Journal of Physics:
Conference Series

PAPER • OPEN ACCESS

Advances and challenges in P2P energy trading: A review of renewable integration and decarbonisation in Ireland

To cite this article: H Borges Schiavon *et al* 2025 *J. Phys.: Conf. Ser.* **3140** 032008

Journal of Physics: Conference Series **3140** (2025) 032008 doi:10.1088/1742-6596/3140/3/032008

Advances and challenges in P2P energy trading: A review of renewable integration and decarbonisation in Ireland

H Borges Schiavon[1, 2*], D Peretti Correa[1, 2, 3], P Lissa[1, 2, 3], and M Keane[1, 2, 3]

[1] College of Science and Engineering, University of Galway, Ireland
[2] Informatics Research Unit for Sustainable Engineering (IRUSE), Ireland
[3] Ryan Institute, University of Galway, Ireland

* Corresponding author: h.borgesschiavon1@universityofgalway.ie

Abstract. Peer-to-peer (P2P) energy trading has emerged as a promising model for decentralised energy markets, allowing consumers to trade electricity directly. This paper explores the advances and challenges in P2P energy trading, with a historical review of its global development and a particular focus on Ireland. Despite technical advancements, several constraints hinder widespread adoption. Ireland lacks a clear legal framework to support P2P energy trading, creating regulatory uncertainty. Additionally, user acceptance remains low due to limited awareness, trust issues, and the complexities associated with participation. These challenges, combined with grid constraints and pricing uncertainties, have slowed progress. This paper shows that while P2P energy trading offers a decentralised, consumer-driven alternative to traditional energy markets, its success in Ireland will depend on regulatory evolution, technological diversification, and increased consumer engagement.

1. Introduction

Ireland's energy grid has undergone significant transformations over the past century, evolving from a centralised generation to a modern interconnected system that increasingly emphasises sustainability and innovation. Taking the reference from 1927, when the state-owned Electricity Supply Board (ESB) was created to oversee the development of a national electricity network, until the current days, Ireland has come across different sources of energy, with the commissioning of a hydroelectric scheme at Ardnacrusha, in 1920, having oil as a dominant fuel, in the 70's, the development of coal-fired plants, in the 80's, starting to use wind farms, in the 90's with the establishment of Bellacorick wind farm in County Mayo [1].

Under the Paris Agreement [2], Ireland has committed to achieving climate neutrality by 2050 and delivering a 51% reduction in greenhouse gas (GHG) emissions by 2030 compared to 2018 levels. These targets are part of the European Union's Nationally Determined Contributions (NDCs), which aim for at least a 40% reduction in GHG emissions from 1990 levels, a 32% share for renewable energy, and a 32.5% improvement in energy efficiency by 2030. Ireland's Climate Action Plan includes a target to increase the share of electricity generated from renewable sources to 80% by 2030. However, projections indicate that Ireland will exceed the first two carbon budgets (2021-2030) by a margin of between 17 and 27 per cent, not keeping the expected track to meet the target by 2030 [3], suggesting that further measures are necessary to achieve these goals.

Peer-to-peer (P2P) energy trading offers the potential to decentralise energy markets by enabling localised trading among individuals and communities. This model relies on interconnected networks managed by Distribution System Operators (DSOs). To enable P2P trading along with the components needed to ensure the system, like electricity infrastructure, ICT system, trading platforms and market regulation, also requires sufficient participants to ensure viability [4].

The intention of this study is to understand how P2P started and how is it being studied nowadays in Ireland. To do so a literature review presents insights from projects and regulatory framework over the years. Then, a quantitative analysis was conducted based on public available data to estimate the potential impact of P2P energy trading in Ireland.

2. P2P in energy trading

In the evolving landscape of decentralised energy systems, various models such as P2P energy trading, peer-to-market (P2M), peer-to-pool (P2Pool), and energy sharing have emerged, each with distinct operational frameworks. P2P energy trading typically involves direct transactions between individual prosumers and consumers, facilitating localised energy exchanges. In contrast, P2M and P2Pool models often incorporate intermediaries or centralised platforms to aggregate and distribute energy among participants. Energy sharing models focus on collective consumption and distribution within a community, emphasising equitable access over direct trading. Despite these differences, these models are frequently grouped under the umbrella of P2P energy systems in literature, which can obscure their unique characteristics and implications for market design and policy development. For instance, a comprehensive review by Capper et al. [5] highlights the need for clear distinctions among these models to better understand their respective benefits and challenges in various contexts. Recognising and delineating these differences is crucial for tailoring regulatory frameworks and technological solutions that effectively address the specific needs and dynamics of each model.

Focusing on decentralising the control of energy flows in the mid-2000s, researchers started analysing the application of the concept of P2P networks to energy trading. In 2007, "Peer-to-Peer Networks Applied to Power Grids" [6] was published, highlighting the potential for using P2P networks in grid management and laying a conceptual foundation for many of the current models explored in subsequent studies. Ethereum [7], a platform launched in 2015, supported the evolution of P2P energy trading by introducing a decentralised blockchain platform capable of running applications and smart contracts. This solution opened the possibility of applying blockchain beyond cryptocurrency, facilitating energy transactions with security and transparency. In 2016, in New York, the Brooklyn Microgrid Project [8] used blockchain to enable local energy transactions between residents. In 2018, with the Renewable Energy Directive (RED II) [9], the EU formally introduced the concept of P2P energy trading across member states to encourage the implementation of frameworks that allow consumers to trade energy locally, typically from renewable sources. From 2020 on, as technology matured, several countries began testing P2P energy trading at pilots, exploring blockchain, smart meters and virtual power plants as mechanisms to enable decentralised energy exchanges.

The current understanding of a P2P energy trading system operates as a decentralised network where prosumers and consumers exchange electricity directly, bypassing traditional utility intermediaries. This system relies on distributed energy resources like solar panels, wind turbines, and battery storage, which are integrated with smart meters that monitor real-time energy production and consumption. Transactions are facilitated through digital trading platforms that employ distributed ledger technologies (DLTs) and smart contracts to ensure transparency, security, and automated settlement. The energy flow is managed by the local grid infrastructure, which balances supply and demand while ensuring stable distribution [10]. Dynamic pricing algorithms determine transaction costs based on market conditions, optimising trade efficiency. Advanced IoT devices and AI-driven analytics enhance grid responsiveness, enabling prosumers to maximise profits while consumers access locally sourced, often more affordable, renewable energy. This interconnected ecosystem fosters energy independence, reduces reliance on centralised grids and enhances overall sustainability [10].

The use of blockchain in P2P energy trading is often highlighted for its ability to ensure the integrity and chronological order of transactions through cryptographic techniques. It operates as a distributed ledger, where each block contains a unique identifier and all transactions are synchronised across participants. This transparency and traceability make it a compelling option for decentralised energy markets. However, cost is frequently cited as a concern, particularly in large-scale or high-frequency applications, due to transactional fees that may rise with network congestion and the computational demands of public validation process. As noted by Munoz et al. [11], these costs can be significant, especially when energy use is high. That said, private or consortium blockchains may reduce costs compared to public blockchains, as they require fewer validators and less infrastructure, but the participating entities must have a process to ensure the transparency in their transactions.

In terms of energy use, a substantial portion of blockchain-related operational costs can be attributed to the electricity needed to maintain the infrastructure, an overhead that could be mitigated if the energy were sourced directly from decentralised P2P networks, rather than from centralised grids. However, it is important to benchmark such costs against those of alternative platforms, as infrastructure-related expenses are often inherent in any digital trading solution and may differ only marginally. Furthermore, servers used in such systems do not need to be exclusive to blockchain applications and could be repurposed to run alternative decentralised energy trading platforms, offering flexibility in system design. While smart contracts are often referred to as distinct applications, they are programmable logic components that may act as part or all application depending on implementation. It is also worth noting that P2P trading models are generally expected to generate sufficient value to offset their operational costs, assuming well-designed incentive and market mechanisms. To address the energy related challenges of the adoption of these solutions, a more nuanced, context-specific assessment is needed, considering technical configuration, governance model, and energy sourcing. Hybrid approaches also exist, for example, off-chain solutions that periodically settle on-chain, enabling reduced costs while retaining some of blockchain benefits.

Developing fair and efficient pricing strategies is complex and must account for factors such as supply-demand dynamics, participants' preferences and network constraints to ensure equitable transactions. In the absence of regulations, some possible models to be considered are bilateral negotiation, market-based pricing or time-of-use pricing [12]. Combining elements and creating hybrid models, as suggested by [12] considering community-based and a full P2P structure, allows participants to engage in local community trading while also accessing the market, optimising both approaches. Enabling local energy exchange, P2P systems can reduce congestion and alleviate stress on the central grid infrastructure, facilitating the distribution of energy resources and contributing to an efficient distribution [10]. To maintain efficiency and participant satisfaction, the diversity of participants, with their varied objectives and consumption patterns, must be considered [12].

3. Initiatives in P2P energy trading in Ireland

The earliest recorded pilot project for a sustainable energy community in Ireland dates back to 2007, when business and public sector leaders in the Dundalk/Newry region signed a charter to establish Ireland's first sustainable energy community [13]. Coordinated by Sustainable Energy Ireland (SEI), the 'Dundalk 2020' project aimed to demonstrate how a community could transition to more sustainable energy practices across various sectors, including housing, industry, education, healthcare, retail, and leisure facilities [14].

The Aran Islands Renewable Energy initiative, known as Comharchumann Fuinnimh Oileáin Árann, is a community-owned energy project launched to make Aran Islands energy-independent and carbon-neutral and was established in 2012 [15]. Besides the aim of reducing environmental impacts, Aran Islands face the challenge of relying its main energy supply on a subsea cable, which can cause, as it did in 2016, power outages in adverse situations [16]. A study published in late 2024, utilising digital twins, predicted that P2P mechanisms could enhance the island's journey toward net-zero emissions by improving the balance between energy production and consumption [17].

In 2016, the European Union's Clean Energy Package [18] introduced directives to promote renewable energy and empower consumers. Specifically, the Renewable Energy Directive, in Article 2, paragraph 18, defined P2P trading as the sale of renewable energy between market participants under pre-determined conditions, either directly or through certified third parties like aggregators. This directive required EU member states, including Ireland, to transpose these definitions and facilitate P2P trading within their national legal frameworks [19], with implementation required by 30 June 2021. Although the directive has set a clear direction for member states, the development of P2P trading services in Ireland remains at an early stage, suggesting a gap between policy intent and the availability of such services to citizens.

In the mid-to-late 2010s, after the EU Clean Energy Package, driven by advancements in smart grid technology, blockchain, and decentralised energy systems, an Irish government and industry-funded collaborative initiative, "EnerPort", [20] started. This project aimed to harness blockchain technology to develop a P2P energy trading model, facilitating energy transactions between microgrids. The collaboration involved the International Energy Research Centre, the National University of Ireland Galway, and University College Cork, addressing challenges related to hardware, software, market structures, and regulatory considerations. Regarding energy community projects that were not registered with the Sustainable Energy Authority of Ireland (SEAI) have limited records. However, the Energy Communities Tipperary Cooperative (ECTC) originated from a pilot scheme in the Drombane/Upperchurch community in rural Tipperary during 2012/2013. This initiative led to the formation of ECTC in 2014, bringing together multiple communities to undertake energy efficiency works on older houses and community buildings, leveraging grants from SEAI's Better Energy Communities scheme [21].

Building on technological advancements, community-focused projects emerged. For instance, in 2019, the Dingle Electrification Project [22] aimed to transform consumers into active energy citizens by enabling local energy trading among residents. Guided by principles that promoted consumer choice and stakeholder involvement, the project sought to maintain supply security while complying with legislative requirements. Also in 2019, the Global Observatory on Peer-to-Peer, Community Self-Consumption, and Transactive Energy Models (GO-P2P) was officially launched at University College London. This operates under the User-Centred Energy Systems Technology Collaboration Programme (UsersTCP) of the International Energy Agency (IEA) [23]. It is an international research initiative that aims to understand how P2P energy trading, community self-consumption, and transactive energy systems can be deployed effectively across different countries. Besides Ireland its participants include Australia, Japan, Netherlands, UK and the USA. Dingle's Project planned the implementation of P2P trading in 2020 but encountered setbacks due to insufficient partner engagement [24]. Requirements for P2P services include licenses, regulatory compliance, data protection, and compatibility with existing grid infrastructure. Barriers include high costs for new entrants, metering complexities, and settlement challenges, all of which require policy and infrastructure support to overcome.

With the publication of the Micro-Generation Support Scheme (MSS) in 2022, small renewable energy producers could start selling their surplus power to the national grid [25], ensuring remuneration for prosumers and supporting individual self-consumption. While this policy marked a positive step for decentralised participation in the electricity market, the scheme primarily enables the export of residual electricity to electricity suppliers, rather than supporting direct consumer-to-consumer exchange. Although the MSS contributes to the transition by empowering prosumers, it does not establish a P2P trading ecosystem in practice. Further regulatory development is required to allow citizens to engage in direct electricity exchange, a key component of P2P models.

Funded by the SEAI's Research, Development & Demonstration (RD&D) Funding Programme 2022, EnerFlex project is expected to run from 2023 to 2026 and aims to develop an open-source local electricity market platform that enables concurrent trading of energy and flexibility services. The project seeks to facilitate customer engagement in P2P energy trading within communities and participation in providing multi-flexibility services at both local and system levels. The initiative is led by the IERC in partnership with the Technological University Dublin [26].

Regarding policies for injecting excess energy into the grid, Ireland has established guidelines for microgeneration installations that facilitate the safe and efficient integration of microgeneration systems into Ireland's electricity network, allowing individuals and businesses to return excess renewable energy to the grid. Historically, these and other policies, particularly those concerning energy communities, have primarily focused on supporting the development of renewable electricity generation, placing emphasis on the supply side of the market. However, the integration of the demand side remains underdeveloped, representing a missing link in enabling P2P energy trading. A comprehensive framework that would allow consumers to access electricity from entities other than the traditional suppliers, whether from collective self-consumption in energy communities, or directly P2P exchanges, is still absent. This gap is further reflected in the lack of regulation on how consumers should calculate the prices for P2P contexts [27], leaving key aspects of P2P transactions undefined and unsupported.

4. Assessment of the potential of P2P energy trading in Ireland

In 2023, solar photovoltaic (PV) systems contributed to approximately 1.9% to Ireland's electricity supply, enough to meet the country's electricity needs for a week [28]. The number of homes using solar panels rose from 60,000 in 2023 to over 94,000 in 2024, according to the Irish Solar Energy Association (ISEA) [29]. In 2023, solar PV contributed 0.41 TWh to the electricity supply, with an installed capacity increasing from 209.31 MW in 2022 to 752.90 MW. Assuming a linear growth over the year, the capacity factor is of approx. 9.6%. SEAI's estimates solar farm generation reach 0.73 TWh in 2024, a 78% increase compared to 2023 [30].

While not all installations are expected to participate in P2P trading, a hypothetical trade rate of 30% would correspond to approximately 92.3 MW of rooftop solar PV capacity available for exchange, based on the total rooftop PV capacity of 307.79 MW in 2023. If 10% of Irish prosumers (around 9,400 homes) engaged in P2P trading, and a 9.6% capacity factor is applied, this would yield approximately 7.728 GWh annually. That output could power approximately 1,700 homes, based on an average household annual consumption of 4,513 kWh [31]. The corresponding emissions savings are estimated at 1,962 tonnes of CO_2 per year, assuming displacement of grid electricity with a carbon intensity of 253.7 g CO_2/kWh, as estimated by SEAI for 2023 [30]. A digital twin simulation of the Aran Islands, suggested that P2P mechanisms could reduce reliance on centralised electricity supply by up to 54%, depending on the scenario and level of renewable energy uptake [17]. These projections underscore the technical potential of P2P energy trading in supporting Ireland's decarbonisation goals, provided regulatory and infrastructural barriers are addressed.

5. Conclusion

While P2P energy trading presents promising advancements in democratising energy markets and promoting sustainability, addressing the associated challenges is essential for its successful implementation. Ongoing research and development are crucial to refine these systems, ensuring they are robust, equitable, and capable of integrating seamlessly into existing energy infrastructures. Mechanisms to manage the limitations of the grid must be incorporated to ensure system reliability and prevent congestion. Likewise, developing strategies that are both efficient and equitable remains a complex task. These models must balance real-time suply-demand dynamics, participants preferences and grid constraints to ensure fair value exchange among users.

Most P2P platforms currently rely on blockchain technology to provide transparency, security and automation through smart contracts. However, a gap remains in the literature regarding the use of centralised platforms and alternative smart contract models that do not rely on blockchain. Regulatory frameworks must also evolve to define rules for grid participation and include audit mechanisms that verify ongoing compliance with grid codes. While this study offers insight into the recent development of P2P energy trading in Ireland, further research should investigate decentralised management alternatives beyond blockchain. A phased approach to implementation may also facilitate user adoption by allowing gradual integration into the existing practices.

It is also important to recognise that many of the barriers limiting the scalability of P2P energy trading at this stage are not unique to this model. Similar challenges can be faced by other emerging digital energy solutions, including fragmented and complex regulatory environments, poor measurement infrastructure, low interoperability and technical and financial uncertainties associated with renewable energy systems installations. These structural issues cut across the energy transition more broadly, and addressing them will be fundamental not only to enable P2P energy trading models, but to unlock the potential of digital innovation across the sector.

Acknowledgements
The research presented in this paper is partly financed by the European Union (Horizon Europe INTELLIGENT project, Grant Agreement No. 101160678)

References
[1] B. Ó. Gallachóir. "Electricity in Ireland: a brief history (1916-2015)." eolas. https://www.eolasmagazine.ie/electricity-ireland-brief-history-1916-2015 (accessed 2025).
[2] UNFCCC, *Paris Agreement*, United Nations Framework Convention on Climate Change, Paris, France, 2015. [Online]. Available: https://unfccc.int/sites/default/files/english_paris_agreement.pdf.
[3] E. P. A.-. epa. "Ireland is projected to exceed its National and EU climate targets." https://www.epa.ie/news-releases/news-releases-2024/ireland-is-projected-to-exceed-its-national-and-eu-climate-targets.php (accessed 2025).
[4] N. Jenkins, *Microgrids and Local Energy Systems*. London: IntechOpen, 2021.
[5] T. Capper *et al.*, "Peer-to-peer, community self-consumption, and transactive energy: A systematic literature review of local energy market models," *Renewable and Sustainable Energy Reviews,* vol. 162, p. 112403, 2022/07/01/ 2022, doi: https://doi.org/10.1016/j.rser.2022.112403.
[6] H. Beitollahi and G. Deconinck, "Peer-to-Peer Networks Applied to Power Grid," 01/01 2007. [Online]. Available: https://www.researchgate.net/publication/228955900_Peer-to-Peer_Networks_Applied_to_Power_Grid.
[7] "Ethereum White Paper: A Next-Generation Smart Contract & Decentralized Application Platform." https://ethereum.org/en/whitepaper/ (accessed 2025).
[8] "Brooklyn Microgrid." LO3 Energy. https://www.brooklyn.energy (accessed 2025).
[9] *Directive (EU) 2018/2001 on the promotion of the use of energy from renewable sources (recast)*, L 328 ed. Official Journal of the European Union: European Parliament and Council of the European Union, p. 103. [Online]. Available: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32018L2001.
[10] IRENA, "Innovation landscape brief: Peer-to-peer electricity trading," International Renewable Energy Agency, Abu Dhabi, 2020. [Online]. Available: https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2020/Jul/IRENA_Peer-to-peer_electricity_trading_2020.pdf
[11] M. F. Munoz, K. Zhang, and F. Amara, "ZipZap: A Blockchain Solution for Local Energy Trading," 2022, doi: https://doi.org/10.1109/ICBC54727.2022.9805486.
[12] M. Khorasany, Y. Mishra, and G. Ledwich, "Hybrid trading scheme for peer-to-peer energy trading in transactive energy markets," *IET Generation, Transmission & Distribution,* 2020, doi: https://doi.org/10.1049/iet-gtd.2019.1233.
[13] SEAI, "Sustainable Energy Communities Programme - Handbook 2018," in "Sustainable Energy Communities (SEC)," Sustainable Energy Authority of Ireland, Report 2018. [Online]. Available: https://www.seai.ie/sites/default/files/publications/Sustainable%20Energy%20Communities%20Handbook.pdf
[14] J. Flynn, "HOLISTIC Site Dundalk," in "PROJECTS," European Commision, Smart Cities Marketplace. [Online]. Available: https://smart-cities-marketplace.ec.europa.eu/projects-and-sites/projects/holistic/holistic-site-dundalk
[15] "Comharcumann Fuinnimh Oileáin Árann (The Aran Islands Energy Co-op)." https://www.aranislandsenergycoop.ie (accessed 2025).

[17] N. Buckley *et al.*, "Evaluation of a Peer-to-Peer Smart Grid Using Digital Twins: A Case Study of a Remote European Island," *Energies (Basel),* vol. 17, no. 22, p. 5541, 2024, doi: https://doi.org/10.3390/en17225541.
[18] "Commission proposes new rules for consumer centred clean energy transition." European Commision. https://energy.ec.europa.eu/news/commission-proposes-new-rules-consumer-centred-clean-energy-transition-2016-11-30_en (accessed 2025).
[19] *Directive (EU) 2018/2001*.
[20] B. O. R. Piyush Verma, Barry Hayes, Subhasis Thakur & John G. Breslin "EnerPort: Irish Blockchain project for peer- to-peer energy trading." Springer Link. https://link.springer.com/article/10.1186/s42162-018-0057-8 (accessed 02/10/2024, 2024).
[21] ecovision. "Our Member Communities - ECTC." https://ecovision.ie/our-member-communities/ (accessed 2025).
[22] F. Egan, "The Dingle Electrification Project: Sharing Learnings from the Peer-to-Peer energy Trading Objective," ESB Networks, Report. [Online]. Available: https://www.esbnetworks.ie/docs/default-source/publications/the-dingle-electrification-project---sharing-learnings-from-the-peer-to-peer-energy-trading-objective.pdf
[23] "GO-P2P - Global Observatory on Peer-to-Peer, Community Self-Consumption, and Transactive Energy Models." https://www.go-p2p.org/ (accessed 2025).
[24] S. Malik, "Peer-to-peer energy trading in microgrids: A game-theoretic approach," S. Thakur, J. Breslin, and M. Duffy, Eds., ed: NUI Galway, 2024.
[25] *Micro-Grid Support Scheme (MSS) - Final Scheme Design,* C. a. C. Department of the Environment, 2022.
[26] "Concurrent Energy and Flexibility Trading in Grid-aware Local Energy Community (EnerFlex)." https://www.ierc.ie/blog/research/enerflex/ (accessed 2025).
[27] CRU. "Microgeneration." Commission for Regulation of Utilities. https://www.cru.ie/consumer-information/microgeneration (accessed 2025).
[28] SEAI, "First Look: Renewable Energy in Ireland 2023," Sustainable Energy Authority of Ireland, 2024. [Online]. Available: https://www.seai.ie/sites/default/files/data-and-insights/seai-statistics/key-publications/renewable-energy-in-ireland/First-Look-Renewable-Energy-in-Ireland-Report.pdf
[29] ISEA, "Scale of Solar," Irish Solar Energy Association, 2024. [Online]. Available: https://www.irishsolarenergy.org/_files/ugd/f7484d_13925c5011d3410e88b0857370b4abd2.pdf
[30] SEAI, "Energy in Ireland," Sustainable Energy Authority of Ireland, 2024. [Online]. Available: https://www.seai.ie/sites/default/files/publications/energy-in-ireland-2024.pdf
[31] SEAI. "Ireland's energy statistics - Residential." Sustainable Energy Authority of Ireland. https://www.seai.ie/data-and-insights/seai-statistics/residential (accessed 2024).