suggests that partnerships between various stakeholders are essential to further understand and mitigate these risks.

The project collectively advanced the understanding of how blockchain smart contracts can serve the renewable energy sector while also highlighting areas that require further exploration.

Tokenisation (WP3)

This work package sought to develop a holistic value proposition and feasibility analysis for a tokenized electricity supply model. It aimed to propose the corresponding marketplace structure, outlining the metering infrastructure, trading arrangements, and incentive structure.

This work package was structured around the four following broad research objectives:

I. Deconstruct the Concept of Tokenized Energy

The first objective aimed to scrutinize the idea of "*energy tokens*" to understand whether the concept held up when its physical, financial, and legal aspects were examined separately. We found that these tokens function more as a cyber-metaphorical legitimizer of energy consumption rather than an actual cryptographic representation of energy. The utility of such tokens is thus primarily regulatory and operational rather than a tool for decentralization.

II. Evaluate Tokenized Energy in Retailing Models

The second objective focused on exploring how a redefined concept of an "*energy tokens*" could be applied to new retailing models for electricity that benefit both consumers and grid operators. Case studies simulating electricity markets showed advantages for both market participants and utilities. However, it was concluded that these benefits might not warrant an industry-wide shift to Peer-to-Peer trading due to operational challenges.

III. Assess New Consumer-Operator Relationships Through Tokenization

The third objective sought to examine how tokenization could redefine relationships between consumers and network operators using “*supply tokens*”. A case study on load shedding indicated potential real-world utility, but also revealed limitations in digitally representing a 'real' commodity like electricity. The conclusion drawn was that the technology may be more limited when extended beyond its original financial context.

IV.Tokenize Revenue Streams for Risk Hedging

The final objective aimed to investigate the feasibility of “*revenue tokens*” that could serve as hedging instruments for electrical generators and offtakers. Case studies confirmed the utility of this approach, showing that such tokens could provide a new automated payment method that easily interfaces with downstream business logic and decentralized finance environments.

Each objective brought forth valuable insights but also illuminated limitations and challenges, setting the stage for further research and technological refinement.

2.4 Summary of Key Findings/Outcomes

Prediction Markets (WP1)

This work package confirmed particular capabilities of blockchain-enhanced prediction markets in the renewable energy sector. Firstly, these markets were shown to outperform single-model forecasts by aggregating a diverse range of forecasting techniques, thereby achieving higher accuracy in predicting renewable energy outputs. Secondly, we demonstrated that prediction markets could serve as effective hedging mechanisms against the volatility of day-ahead electricity prices, directly reducing financial risk for renewable energy producers. Thirdly, our work showed that these markets could function similarly to weather derivatives, offering yet another financial instrument for stabilizing revenue streams. Lastly, prediction markets were validated as actionable indicators for policy decisions in the renewable energy ambit, underlining their multifaceted utility. Each of these findings represents a significant step forward in the practical application of prediction markets and blockchain technology in the renewable energy sector.

Hedging (WP2)

The research robustly addressed five key questions around the viability and functionality of blockchain smart contracts in the renewable energy sector. The findings indicate that blockchain smart contracts can indeed be customized to mitigate a multitude of traditional risks including liquidity, credit, and legal issues. These decentralized applications (dApps) not only preserved the core functionalities of traditional financial and legal structures but also introduced flexibility and cost-effectiveness, thereby making renewable energy projects more attractive for risk-averse investors. Furthermore, the research developed bespoke smart contracts tailored to specific needs, such as hedging volumetric and electricity price risks for Solar Power Plants (SPPs) and Wind Power Plants (WPPs) respectively.

However, the study also surfaced new challenges, notably in the realms of security and volatility, which must be thoroughly addressed before mainstream adoption can occur. While some of these emerging risks were hedged in the proposed models, security risks, in particular, remain a significant concern. These findings collectively suggest that while blockchain smart contracts offer transformative potential, a nuanced understanding and mitigation of both traditional and novel risks are essential for their successful industry integration.

Tokenisation (WP3)

The work package found that blockchain and smart contracts are most credible in their original native financial context. Efforts to adapt this technology to other sectors, particularly those interfacing with the physical world, introduce inherent compromises, most notably the unresolved Oracle problem. Our research questioned the overly optimistic narrative that blockchain could easily transition into the energy sector, highlighting that the complexities involved were often underestimated, especially in early literature. Tokenization strategies that align closely with blockchain's strength as a financial tool were found to be the most feasible. More speculative applications require substantial operational shifts, debunking the notion that peer-to-peer tokenized energy trading could be easily implemented. This nuanced understanding should guide future investments and development strategies.

2.5 Project Impact

The impact of this project is significant in providing evidence-based insights to demystify the blockchain hype that emerged around 2016 within the energy sector. In the context of Ireland's renewable energy landscape, the project establishes a concrete pathway for employing blockchain technology in risk management, notably through smart contracts. This aligns with both national objectives, such as the Irish Government's Climate Action Plan, and international commitments to boost renewable energy uptake and mitigate climate-related financial risks.

Contrary to the broad claims often attributed to blockchain technology, such as its purported ability to revolutionize peer-to-peer energy trading, our research identifies a more nuanced application. Specifically, we find that blockchain is most efficacious in bilateral hedging arrangements for the Irish energy industry. These smart contracts can substantially reduce the costs and complexities traditionally associated with hedging, thereby directly contributing to the Sustainable Energy Authority of Ireland's (SEAI) remit of fostering a more efficient and sustainable energy system. While we also indicate the utility of prediction markets for more accurate renewable energy forecasting, we clarify that these do not necessarily require blockchain for effective implementation. Thus, this project serves as a pivotal guide for the Irish energy sector in identifying where blockchain technology can add true value and where it cannot, aiding in more informed decision-making aligned with both national and international policy objectives.

2.6 Recommendations

Based on the comprehensive analysis and findings of this project, we put forth the following key recommendations targeted at policymakers, the research community, and the industrial sector in Ireland:

Crowdsourced Forecasting Platforms for Renewable Energy Output: Policymakers and industry stakeholders should seriously consider the integration of crowdsourced forecasting platforms, such as prediction markets, into the energy planning and management framework. These platforms can provide robust and reliable forecasts for wind and solar output across varying time horizons. This is particularly critical for grid management and the effective utilization of renewable resources. While blockchain technology has been touted for such applications, our findings suggest that these crowdsourced mechanisms can be effectively implemented without blockchain, thus reducing implementation complexities.

Focused Research on Blockchain for Financial Applications: For the research community, a targeted approach in blockchain investigation is advised. Our research highlights the potential of blockchain in financial risk management applications, notably in bilateral hedging and revenue fractionalisation. While full-scale business adoption at this stage would be premature, these applications merit further research to explore their viability. Contrary to popular discourse, blockchain-based peer-to-peer energy trading does not appear to offer substantial value for the Irish energy sector and thus should not be a focus area for future research investments.

2.7 Conclusions and Next Steps

The project was a success; three bright, highly engaged PhD students delved into open-ended research questions, investigating the capabilities and limitations of an emergent technology — blockchain — in the renewable energy sector. The research approach adopted was fundamentally open-minded and scholarly, aimed at unbiasedly dissecting the technology's potential for creating new value streams in the energy domain.

The investigative framework allowed for a balanced view, fostering optimism where blockchain demonstrated clear advantages — such as in financial risk management through bilateral hedging and revenue fractionalisation — while also invoking skepticism in over-hyped applications like peer-to-peer energy trading. This nuanced understanding has produced actionable insights that are directly relevant to Ireland's energy strategies and policies. Moreover, it has charted a course for future research by identifying the most promising areas where blockchain technology can genuinely contribute to the evolving needs of the Irish energy sector.