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Enhancing Access to Affordable Energy through Peer-to-Peer Automated Negotiations

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***Abstract*—Access to affordable energy has become a major concern in many European countries due to significant increases in energy prices. Concurrently, energy communities have emerged as a potential solution to mitigate this issue. In this paper, we propose a Local Energy Market (LEM) mechanism based on automated negotiations designed to reduce electricity bills for community members, particularly those experiencing fuel poverty (i.e. limited ability to meet rising energy costs). This LEM necessitates consumers to submit energy requests, including specific ones for their essential needs. It also supports consumers flexibility to maximise access to cheaper electricity offered by local producers. The advantages of the proposed P2P automated negotiation process between consumers and producers are showcased through a small stylized use case followed by an extension of the findings to the context of the Orkney Islands in the UK, an area significantly affected by fuel poverty. Results indicate that a maximum bill reduction of 30% can be achieved with such LEM, showing the potential of the method to improve access to affordable energy.**

***Index Terms*—Automated negotiations, energy communities, fuel poverty, peer to peer, residential flexibility**

I. INTRODUCTION

The recent surge in energy prices has heightened financial strain on households with high energy consumption and low revenues. Consequently, countries such as Scotland are experiencing an increase in households affected by fuel poverty. Fuel-poor households can be defined as households that must allocate a significant portion of their income to maintain a suitable indoor temperature. It is influenced by household income, energy consumption, and energy costs [1]. Alternative definitions include situations where households spend more than 10% of their net income on essential fuel needs. Projections from 2021 in the UK suggested a potential 180% increase in households facing fuel poverty, rising from 20% in 2020 to 36% by 2024 [1], [2]. To address this situation, solutions range from energy price guarantees and subsidies for fuel-poor households to initiatives aimed at improving buildings insulation. However, these solutions require significant investments, which are less accessible because of current monetary policies. Indeed, current interest rates are discouraging investments in low-carbon technologies such as insulation or renewable energy production [3]. Nonetheless, other solutions such as energy communities could empower individual households to invest in local-generated renewable energy, and hence reduce their bills. By forming energy communities, households can share local energy generation resources, and reduce their energy imports from large energy suppliers. The European Union has already introduced the concept of renewable energy communities and citizen energy communities in its legislation, and the directive on common rules for the internal electricity market paves the way toward Local Energy Markets (LEMs). As a result, over the past few years, numerous studies have proposed different approaches to implementing energy trading between peers, ranging from simple optimizations for double auction-based LEMs to more advanced frameworks with decentralized optimization using alternating direction methods of multipliers while ensuring grid constraints are met [4]. So far, peer-to-peer trading in LEM have been based on constrained optimization, auction theory, or game theory with coalition formation games, Stackelberg, or canonical coalition games [5]. However, few studies have attempted to design LEMs based on automated negotiations between buyers and sellers [6], which play an important role at the wholesale energy market level as a significant portion of energy quantities traded in wholesale markets today are bilateral trades made over the counter [7]. In this work, we significantly extend the approach presented in [6] to enable flexibility in peer-to-peer trading

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based on automated negotiations. Furthermore, since this work is the result of a trans-disciplinary collaborative work that followed the Transition Engineering approach [8] to explore new concepts for local energy trading to address fuel poverty, we introduce and integrate the concept of "essential needs" within the automated negotiations framework to ensure that individuals facing fuel poverty can reduce their energy bills by accessing low cost energy.

Section II presents the novel framework for automated negotiations, while in Section III, we implement this framework in an energy community with real household data to explore the potential for bill reduction through the implementation of peer-to-peer trading based on automated negotiations.

II. AUTOMATED NEGOTIATION FRAMEWORK

Peer-to-peer (P2P) energy trading consists in local trades of energy between a prosumer (e.g. a house with a source of electricity production such as solar PV, that produces more than it consumes) and a consumer. The prosumer and consumer belong to an energy community in which P2P energy trading can be implemented as a direct trade between the prosumer and the consumer, or indirectly as a trade between the prosumer and an entity representing a coalition or energy community [9]. In this paper, we propose a framework based on automated negotiations that implement direct trades between prosumers and consumers.

A. Automated Negotiations Principles

In automated negotiations, prosumers and consumers are each represented by a software agent that will negotiate for them. Therefore, it does not require the prosumer nor the consumer to be actively involved in the process of the negotiation. This process starts by initiating the number of rounds of the negotiations ($k = 1$). Then, both the seller and the buyer update their utility thresholds $U_{th}^{b/s,k}$ (b =buyer, s =seller) such that if an offer received or proposed by the agent leads to a utility that is greater than this threshold, the offer will be accepted. Then, an offer O^b is proposed by the consumer, also named buyer, to the producer, named seller. An offer consists in an energy quantity E_t for each time slot t of the market (e.g. 48 for a daily market with time intervals of 30 minutes), an associated price π_t for each of these energy quantities, and possibly a required maximum power P_t for each one of these time intervals T. Although the energy quantities E_t and the associated prices π_t should be noted E_t^b or E_t^s and π_t^b or π_t^s respectively to differentiate if these quantities correspond to an offer proposed by the buyer (b) or the seller (s), we remove the upper script for better readability. As a result, E_t refer either to E_t^b or E_t^s depending on which offer is considered (the one from the buyer or the one from the seller). Similarly, all these variables are updated at each iteration of k.

After receiving this offer, the seller will compute its utility as described in the next subsection (Eq. 3). If the seller's utility of this offer is greater than the utility threshold $U_{th}^{s,k}$ defined at the beginning of this negotiation's round, then a bargain is reached and the negotiation process is over between these two community members. Otherwise, the seller will propose another offer O^s (energy quantities E_t, associated prices π_t and possibility maximum powers P_t). If this counteroffer is accepted by the buyer (i.e. the buyer's utility of this offer is greater than the buyer's utility threshold $U_{th}^{b,k}$), the negotiation ends with a bargain. Otherwise, a new round of negotiation starts, k is increased by 1, and utility thresholds are updated using Eq. 1, with $U^{s/b,0}$ the utility of the initial offer from the seller/buyer, $U_{min}^{s/b}$ the lowest utility acceptable by the seller or buyer, k_{max} the maximum number of negotiation rounds (e.g. 100), and $\beta_{s/b}$ the conceding rate of the seller/buyer that correspond to the speed at which the agent agrees to reduce its expectations.

$$U_{th}^{s/b,k} = U^{s/b,0} + \left[\frac{k}{k_{max}}\right]^{\frac{1}{\beta_{s/b}}} \left[U_{min}^{s/b} - U^{s/b,0}\right] \qquad (1)$$

B. Energy Agents Modelling

Two agents are involved in the negotiation process: a buyer and a seller. In energy applications, they have specificities that are described below:

- **Buyer**: The human owner of the software agent only provides their requirement for energy quantities $E_{t,r}^b$ for each time interval t, his preferred price π_o^b and his concession rate β^b. A utility function U^b is defined for the buyer in Eq. 2, and correspond to the perceived worth of an offer. For this work, $U^b\left(O^{b/s,k}\right)$, the utility value of an offer $O^{b/s,k}$ is given by Eq. 2, where the upper script b refers to the buyer; ω_π, ω_E and ω_P are weights that define the importance given by the agent (here, the buyer) to the cost of energy, to the quantity of energy that is negotiated, and to the amount of power respectively. The sum of these three weights equals one. In Eq. 2, E_t is the quantity of energy for time interval t in the offer that is considered, g_{lcoe}^b is the buyer's cost of production of 1kWh (which can correspond to the cost of energy from the grid), π_t is the price that is proposed in this offer, E_{min} and π_{min} are the minimal energy quantity and price that can be traded in this market (can be equal to 0 or greater), w_t is the importance given by the buyer to the energy of the time interval t (w_t is high when the consumer is not flexible); P_t and $P_{t,r}^b$ are the power offered in time interval t, respectively the power requested by the buyer.
- **Seller**: Similarly, the producer is also represented by a software agent that will by itself propose to the buyer energy quantities and prices for each time interval. His utility value is defined in Eq. 3 where the numerator represents the financial benefits from selling energy quantities E_t at prices π_t, and s_{lcoe} is the levelized cost of electricity for the seller.

C. Design of Offers

Each time an agent calculates a new offer, they initially determine the optimal quantity of energy and power they can

$$U^b = \omega_\pi^b \frac{\sum_{t=1}^T E_t g_{lcoe} - \sum_{t=1}^T E_t \pi_t}{\sum_{t=1}^T E_t g_{lcoe}^b - \sum_{t=1}^T E_{min} \pi_{min}} + \frac{\omega_E^b}{2} \left[\sum_{t=1}^T w_t \frac{E_t}{E_{t,r}^b} + \frac{\min\left(\sum_{t=1}^T E_{t,r}^b, \sum_{t=1}^T E_t\right)}{\sum_{t=1}^T E_t} \right] + \omega_P^b \sum_{t=1}^T w_t \frac{P_t}{P_{t,r}^b} \tag{2}$$

$$U^s = \frac{\sum_{t=1}^T E_t \left(\pi_t - s_{lcoe}\right)}{\sum_{t=1}^T E_t \pi_{max} - E_{min} s_{lcoe}} \tag{3}$$

$$\min_{E_t} \left[- \sum_t E_t \left(\pi_t - \pi_t^e\right) + E_t^{bat} \pi_{bat} + \alpha^s \left| \sum_t E_t - \sum_t E_{t,r}^b \right| + \sum_t F_t^b \left| E_t - E_{t,r}^b \right| \right] \tag{4}$$

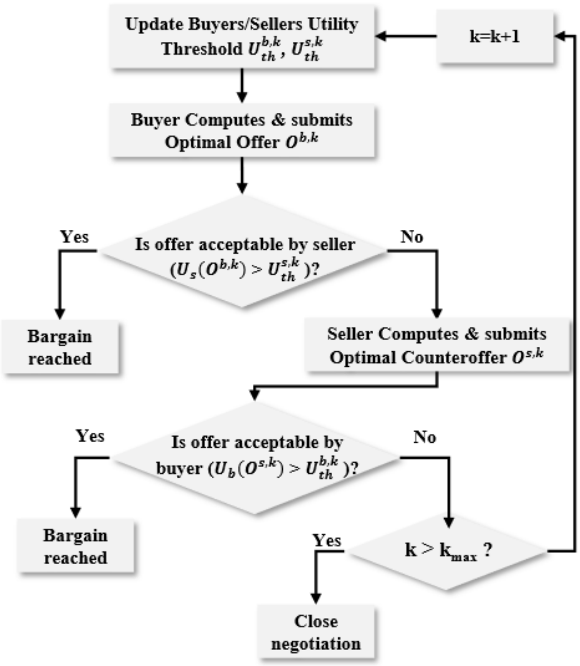

Fig. 1. Automated negotiation iterative process.

propose. Subsequently, they will compute a price that leads to an offer O^k with a utility $U\left(O\right)$ high enough for the agent.

1) Optimal energy quantities: for the buyer, we consider that consumers can be flexible or not, and could have parts of their consumption shifted to other time slots than the ones requested originally ($E_{t,r}^b$). This allows consumers to shift part of their demand to better align with the production profiles of producers from the community. The energy quantities E_t proposed by the buyer are computed by running a linear programming optimisation that aims to minimise a multi-objective function given in Eq. 2, where the first term represents the cost of energy, the second represents the cost of a potential energy deficit or excess compared to the energy requirement, and the last term correspond to the cost of flexibility, if the buyer has flexible consumption, with F_t the flexibility cost at time interval t, and α^b is the weight that makes it acceptable or not to have an offer in which the user has more or less daily energy than what is actually needed.

$$\min_{E_t} \left[\sum_t E_t \pi_t + \alpha^b \left| \sum_t E_t - \sum_t E_{t,r}^b \right| + \sum_t F_t^b \left| E_t - E_{t,r}^b \right| \right] \tag{2}$$

Similarly, the seller can also optimise his production profile (when he owns a battery or can trigger flexible demand for example) in order to better match the energy requirements from the buyer. In the case of a producer who owns a battery, the objective function that is optimised by a mixed integer linear programming approach is given in Eq. 4, where π_t^e is the export tariff for the grid, E_t^{bat} is the energy charged or discharged from the battery, and π_{bat} is the cost of usage of the battery, which can be taken as 0 when the battery is used with less than two full cycles per day [10], α^s is the weight that quantifies the acceptability of the seller to propose more or less energy quantity than requested by the buyer.

2) Price design: unlike energy quantities that are optimised to address the buyer's needs and the seller's energy availability, the prices that are proposed in each offer are either decreased by the seller or increased by the buyer at each round of the negotiation following an adapted gradient descent approach. The new price $\pi_t^{s/b}$ proposed by the seller (s) or the buyer (b) for iteration k is given by Eq. 3, where $\pi_t^{b/s,k-1}$ is the price for time interval t that was proposed within the last offer from the buyer/seller respectively. $\lambda^{s/b}$ is the speed at which the agent changes his offer to get closer to the offer of his opponent, and $\mathcal{S}_{\pi_t}^{s/b}$ represents the sensitivity of the seller/buyer towards the variable π_t and is given for the buyer by Eq. 4 where Δ represents a small change in price and O^b corresponds to the last offer from the buyer. The same applies to the seller.

$$\pi_t^{s/b} = \pi_t^{s/b,k-1} + \mathcal{S}_{\pi_t}^{s/b} \lambda^{s/b} \left(\pi_t^{b/s} - \pi_t^{s/b} \right) \tag{3}$$

$$\mathcal{S}_{\pi_t}^b = \frac{\partial U^b}{\partial \pi_t} \approx \frac{U^b \left(O^b + \Delta \frac{\pi_t^s - \pi_t^b}{\left|\pi_t^s - \pi_t^b\right|} \right) - U^b\left(O^b\right)}{\Delta} \tag{4}$$

D. Addressing Fuel Poverty

One drawback of such a peer-to-peer (P2P) framework is that sellers will prioritize accepting offers that yield them the highest utility as defined in Eq. 3, which might correspond to offers with high energy quantities and higher prices, which might not correspond to offers from fuel-poor houses. Furthermore, negotiation strategies might depend on the nature of the electric usage. Indeed, the charge of an electric vehicle might be flexible and might be accepted by a buyer only if the price of electricity is low, whereas the electricity demand for, e.g. cooking can hardly tolerate any flexibility and could be purchased even if the price of electricity is high. Given the different priorities in energy usage, buyers can engage in multiple negotiations with each potential seller, encompassing various energy requirements, including what may be termed as *essential needs*. This approach guarantees that every community member can access affordable local energy by prioritizing negotiations for essential needs before addressing other energy requests. However, it necessitates framing these offers for essential needs, such as by imposing a maximum energy amount per time slot and per day.

III. EXPERIMENTATION AND RESULTS

In this section, we will apply the automated negotiation framework to two communities to evaluate the financial benefits for consumers. Initially, we examine a small energy community comprising 5 consumers and one seller. Subsequently, we implement this automated negotiation framework on a real community from the Orkney Islands, consisting of 49 consumers and one large producer (wind turbine owner). The anonymized consumption and production data used for this analysis are derived from real data monitored during research and industrial projects in Orkney.

A. Small Community

In this setup, we examine a small community comprising 6 members to illustrate the impacts of the framework proposed in Section II. The seller in this community owns solar PV but does not have a battery. We calculated the reduction in monthly electricity bills achieved by each buyer by participating in an energy community with P2P energy trading across various configurations. We formulated 5 specific scenarios:

- Scenario S_1 depicts the business-as-usual benchmark scenario, wherein all consumption from community members is not traded within the community but is directly purchased from the supplier. The bill reduction for all other scenarios will be benchmarked against this scenario.
- Scenario S_2 is the reference P2P scenario in which community members trade energy using automated negotiations, but without flexibility from the buyer (i.e. the demand $E_t \leq E^b_{t,r} \forall t$), and without giving priority to *essential needs* offers.
- Scenario S_3 mirrors scenario as S_2, with the distinction that buyers were instructed to separate their offers into one specifically for essential needs. This essential needs' offer assigns greater importance to the acquisition of energy quantities than to securing a lower price (i.e. higher weight ω^b_E).
- Scenario S_4 replicates scenario S_3, except for the seller, who has a significantly increased renewable production. Consequently, the energy community becomes a net energy producer for the month under consideration. However, due to consumer inflexibility, only a small number of consumers capitalize on this surplus energy supply.
- Scenario S_5 represents the final scenario wherein we fully implemented the framework outlined in Section II. It also includes excess generation from the seller to assess the potential for residential flexibility.

Each of these scenarios was implemented for the small community under consideration to evaluate the potential for bill reduction. Bills were calculated by employing the breakdown proposed in [11], where the prices π_t replaced the wholesale market component. Supplier fees were excluded, although a small percentage could be added in real implementations where a third party conducts automated negotiations on behalf of the energy community. Network charges for E_t were reduced by 50-67% depending on the time of use [12]. Lastly, concession rates were randomly generated for each buyer to create a realistic scenario.

Fig. 2 illustrates the bill reduction for all scenarios relative to Scenario S_1 (Business as Usual). This reduction in bills for consumers ranges from 3% to nearly 30%, representing the maximum potential benefit of joining an energy community with P2P energy trading. However, in Scenario S_2, where no prioritization is given to essential needs, certain buyers (such as Buyer 2) may not benefit from the local energy market at all. This is attributed to Buyer 2's low concession rate, resulting in offers that fail to attain sufficient utility value for the seller, unlike offers from other consumers. Scenario S_3 resolves this issue by prioritizing essential needs offers. As depicted in Fig. 2, Buyer 2 begins to reduce its bill as its essential energy needs are fulfilled within the community, although for this simulation, only a small portion of the overall energy quantity was allocated to essential needs. The bills of other agents increase in Scenario S_3 because the energy quantities allocated to Buyer 2 are unavailable to others. In Scenario S_4, there is a notable reduction in bills for all buyers due to the significant increase in renewable production from the seller. Despite lower concession rates, Buyers 1 and 2 receive all the energy they request that aligns with the energy production from the seller. However, as none of the buyers are flexible, only a limited proportion of their energy demand can be supplied by the seller. Scenario S_5 addresses this limitation by enabling flexibility for all buyers except Buyer 1 to evaluate the effectiveness of the proposed framework. In S_5, the bill reductions are most significant as buyers can adjust most of their demand to align with the excess production from the seller. This highlights the benefit of enabling residential flexibility for people in fuel poverty situations. However, achieving this flexibility either requires manual control of appliances based on an external signal or having an automated household, both of which entail initial investments and ongoing maintenance, posing challenges for people in fuel poverty situations.

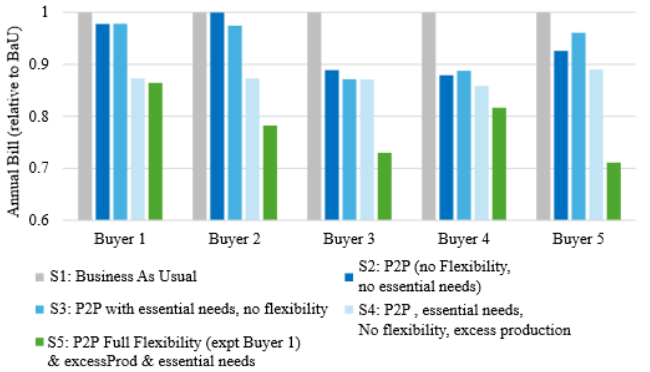

Fig. 2. Comparison of the Gains from P2P energy trading for all the 5 scenarios studied.

B. Real Community from Orkney

The automated negotiation framework was subsequently applied to a real community in Orkney, comprising 49 consumers with actual consumption data and a large-scale wind turbine often curtailed due to excess wind production. Negotiation parameters and the amount of flexible load were randomly generated for all community members. Simulations were conducted for the month of March 2023 and extrapolated to illustrate an annual bill, as depicted in Fig. 3. It is noteworthy that some members have very small bills, which may be attributed to houses that are rarely occupied (e.g. holiday lets) or experiencing monitoring issues. The maximum bill reduction achieved was approximately 33% for large consumers who presented compelling offers to the seller, with energy quantities that were sufficient to yield significant utility values.

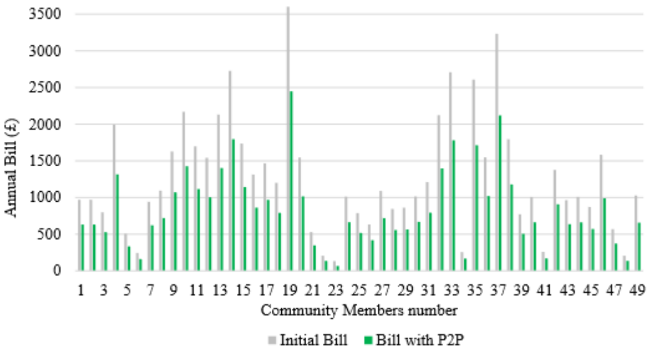

Fig. 3. Gains from P2P energy trading for an energy community in Orkney with excess wind generation.

IV. CONCLUSION

The paper introduces a novel peer-to-peer (P2P) framework for Local Energy Markets (LEMs), leveraging automated negotiations to facilitate energy trading among community members while encouraging residential flexibility to alleviate energy costs. Simulation results indicate a potential maximum bill reduction of 30% for consumers joining in a P2P energy community. However, realizing such reductions necessitates consumers flexibility and sufficient provision of low-cost energy by local producers. Additionally, the concept of trading an energy product termed ”essential needs” is proposed to ensure equitable access to affordable energy within the community.

While the implementation of such energy communities requires technical solutions like smart home automation and increased social acceptance from citizens, they hold promise for assisting households facing fuel povery to reduce their costs and foster investment in local renewable energy sources. Future research directions include technical validation of the market by Distributed System Operators and optimization refinements tailored to various flexible assets such as electric vehicles, washing machines, and heating systems.

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REFERENCES

[1] S. Hinson and P. Bolton, “Fuel poverty,” House of Commons, Tech. Rep., 2024. [Online]. Available: https://researchbriefings.files.parliament.uk/documents/CBP-8730/CBP-8730.pdf

[2] A. Keung and J. Bradshaw. Fuel poverty estimates for april 2023 following the autumn statement, including social security mitigations. (2022). [Online]. Available: https://cpag.org.uk/news/fuel-poverty-estimates-april-2023-following-autumn-statement-/including-social-security-mitigations

[3] I. S. ECB. Monetary policy tightening and the green transition. (2023). [Online]. Available: https://www.ecb.europa.eu/press/key/date/2023/html/ecb.sp230110~21c89bef1b.en.html

[4] M. A. Putratama, R. Rigo-Mariani, A. D. Mustika, V. Debusschere, A. Pachurka, and Y. Besanger, “A three-stage strategy with settlement for an energy community management under grid constraints,” *IEEE Transactions on Smart Grid*, vol. 14, no. 2, pp. 1505–1514, 2023.

[5] W. Tushar, T. K. Saha, C. Yuen, D. Smith, and H. V. Poor, “Peer-to-peer trading in electricity networks: An overview,” *IEEE Transactions on Smart Grid*, vol. 11, no. 4, pp. 3185–3200, 2020.

[6] C. Etukudor, B. Couraud, V. Robu, W.-G. Früh, D. Flynn, and C. Okereke, “Automated negotiation for peer-to-peer electricity trading in local energy markets,” *Energies*, vol. 13, no. 4, 2020. [Online]. Available: https://www.mdpi.com/1996-1073/13/4/920

[7] Ofgem, “Power market liquidity,” Ofgem, Call for Input, 2024. [Online]. Available: https://www.ofgem.gov.uk/sites/default/files/2023-12/Call%20for%20Input%20-%20Power%20Market%20Liquidity.pdf

[8] S. Krumdieck, *Transition Engineering: Building a Sustainable Future*. CRC Press, 2020. [Online]. Available: https://books.google.fr/books?id=f9frxQEACAAJ

[9] Y. Zhang, V. Robu, S. Cremers, S. Norbu, B. Couraud, M. Andoni, D. Flynn, and H. V. Poor, “Modelling the formation of peer-to-peer trading coalitions and prosumer participation incentives in transactive energy communities,” *Applied Energy*, vol. 355, p. 122173, 2024.

[10] B. Couraud, S. Norbu, M. Andoni, V. Robu, H. Gharavi, and D. Flynn, “Optimal residential battery scheduling with asset lifespan consideration,” in *2020 IEEE PES Innovative Smart Grid Technologies Europe (ISGT-Europe)*, pp. 630–634, 2020.

[11] Ofgem. Breakdown of an electricity bill. (2021). [Online]. Available: https://www.ofgem.gov.uk/energy-data-and-research/data-portal/all-available-charts?sort=created&page=3

[12] Enedis. Network charges and energy communities. (2023). [Online]. Available: https://www.enedis.fr/sites/default/files/documents/pdf/enedis-essentiel-turpe6.pdf