ASSESSING THE TECHNICAL AND ECONOMIC VIABILITY OF PEER-TO-PEER ENERGY SHARING IN OFF-GRID ENVIRONMENTS

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Examiner: Henock Dibaba, Junior Researcher, Lasse Laurila, Associate professor

ABSTRACT

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This thesis introduces the concept of peer-to-peer energy sharing in off-grid environment and analyze the technical and economic feasibility of this energy model. In the traditional power main network, many remote areas have difficulties in electricity, and P2P energy sharing discussed in this thesis is very suitable for this environment. In this thesis, P2P energy sharing technology is proven economically and technically feasible. However, it still faces many challenges, and we need more attempts and cases to promote its development.

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1.INTRODUCTION

1.1. Background

P2P is a resource transmission or sharing model. It refers to a distributed network structure that directly connects facilities without uploading central network nodes. There is an equal relationship between every user, and there is no distinction between superior and inferior devices.

“The initial use of P2P networks in business followed the deployment in the early 1980s of free-standing PCs.” [1]. The earliest practical application of P2P was born in 1999. In that year, a program called Napster was developed. Napster allowed millions of internet users to connect directly, simply implementing P2P. Since then, P2P has begun its tortuous but vital development.

Today, P2P has played a role in many fields. For example, file sharing, blockchain technology, instant messaging, etc. Especially in terms of "resource sharing", P2P technology can improve resource utilization and reduce the risk of single point failure of the system. Because of this, this thesis will explore the feasibility of P2P in Energy Sharing in Off-grid mode.

At the same time, P2P is itself a form of energy sharing. People store up excess energy and share it when other peers lack energy. It can be seen that, the system combines many advanced systems and technologies. It has great potential.

1.2. Problem statement

This thesis tries to cover the following research areas in P2P energy sharing and off-grid system:

- The role of P2P in energy sharing and its role in energy-constrained off-grid systems.
- discussion of the technical feasibility of P2P when applied to off-grid systems.
- discussion of the economic feasibility of P2P when applied to off-grid systems.

1.3. Research purposes

The purpose of this study is to investigate how peer-to-peer energy sharing can establish reliable energy facilities for off-grid systems facing energy constraints while creating incentives for community members.

2.LITERATURE REVIEW

2.1. Energy sharing

According to previous literature, we already have a relatively complete understanding of the reasons, basic structure and applications of energy sharing. On the meaning of energy sharing. There are two kinds of energy sharing. The first one is global sharing, and the other one is energy sharing in community.

About energy sharing in the world. The current global energy distribution is uneven, which is especially reflected in the distribution of regional energy use. And that make some area have to use energy sharing to improve energy distribution structure. And the energy is a good choose.

The energy use is not distributed evenly across the globe. According to the 2022 data from the 27th edition of the Statistical Yearbook of World Energy, North America's renewable energy consumption accounts for 20.9% of the world's total. Among them, the United States accounts for 18.7% of global consumption, but Canada and Mexico only account for 1.3% and 1.0% respectively.

Table 1. World energy consumption (three countries)

	2022 consumption（EJ）	2022 Proportion of global
Canada	0.59	1.3%
Mexico	0.46	1.0%
America	8.43	18.7%
Total amount	9.46	20.9%

Data Sources: Energy Research Institute, World energy statistical yearbook, page46 [2].

Table 1 illustrates that the current global energy distribution is uneven, and energy sharing can solve this problem by sharing excess energy. For example, energy sharing technologies such as distributed generation give energy consumers the opportunity to produce energy. Furthermore, in the community, consumers will have the ability to produce energy. This means that when power supply problems occur in the community, users can reduce the impact of power outages through energy sharing.

About the basic structure and applications of energy sharing, there are about three modes of energy sharing in total: centralized, distributed and decentralized. Firstly, among them, centralized pricing is very difficult due to privacy issues and scale issues. According to many literatures, I realize that this traditional structure is somewhat outdated and difficult to achieve energy sharing. Secondly, about the distributed energy sharing, we know: *"Distributed settlement of transactions in a horizontal peer-to-peer (P2P) manner. Agents can enjoy a high degree of autonomy in decision-making while protecting their privacy by disclosing limited information to operators"* [3]. Then, about the decentralized structures: *"About decentralized structures. This structure renders agents the highest levels of flexibility and privacy but makes it difficult for agents to provide grid services as an aggregate or to maximise their social welfare, due to lack of coordination."*[3].

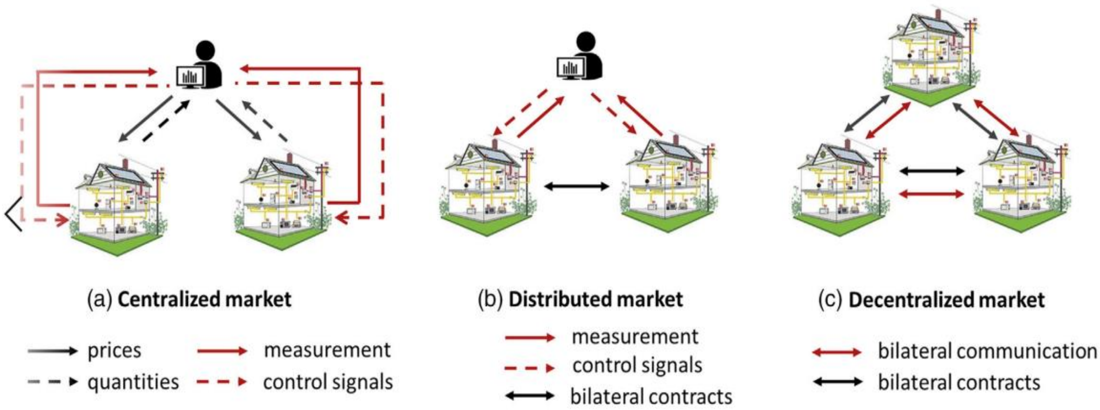

Figure 1. Typical market structures for energy sharing (2022, Yue Chen, Changhong Zhao) [3].

The applications of energy sharing are very wide and can play a role in different energy fields. In Review of energy sharing: business models, mechanisms, and prospects(Yue

Chen & Changhong Zhao, 2022), the author shows the applications of solar energy, wind energy and hydrogen energy in the chapter 2.2 Applications.

Technologies and innovations such as these help us reduce our reliance on traditional energy sources, mitigate climate change, and provide regions and societies with more flexible and sustainable energy solutions. This demonstrates the diversity of energy systems in practical applications.

2.2. Sharing economy

The sharing economic is a P2P model. In today's world, Many economic models will have a market as the center (that is, a network distribution model). Economic sharing can connect fragmented resources and improve efficiency. The sharing economy is a P2P economic model. It facilitates acquiring, providing, or sharing access to goods and services.

From the many literatures and studies we know about the sharing economy and P2P, we can learn that the P2P model focuses more on energy and economic sharing between individuals. Taking the power network as an example, P2P energy trading makes the power system more balanced. Users can conduct private transactions with each other, and at the same time, users' excess energy like electricity can be consumed faster through the "residual balance mechanism". The residual balance mechanism comes from the financial or business field. This mechanism usually sets a target balance. When the balance in an account or portfolio exceeds or falls below this target, the mechanism adjusts the balance back to where it should be. In energy systems such as power networks, this mechanism enables energy balance between individuals to be adjusted.

The following is an illustration of the traditional trading model and the P2P electricity trading model:

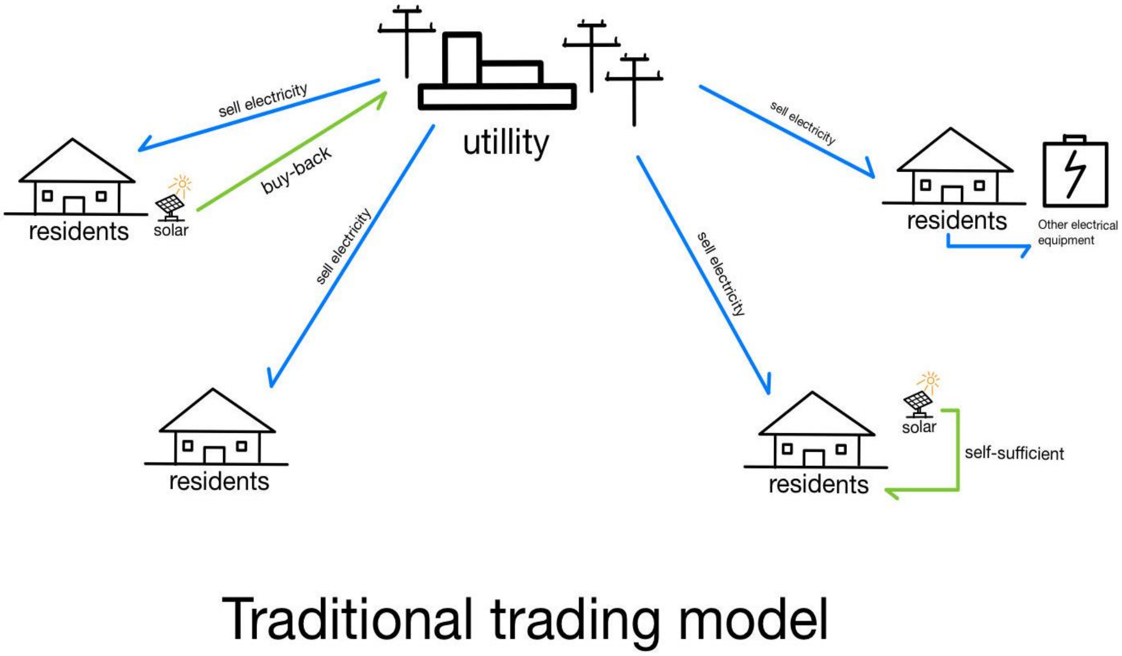

Figure 2. Traditional trading model (1.2024, Suiyuan Wang)

The model was drawn by the author of this article. This model shows the traditional power trading model:

The traditional model presents a network-like distribution, with the largest power provider providing most of the electricity to residents. Some residents can power themselves through solar equipment. Even in some cases, users can transfer the excess power generated by solar energy to the power supply network. This is the "buy-back" in the picture.

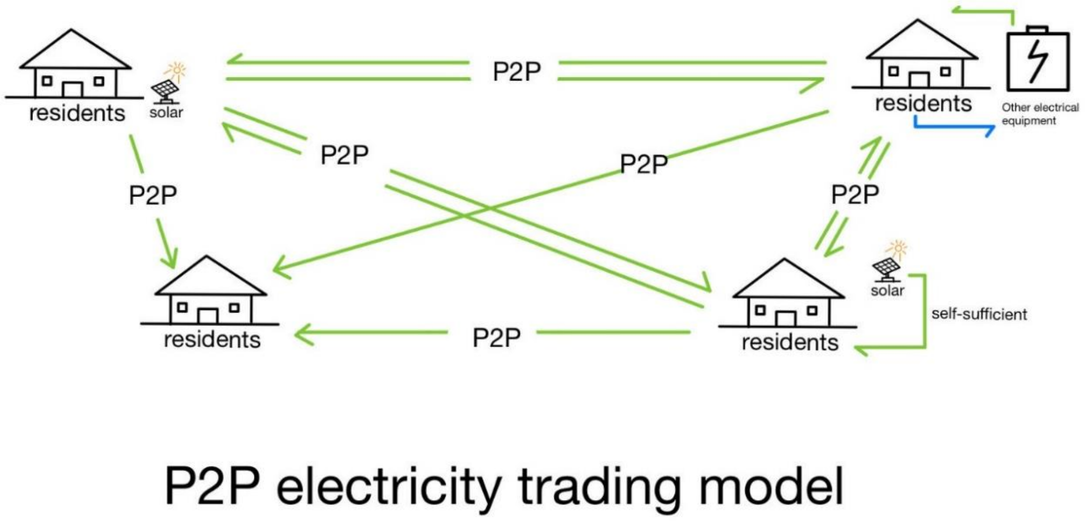

Figure 3. P2P electricity trading model (1.2024, Suiyuan Wang)

The model was drawn by the author of this article. This model shows the P2P electricity trading model:

In this model, it mainly reflects the sharing economic model brought by P2P. Almost every resident (provided that the user has power generation equipment such as solar or wind energy) can act as a producer and at the same time a consumer.

As peer-to-peer energy trading and economic sharing systems gradually mature, *"P2P research continues to increase in the academic field of energy trading, with multiple studies conducted from the perspectives of market design, trading platform information, infrastructure policy, formulation, and scientific society. Among them, there are centralized designs and decentralized designs in terms of economic-related markets."* [4].

For the community, P2P energy trading and the auxiliary services of the residual balancing mechanism have provided good services to the power company and community members. At the same time, it also maximizes the interests of customers and power companies.

In the article Framework design and optimal bidding strategy for ancillary service provision from a peer-to-peer energy trading community (2020, Yue Zhou, Jianzhong Wu, Guanyu Song, Chao Long), the author verified the effectiveness of the P2P and residual balancing mechanisms based on the simulation results of a British residential community and obtained it through a series of calculations. Expected results：

"The social welfare of the whole community with the proposed P2P energy trading and residual balancing mechanism is significantly higher (being 98% in the case of this paper) than that with the conventional Power-to-Grid mode, and the adoption of ancillary service mechanism can further improve the social welfare (by 144% with the Type-2 Ancillary Service and by 135% with the Type-1 Ancillary Service in this paper). " [4] .

2.3. Off grid energy systems

"Off-the-grid or off-grid is a characteristic of buildings and a lifestyle designed in an independent manner without reliance on one or more public utilities. " [5].

The world's mainstream energy systems, especially power network systems, basically use energy networks to supply energy. Off-grid systems are different from traditional power networks in that they mainly provide energy to remote areas that are far away from the grid and lack energy. "*This phenomenon is more common in Africa, where lack of access to energy is a major challenge on the continent, with more than 55% of the population lacking access to electricity."* [6].

Since solar radiation resources are very abundant in Africa, hybrid photovoltaics and distributed power generation can well solve the problem of off-grid systems. According to Oluwarotimi Delano Thierry Odou: “*The analysis showed that hybrid solar photovoltaics (PV)/diesel generator (DG)/battery (of 150 kW/62.5 kVA/637 kWh) is the least cost optimal system. This system ensures a reliable power supply, reduces battery requirements by 70% compared to PV/battery system and achieves 97% CO2 emissions reduction compared to a conventional DG. Moreover, the study demonstrated that the most economical HRES depends strongly on the potential energy sources available at a location and power plant's remoteness from the beneficiary.*” [6].

We can learn how this off-grid system differs from most power network models. It focuses on a small area and does not have large and complex connection methods. At the same time, it has the advantages of lower energy consumption, higher flexibility, and is suitable for power supply in remote areas.

The following is a common type of solar off-grid storage device:

Figure 4. Mono crystalline silicon solar panel (1.2024, Lianbang Product Center) [7]

2.4. Summary

In general, according to previous literature, energy sharing and sharing economy are more substantial topics. But off-grid systems and peer-to-peer energy sharing are relatively new concepts. Electricity and network models based on peer-to-peer energy sharing are often applied in off-grid communities, especially in some remote mountainous areas or deserts. Next, this article will further explore the feasibility of point-to-point energy systems and equipment without the main network from the perspective of technical and economic feasibility.

3.METHODOLOGY

3.1. Research methods

This research employs a combination of literature review and economic analysis to achieve its objectives.

3.2. Technical feasibility assessment method

For P2P systems that off the main network of a system, this thesis will consider the following factors to analyze the technical feasibility:

1. P2P reliability in off-grid communities.
2. In off-grid communities, the ability of P2P equipment to withstand harsh environments.
3. The stability and power generation capacity of peer equipment.
4. Summary of technical feasibility.

For the specific demonstration method, I plan to analyze the feasibility of energy sharing in P2P systems in off-grid environment through literature. Also, find relevant literature on power storage technologies for off-grid communities. Additionally, I contacted a company. I consulted some companies that sell /off-grid P2P devices/ to get more information about the devices.

3.3. Economic feasibility assessment method

1. Transportation and installation costs.

2. The time period for the P2P system to recover costs.

3. User electricity price issue.

I plan to still contact a company to learn more about their product prices. At the same time, I also plan to check the income of some communities in remote areas to compare whether they can afford the equipment.

4.TECHNICAL VIABILITY ASSESSMENT

4.1. P2P reliability in off-grid communities

In most cases, some communities facing geographical problems need P2P technology to solve the problem.

We know that villages that are far from the power grid use fossil fuels like diesel and natural gas to meet their energy needs. At the same time, the installation of power grids in such areas requires huge capital, technology, equipment and personnel support. However, some technologies used in P2P networking devices can solve this problem perfectly. For example, the most common solar independent power generation equipment. People often only need a set of equipment and instructions to complete the construction of equipment.

Furthermore, *"for ensuring appreciable match between electrical load and supply, electrical energy storage (EES) systems are typically used to offset the intermittency issues of local RES technology. Therefore, considerably higher penetration levels of RES could be achieved, ensuring the provision of sustainable electrical power output."* [8].

I have created a model of a P2P power transmission network to demonstrate its stability in an off-grid environment:
These figures demonstrate two operating model.

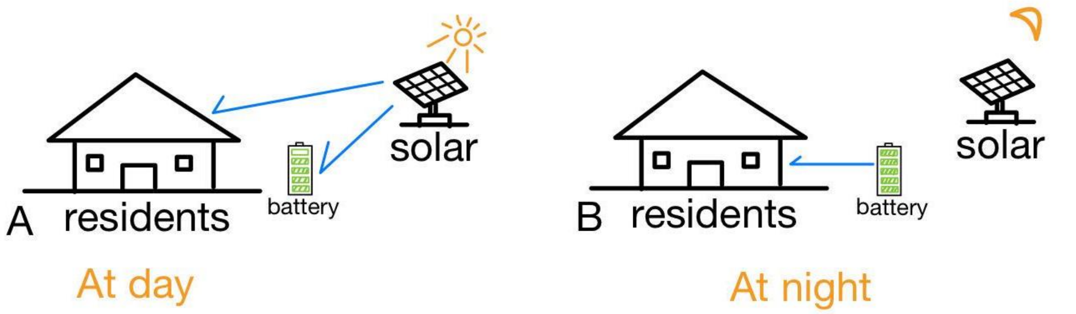

Figure 5. P2P model case 1 (1.2024, Suiyuan Wang)

In the first condition, the A residents use the solar power facility to supply the daily usage electricity during the daytime. At the same time, the facility stores the extra electricity in the battery.

In the second condition, the B residents use the power comes from the battery. And the power in battery is stored during the daytime which happened like first condition.

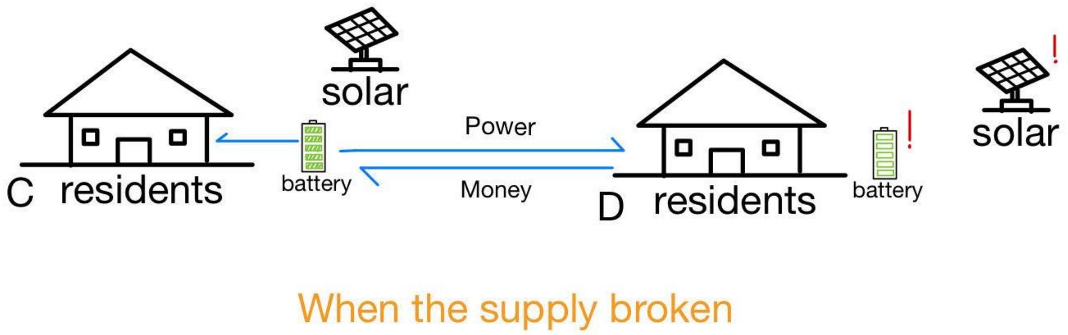

Figure 6. P2P model case 2 (1.2024, Suiyuan Wang)

In the final condition, the power facility of D residents has broken. The damage can happen on the battery and/or solar generator. In this condition, the D residents can spend money to buy power from C residents' battery to make sure it can get constantly power supply.

According to the above example, P2P system in off-network environment. The system shows us a good adaptability and stability. The system can quickly get help from other residents when an individual in a community has a power supply problem. It can be seen that the existing technology is sufficient to support the operation of P2P systems in off-grid communities and can effectively maintain a stable power supply.

4.2. In off-grid communities, the ability of P2P equipment to withstand harsh environments

Some examples show that the ability of P2P devices to resist harsh environments is also sufficient. In the case of solar equipment, I consulted a company that "produces independent solar power generation equipment." They provided me with some data on the durability of solar equipment:

Table 2. The lifespan of solar panels

Name	**material**	**working life**	**quantity**
Solar panel	Polycrystalline silicon	20 years	1
storage battery	Lithium battery	8 years	1
Intelligent digital controller		10 years	1
Electrical box	Stainless steel	20 years	1
Solar mounting bracket	Q235	20 years	1
Solar panel support pole	Q235	20 years	1

[9]

It can be seen that the components of the company's solar equipment, except from batteries and intelligent controllers, they all have a life of 20 years. In addition, the battery and controller are replaceable. So, I think the overall life of the device is around 20 years, which is enough to prove its durability.

At the same time, the company also provided me with a photo of the device that is about 10 years old, and you can see that it is largely undamaged. And they also told me that the device is still performing well. Here are the photos provided by the company:

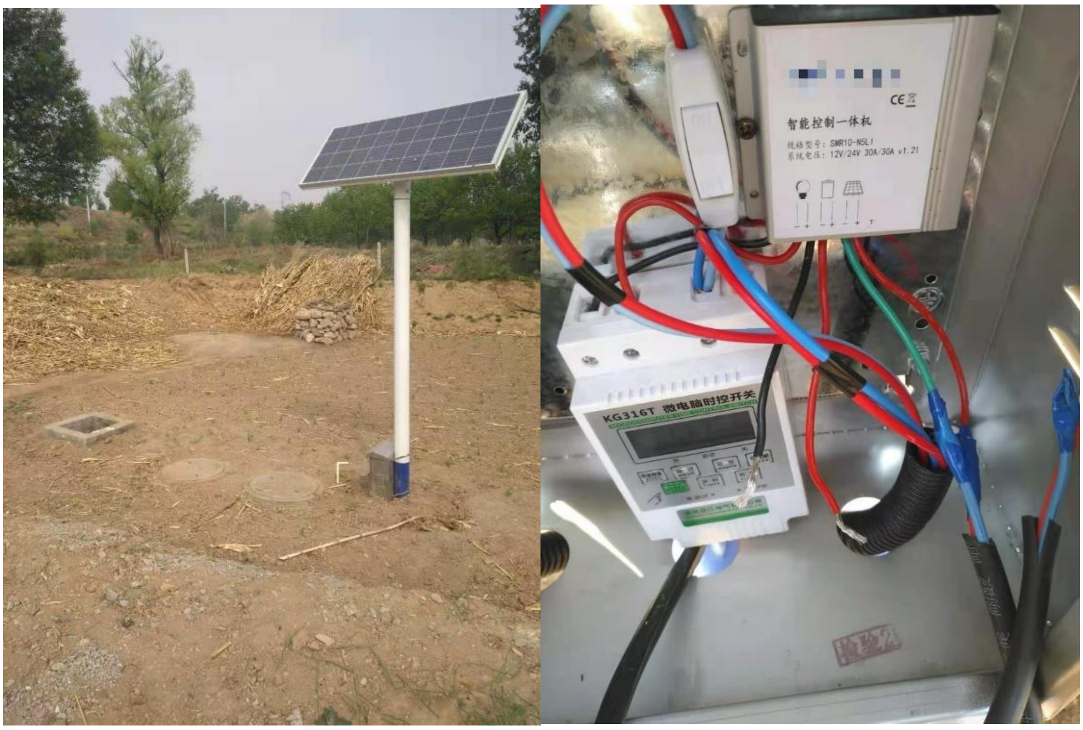

Figure 7. Solar panels and distribution boxes (6.2023, Suiyuan Wang)

This image represents the condition of this device. The solar exterior equipment is already looking a bit old, but the electronics in its distribution box are brand new. As a result, the company's equipment repair operations primarily occur at electrical distribution boxes. The repair cost is also much lower than directly replacing solar panels.

4.3. The stability and power generation capacity of peer equipment

In terms of the generating capacity of the equipment, I consulted the companies mentioned above again. The company provided me with data on their solar power facilities:

Table 3. Power generation efficiency

Description	Quantity	Unit
Effective daylight hours per day	5	h
The actual power used by the solar panel during the charging process	70%	
The output power of solar panels	120	w
Safety factor	1.20	

[10]

Based on the data, it is calculated that the energy stored by the device per day is about:

$$power * time = Energy \quad (1)$$

$$0.12kw * \frac{5h}{perday} = \frac{0.6kwh}{day}$$

The device gets 0.6kwh/day, and the size of the device covers a small area and often makes up a solar array. Due to its remote mountainous location, there will be about 200 solar devices set up on the hillside (because the device really occupies a small area). Therefore, the daily electricity generation is about: 120kwh. This energy can basically meet the daily demand for electricity in remote areas. As a result, users will have a portion of their electricity available for trading and storage.

In addition, in terms of energy storage, photovoltaic hydrogen production is also an emerging way of energy storage. If we can apply this technology on a large scale in the future, it will be good news for P2P systems in off-grid communities. According to some data, 'photovoltaic hydrogen production' is regarded as a potential energy storage method. The biggest advantage of photovoltaic hydrogen production is energy storage. In addition, studies have shown that:

"In the areas characterized by seasonal solar and wind energy variations, hydrogen storage has proven to be economically profitable. As opposed to the battery bank reserve, incorporating hydrogen storage is more feasible when electricity consumption is much higher at nighttime. Especially in insular locations, RES based hybrid configurations have proven economically superior to the diesel generators in several studies." [11] .

4.4. Summary of technical feasibility

The technical feasibility is discussed from three aspects above. The reliability of P2P community, the ability of P2P equipment to resist the harsh environment, and the stability and power generation capacity of peer equipment are proved in turn. In microgrids, we usually need the following technologies: First, energy capture technology; Second, energy storage technology; Third, electronic or digital control technology; Fourth, security measures. In the above analysis, we have taken the most common solar capture energy sources and analyzed the advantages of hydrogen energy storage through the literature. Digital control technology and security measures are now relatively mature. In general, P2P systems perform well in off-grid environments. But there are still many technologies to be developed, such as: solar power efficiency improvement, energy storage technology, material technology and so on.

5.ECONOMIC VIABILITY ASSESSMENT

5.1. Decentralized P2P energy markets

The P2P market model is very different from the traditional trading network model. *"This model allows direct trading and establishing of contract between prosumers, forgoing the need for an intermediary. As opposed to markets relying on a clearing entity/market maker, peer-to-peer markets allow prosumers to select who they trade with — for example they could make or request offers with several other prosumers of their own choice (e.g. neighbors, friends in the community etc.), and select the most favorable one."* [12]

This kind of exchange market is very new for consumers and merchants. And it has the following advantages:

1. The participation of intermediaries is reduced, thus avoiding the poor information of users.

In the traditional market model, information about consumers and prices is often held by intermediaries. But in p2p energy trading in off-grid communities, the information is open and transparent to members of the community.

2. In an off-grid environment, energy prices are more closely aligned with the local economy.

In the main network electricity trading market, the range of price choice is relatively limited. Similar electricity prices bring different financial burdens to users with different income conditions. For off-grid communities, electricity prices are more closely matched with local income levels.

3, protect user privacy.

In most cases, large power grids tend to collect large amounts of data which may consists of the users' privacy. Once these data are leaked, it will cause serious harm to the user's information security. However, in the off-grid system, the privacy of both parties can be guaranteed according to the agreement between users.

4. The price of electricity in the market is relatively stable and not easily disturbed.
In a traditional power network, the price of electricity may be affected by the price of coal, oil and other non-renewable energy sources. But the energy market in off-grid communities is often only affected by natural factors such as weather conditions, and not susceptible to man-made economic shocks.

The above four points summarize the advantages of P2P energy communities and demonstrate their viability in the market.

5.2. P2P energy trade model

The models discussed in this chapter are from the Modelling the formation of peer-to-peer trading coalitions and prosumer participation incentives in transactive energy communities (2024, Ying Zhang and Valentin Robu et al.).

In Chapter 3.5 of Ying Zhang's thesis, the authors present a peer-to-peer trading model. In this chapter, the author provides us with two formulas, which are as follows:

The total energy exchanged by a prosumer i is:

$$e_i^{p2p}(t) = \sum_{(i,j,\theta)\in\Omega_i^a} \theta(t) - \sum_{(j,i,\theta)\in\Omega_i^a} \theta(t), \quad \forall j \in K \qquad (2)$$

The net demand of the prosumer after trading is:

$$\widetilde{e_i}(t) = e_i(t) - e_i^{p2p}(t) \qquad (3)$$

Where i: consumer

j: provider

θ: the optimal energy exchange at each time step

Ω_i^a: the set of trades by prosumer i

The above three formulas describe the total energy, net demand and bill of the consumer when trading energy, respectively. In the actual situation, we can judge the situation of the user exchange energy based on the positive and negative results. [13]. For example, when $e_i^{p2p}(t) > 0$, This formula indicates that the individual receives more energy than it sends to other producers at time t. This means that during this period, the net demand of the individual is positive. In other words, the individual consumes energy in the P2P system as a consumer of energy. Otherwise, the individual has generated energy and completed the storage of energy during this period.

In addition, the author also introduces in other chapters the calculation of costs, energy trade benefits and so on. Energy trade and negotiation models are complex. This is related to the size of off-grid communities, the technical maturity of energy facilities, and the benefit distribution of users. Therefore, the P2P energy sharing model needs more attempts and improvements. In addition, it is worth considering to modify the model or modify the parameters in the model according to the actual local situation.

5.3. Problems existing in off-grid community power trading

The challenges existing in off-grid community power trading are presented as follows:

1. The system is difficult to promote in large communities.

The considerations for large communities are more complex. For example, each household has a different share of land, sunlight and other resources. So, the existing P2P system works for smaller communities. Due to the different scale of resources of each user in this P2P energy sharing model, their benefits may also be somewhat different. For example, when households are scattered across an island, the area per capita is significant and energy production is high. In this case, the excess energy can be transferred to the P2P energy sharing system. In densely populated areas, it is difficult to allocate enough energy to everyone.

However, this problem does not occur very often. Because densely populated areas tend to be connected to large local grid systems rather than P2P systems. In this case, P2P systems can be used as a secondary option, thus guaranteeing grid stability during peak consumption times.

2. P2P energy modelling is complex.

As mentioned at the end of 5.2 above, P2P energy sharing models often need to consider many references. And in many cases, we also need to consider uncontrollable factors like geography and climate. So, sadly, it may be that the P2P energy trade model between the two regions will be quite different. This makes it difficult to fully replicate the model from one region to another. Therefore, it is meaningful to develop an off-network P2P system model with high matching degree for each region.

5.4. Summary of economic feasibility

Decentralized P2P energy modelling differs from traditional energy trading methods in that its market is built between each user of the microgrid. In this section, trading models and related computing schemes are mentioned. Modelling the formation of peer-to-peer trading coalitions and prosumer participation incentives in transactive energy communities（Ying Zhang and Valentin Robu et al.）is referenced in Section 5.2 of this chapter. In general, P2P can generally be considered economically viable. However, because there is no specific centralized market, its transaction data is difficult to collect. Its economic feasibility will be further verified in the future with more data and cases.

6.DISCUSSION

6.1. Applicable environment for P2P power networks and decentralized structures

In fact, the optimal application of P2P energy sharing is not widespread. As the topic of this thesis, the most suitable environment for this energy model is off-grid environment. Compared with traditional networks, one of the most significant characteristics of P2P power networks is their "decentralized" characteristics. Based on the analysis of this thesis and the demonstration of the above materials, we find that P2P microgrids can play a greater role than traditional energy networks in off-grid environments. This is because in some areas far from the main power network, the power supply is very inconvenient, and the power supply to the autonomous network is not smooth. The microgrid based on P2P energy trading and energy sharing model can deal with this problem well.

6.2. Development of P2P energy sharing model

Overall, P2P energy sharing requires more market trials and more efficient energy technologies. Most of the time, people focus on traditional power networks, and most off-grid environments today have fewer energy networks. Even in some areas, energy networks are missing. Therefore, the development of P2P energy sharing needs more attempts, and the cases generated by these attempts can help us further verify the feasibility of P2P energy sharing in the off-grid environment.

7.CONCLUSION

P2P energy sharing in an Off-grid environment: It presents opportunities as well as challenges. Based on the above analysis, the model has largely proved to be feasible (both economically and technically).

P2P energy technology has the following advantages: First, in geographically remote areas, P2P can provide users with more flexible and reliable energy supply. Microgrid size is small, flexible operation, easy turnover, these characteristics are very suitable for remote areas. Furthermore, traditional power facilities require large areas of land to build large substations and power plants. In microgrids, however, each user has their own micro-power plant (most commonly solar panels). Second, the trading system of the energy network is difficult to be affected by fluctuations in the price of electricity on the main network. The pricing of the micro-grid trading system based on the P2P model is often only affected by the local climate environment, but not by external factors (such as international oil price fluctuations, etc.). Third, most P2P energy devices run on clean energy. Traditional coal, oil, and natural gas are often difficult to transport to remote areas far from power grids. However, clean energy sources, including wind, hydro and solar, can ignore these problems. According to section 4.3, "In areas with seasonal variations in wind and solar energy, hybrid configurations based on renewable energy are economically superior to diesel generators." I can be more certain of the positive effect of P2P on environmental protection.

However, P2P energy sharing technology is not perfect. It still faces the following challenges: First, the technology of P2P devices is not yet mature. The existing technology is not sufficient to design an energy device that generates electricity very efficiently. At present, solar energy can only achieve about 40% of the power generation efficiency in the laboratory environment. Second, in densely populated areas, P2P off-grid community power trading is more difficult. Dense population means less land, wind and other resources per capita, which means it is difficult to generate enough excess energy for storage and trading. Third, it is difficult to use the same microgrid model on a large scale. Because the specific situation of each off-grid area is different, the microgrid model is also difficult to produce a template for replication.

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