MASTER´S DEGREE IN INDUSTRIAL ENGINEERING

MASTER´S THESIS

Energy Trading Platforms with Blockchain Technology, Analysis and Optimal Model Proposal

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Director: Jaime Navarro Ocón

Madrid

Declaro, bajo mi responsabilidad, que el Proyecto presentado con el título “Plataformas de compraventa de energía con tecnología Blockchain, análisis y propuesta de modelo optimo” en la ETS de Ingeniería - ICAI de la Universidad Pontificia Comillas en el curso académico 2022-2023 es de mi autoría, original e inédito y no ha sido presentado con anterioridad a otros efectos. El Proyecto no es plagio de otro, ni total ni parcialmente y la información que ha sido tomada de otros documentos está debidamente referenciada.

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ENERGY TRADING PLATFORMS WITH BLOCKCHAIN TECHNOLOGY, ANALYSIS AND OPTIMAL MODEL PROPOSAL

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ABSTRACT

This project studies the operation of P2P trading platforms, analyzing existing pilot projects and extracting the optimal characteristics for the development of these platforms. Moreover, through further literature review, essential elements for the design are evaluated, as well as methods to aggregate DERs in order to maximize the efficiency of the platforms.

Keywords: P2P, energy trading, peer to peer, blockchain, Virtual Power Plant, Federated Power Plant

1. Introducción

Historically, the power grid operated with centralized control, transmitting electricity from large plants to consumers. However, the rise of renewable energy, especially solar, is altering this trend since the development of DERs is driving localized energy generation to address congestion and supply issues.

This transition offers advantages like reduced grid losses, deferred infrastructure investment, enhanced resilience, and economic benefits, hence, it is believed that DERs have the potential to lower electricity prices by curbing demand peaks. Yet, integrating DERs into the network presents challenges that need to be solved to realize the maximum benefit, and the most efficient manner to manage this DERs is still to be developed.

A new energy market model is emerging, enabling "prosumers" to trade energy in peer-to-peer (P2P) networks, bypassing traditional utilities, and offering participants a fairer compensation for their energy. However, P2P energy trading faces challenges like establishing trustless systems for autonomous exchanges and complex decision-making to balance trading and network constraints. Numerous projects worldwide are developing these platforms, and this thesis aims to optimize their integration and performance within the grid.

2. Project description

This project focuses on the concept of P2P trading in itself, rather than analyzing the blockchain technology that builds these platforms and considers this just as the information system that will englobe all the elements required for P2P energy trading. In this manner, the objective of the thesis is to analyze the elements and characteristics that the platforms of this type must include to operate in the most efficient manner, while interacting with the grid and considering the physical constraints that the act of trading electricity presents.

Firstly, a state-of-the-art analysis is developed, with the focus on four pilot projects that have been deployed in different parts of the world. These projects and their results are studied to extract the elements that aid in the optimization of P2P platforms, as well the elements that need to be changed to operate more efficiently. The first project studied is the Quartierstrom platform, were the elements extracted are the use of community batteries for overall efficiency and the use of price automation mechanisms. Next, the VERV project presents the use of advanced demand forecasting and trading automation as a more innovative manner to increase consumer engagement. Then, the Brookly Microgrid, one the most well renowned P2P platforms is studied. From this platform the importance of the location of these projects is determined, as well as the possibility of including EVs in P2P trading. Lastly, the Renew Nexus projects helps provide very valuable insights on the importance of changing fixed network tariffs to allow participants to be able to realize an economic benefit through the participation in these platforms. Moreover, the concept of VPPs is introduced as a way to allow battery owners to obtain additional revenue sources, and the idea of the need for automation in the trading process is further established by seeing how participants are unable to trade energy efficiently on their own.

After the state-of-the-art analysis, a general literature review is conducted on the topic of how P2P trading affects the physical network. In this literature several strategies are studied to ensure that P2P platforms don not endanger the normal operation of the grid by respecting and considering the different network constraints that are required. In this manner strategies for voltage variation control, power loss allocation and frequency stability are studied, but the main subject of interest is the integration of the physical network constraints directly in the market mechanism, as a way to ensure that all transactions respect the limits required by the grid.

Finally, the concept of a Federated Power Plant is studied as a natural development of a P2P platform into a Virtual Power Plant allowing for DER aggregation. The benefits of DER coordination to improve network efficiency and distributed energy reliability are studied, and the P2P platforms are envisioned as market facilitators that enable energy transactions between participating prosumers, what leads to mutually beneficial exchanges and allows the platform to identify opportunities for grid services and present them as contracts that groups of prosumers may undertake. As a result, coalitions of prosumers naturally form to fulfill these contracts. Moreover, an energy sharing to efficiently create and manage these coalitions is studied, helping communities fully realize the value of DER integration by utilizing the available energy capacity towards a community benefit rather than an individual optimum.

3. Results

The results of this thesis consist in a set of proposals for optimal characteristics and design, based on critical analysis of the literature reviewed. In summary, the optimal characteristics for the development of these platforms are the following.

- **Automation**: the need for automation in the trading process and price setting mechanism was realized as need due the consumers’ lack of knowledge and participation, what caused inefficient trades and energy utilization.
- **Advanced demand forecasting**: advanced demand forecast was studied as a necessity to accurately manage demand and supply in the community. As well, the information offered by devices that included this technology can increase consumer

engagement by helping consumers make more informed decisions in their energy usage.

- **Location**: the main value of DERs is their capability of generating energy in the points of demand, and through the analysis of the projects it has been seen that this benefit can be better leveraged in certain parts of the grid with highly congested systems. Therefore, the implementation of tariffs and incentives that account for this factor is proposed in the project.
- **Electric vehicles**: the rapid growth of EVs presents a challenge for the grid, but if managed properly it can also present an opportunity to utilize excess solar generation. It is seen in the project that by developing P2P platforms in metropolitan areas and workplaces, the demand from EVs can be leveraged to absorb excess solar generation in the community.
- **Prosumer – consumer ratio**: the number of prosumers and consumers in a P2P platform is important to ensure that the normal operation of the grid is not negatively affected. Therefore, in this project this ratio has been studied using Helioscope, setting a limit on the kW of solar that can be installed to avoid reverse flows on the grid.
- **Virtual Power Plants**: DER coordination through FPPs is studied as a way to more efficiently manage these platforms, and VPPs in particular are studied as ana ddtional source of revenue for battery owners. For this, several project cash flow studies are developed to find that the ROI is reduced for battery owner by participating in VPPs.
- **Rate structures**: P2P platforms still rely on the grid for demand and supply balance when the P2P traded energy does not match the demand. Therefore, this project analyses the ways that P2P platforms should be charged for their interaction with the grid, finding that dynamic tariffs, demand charges and locational incentives are the best structures to adequately charge participants.

4. Conclusions

In conclusion, this thesis has synthesized the key concepts and provided insights into the optimal characteristics of a Peer-to-Peer (P2P) platform and outlined the objectives and prerequisites for implementing these components effectively. Designing a successful P2P platform necessitates addressing these objectives and structuring platform elements to achieve them. A summary of these key findings demonstrates how the project contributes to these objectives:

Economic Benefit for Participants: the importance of participants deriving economic benefit from the platform requires dynamic network tariffs, demand charges, and well-designed buyback tariffs, such as the Value of Distributed Energy Resources (VDER) tariff, to ensure fair compensation and incentivize demand shifting.

Consumer Engagement: while P2P trading encourages demand shifting, automated trading mechanisms and advanced demand forecasting can optimize consumer participation. Pairing demand forecasting with automation can further amplify value by enabling automated demand response, enhancing energy efficiency.

Providing Services to the Grid: P2P platforms offer grid support, but quantifying benefits and ensuring effective integration is essential. To incentivize peak demand reduction, optimal network tariffs and FPPs can be employed, empowering participants to maximize benefits, as well as leveraging DERs' location-based advantages is essential in offering relief in congested areas and enhancing system performance.

Grid Interaction: while P2P platforms bring about grid benefits, managing grid constraints and preventing reverse flows is crucial. Integrating network constraints and devising solutions to manage reverse flows without compromising stability is essential in the development of the platforms.

DER Aggregation through FPPs: this method offers aggregated DER management. While they increase DER adoption and demand flexibility, careful consideration of excess midday solar generation is vital. Leveraging P2P as an aggregator across different communities can mitigate these challenges, enabling participation in demand response or market programs.

In summary, this thesis underlines the significance of aligning platform design with identified objectives. It emphasizes the crucial role of economic incentives, consumer engagement, grid services, effective grid interaction, and innovative DER aggregation strategies in realizing the full potential of P2P energy trading platforms.

PLATAFORMAS DE COMPRAVENTA DE ENERGÍA CON TECNOLOGÍA BLOCKCHAIN, ANÁLISIS Y PROPUESTA DE MODELO ÓPTIMO

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RESUMEN DEL PROYECTO

Este proyecto estudia el funcionamiento de las plataformas P2P, analizando los proyectos piloto existentes y extrayendo las características óptimas para el desarrollo de estas plataformas. Además, mediante una revisión bibliográfica más profunda, se evalúan los elementos esenciales para el diseño, así como los métodos para agregar DERs con el fin de maximizar la eficiencia de las plataformas.

Palabras clave: P2P, energy trading, peer to peer, blockchain, VPP, FPP

1. Introducción

Históricamente, la red eléctrica funcionaba con un control centralizado, transmitiendo la electricidad desde las grandes centrales hasta los consumidores. Sin embargo, el auge de las energías renovables, especialmente la solar, está alterando esta tendencia, ya que el desarrollo de los DERs está impulsando la generación localizada de energía para hacer frente a los problemas de congestión y suministro.

Esta transición ofrece ventajas como la reducción de las pérdidas en la red, el aplazamiento de la inversión en infraestructuras, la mejora de la resiliencia y beneficios económicos, por lo que se cree que los DER tienen el potencial de reducir los precios de la electricidad al frenar los picos de demanda. Sin embargo, la integración de los DER en la red presenta retos que deben resolverse para obtener el máximo beneficio, y aún está por desarrollar la manera más eficiente de gestionar estos DER.

Está surgiendo un nuevo modelo de mercado energético que permite a los "prosumidores" comerciar con energía en redes entre iguales (P2P), eludiendo a las empresas de servicios públicos tradicionales y ofreciendo a los participantes una compensación más justa por su energía. Sin embargo, el comercio de energía P2P se enfrenta a retos como el establecimiento de sistemas fiables para intercambios autónomos y la toma de decisiones complejas para equilibrar el comercio y las limitaciones de la red. Numerosos proyectos en todo el mundo están desarrollando estas plataformas, y esta tesis pretende optimizar su integración y rendimiento dentro de la red.

2. Descripción del proyecto

Este proyecto se centra en el concepto de comercio P2P en sí mismo, en lugar de analizar la tecnología blockchain que construye estas plataformas y considera ésta sólo como el sistema de información que englobará todos los elementos necesarios para el comercio de energía P2P. De esta forma, el objetivo del proyecto es analizar los elementos y características que deben incluir las plataformas de este tipo para operar de la forma más eficiente, interactuando con la red y considerando las restricciones físicas que presenta el acto de comercializar electricidad.

En primer lugar, se desarrolla un análisis del estado del arte, centrándose en cuatro proyectos piloto que se han desplegado en diferentes partes del mundo. Estos proyectos y sus resultados se estudian para extraer los elementos que ayudan a la optimización de las plataformas P2P, así como los elementos que deben modificarse para funcionar de forma más eficiente. El primer proyecto estudiado es la plataforma Quartierstrom, donde los elementos extraídos son el uso de baterías comunitarias para la eficiencia global y el uso de mecanismos de automatización de precios. A continuación, el proyecto VERV presenta el uso de la previsión avanzada de la demanda y la automatización del comercio como una forma más innovadora de aumentar el compromiso de los consumidores. A continuación, se estudia la microrred de Brookly, una de las plataformas P2P más conocidas. A partir de esta plataforma se determina la importancia de la ubicación de estos proyectos, así como la posibilidad de incluir los VE en el comercio P2P. Por último, los proyectos Renew Nexus contribuyen a proporcionar información muy valiosa sobre la importancia de modificar las tarifas fijas de la red para que los participantes puedan obtener un beneficio económico mediante la participación en estas plataformas. Además, se introduce el concepto de VPP como una forma de permitir a los propietarios de baterías obtener fuentes de ingresos adicionales, y se establece aún más la idea de la necesidad de automatización en el proceso de comercio al ver cómo los participantes son incapaces de comerciar eficientemente con la energía por sí mismos.

Tras el análisis del estado del arte, se realiza una revisión bibliográfica general sobre cómo afecta el comercio P2P a la red física. En esta literatura se estudian varias estrategias para asegurar que las plataformas P2P no ponen en peligro el funcionamiento normal de la red, respetando y considerando las diferentes restricciones de red que se requieren. Así, se estudian estrategias para el control de las variaciones de tensión, la asignación de pérdidas de potencia y la estabilidad de la frecuencia, pero el principal tema de interés es la integración de las restricciones físicas de la red directamente en el mecanismo de mercado, como forma de garantizar que todas las transacciones respeten los límites exigidos por la red.

Por último, se estudia el concepto de central eléctrica federada como desarrollo natural de una plataforma P2P a una central eléctrica virtual que permite la agregación de DERs. Se estudian los beneficios de la coordinación de los DERs para mejorar la eficiencia de la red y la fiabilidad de la energía distribuida, y las plataformas P2P se conciben como facilitadores del mercado que permiten las transacciones de energía entre los prosumidores participantes, lo que conduce a intercambios mutuamente beneficiosos y permite a la plataforma identificar oportunidades de servicios de red y presentarlos como contratos que los grupos de prosumidores pueden asumir. Como resultado, se forman naturalmente coaliciones de prosumidores para cumplir estos contratos. Además, se estudia una forma de compartir la energía para crear y gestionar eficientemente estas coaliciones, ayudando a las comunidades a aprovechar plenamente el valor de la integración DER mediante la utilización de la capacidad energética disponible hacia un beneficio comunitario en lugar de un óptimo individual.

3. Resultados

Los resultados de este proyecto consisten en un conjunto de propuestas de características y diseño óptimos, basados en el análisis crítico de la literatura revisada. En resumen, las características óptimas para el desarrollo de estas plataformas son las siguientes.

- **Automatización**: la necesidad de automatización en el proceso de negociación y en el mecanismo de fijación de precios se hizo patente debido a la falta de conocimiento y participación de los consumidores, lo que provocaba negociaciones y utilización de la energía ineficientes.

- Previsión avanzada de la demanda: la previsión avanzada de la demanda se estudió como una necesidad para gestionar con precisión la demanda y la oferta en la comunidad. Además, la información ofrecida por los dispositivos que incluyen esta tecnología puede aumentar el compromiso de los consumidores al ayudarles a tomar decisiones más informadas en su uso de la energía.

- **Ubicación**: el principal valor de los DERs es su capacidad de generar energía en los puntos de demanda, y a través del análisis de los proyectos se ha visto que este beneficio puede ser mejor aprovechado en ciertas partes de la red con sistemas altamente congestionados. Por ello, en el proyecto se propone la implantación de tarifas e incentivos que tengan en cuenta este factor.

- **Vehículos eléctricos**: el rápido crecimiento de los vehículos eléctricos supone un reto para la red, pero si se gestiona adecuadamente también puede presentar una oportunidad para utilizar el exceso de generación solar. En el proyecto se observa que, mediante el desarrollo de plataformas P2P en áreas metropolitanas y lugares de trabajo, se puede aprovechar la demanda de los VE para absorber el exceso de generación solar en la comunidad.

- **Ratio prosumidor-consumidor**: el número de prosumidores y consumidores en una plataforma P2P es importante para garantizar que el funcionamiento normal de la red no se vea afectado negativamente. Por ello, en este proyecto se ha estudiado este ratio mediante Helioscope, estableciendo un límite en los kW solares que se pueden instalar para evitar flujos inversos en la red.

- Centrales eléctricas virtuales: La coordinación DER a través de FPPs se estudia como una forma de gestionar más eficientemente estas plataformas, y las VPPs en particular se estudian como una fuente ddcional de ingresos para los propietarios de baterías. Para ello, se desarrollan varios estudios de flujo de caja de proyectos para descubrir que el ROI se reduce para el propietario de la batería al participar en VPPs.

- **Estructuras tarifarias**: Las plataformas P2P siguen dependiendo de la red para equilibrar la oferta y la demanda cuando la energía comercializada por las P2P no coincide con la demanda. Por lo tanto, este proyecto analiza las formas en que se debe cobrar a las plataformas P2P por su interacción con la red, encontrando que las tarifas dinámicas, los cargos por demanda y los incentivos de localización son las mejores estructuras para cobrar adecuadamente a los participantes.

4. Conclusiones

En conclusión, este proyecto ha sintetizado los conceptos clave y ha aportado ideas sobre las características óptimas de una plataforma Peer-to-Peer (P2P) y ha esbozado los objetivos y requisitos previos para implementar estos componentes de forma eficaz. Para diseñar con éxito una plataforma P2P es necesario abordar estos objetivos y estructurar los elementos de la plataforma para alcanzarlos. Un resumen de estas conclusiones clave demuestra cómo el proyecto contribuye a estos objetivos:

Beneficio económico para los participantes: la importancia de que los participantes obtengan un beneficio económico de la plataforma requiere tarifas de red dinámicas, cargos por demanda y tarifas de recompra bien diseñadas, como la tarifa Value of Distributed

Energy Resources (VDER), para garantizar una compensación justa e incentivar el desplazamiento de la demanda.

Participación de los consumidores: aunque el comercio P2P fomenta el desplazamiento de la demanda, los mecanismos de comercio automatizados y la previsión avanzada de la demanda pueden optimizar la participación de los consumidores. La combinación de la previsión de la demanda con la automatización puede amplificar aún más el valor al permitir la respuesta automatizada de la demanda, mejorando la eficiencia energética.

Prestación de servicios a la red: Las plataformas P2P ofrecen apoyo a la red, pero es esencial cuantificar los beneficios y garantizar una integración efectiva. Para incentivar la reducción de los picos de demanda, se pueden emplear tarifas de red óptimas y FPP, capacitando a los participantes para maximizar los beneficios, así como aprovechar las ventajas basadas en la ubicación de los DER es esencial para ofrecer alivio en las zonas congestionadas y mejorar el rendimiento del sistema.

Interacción con la red: aunque las plataformas P2P aportan beneficios a la red, es crucial gestionar las limitaciones de la red y evitar los flujos inversos. Integrar las limitaciones de la red e idear soluciones para gestionar los flujos inversos sin comprometer la estabilidad es esencial en el desarrollo de las plataformas.

Agregación de DER mediante FPP: este método ofrece una gestión agregada de DER. Aunque aumentan la adopción de DER y la flexibilidad de la demanda, es vital tener muy en cuenta el exceso de generación solar del mediodía. Aprovechar el P2P como agregador en diferentes comunidades puede mitigar estos retos, permitiendo la participación en programas de respuesta a la demanda o de mercado.

En resumen, esta tesis subraya la importancia de alinear el diseño de la plataforma con los objetivos identificados. Destaca el papel crucial de los incentivos económicos, la participación de los consumidores, los servicios de red, la interacción efectiva con la red y las estrategias innovadoras de agregación de DER para aprovechar todo el potencial de las plataformas de comercio de energía P2P.

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Chapter 1. INTRODUCTION

Historically, the power grid has always been managed in a centralized manner. In other words, electricity has been transported from large conventional power plants to consumers in a process known as generation, transmission, distribution, and consumption. However, in recent years, and due to the development of renewable energies (mainly solar), this trend is changing.

The main factor driving this change in system management is the fact that the population is increasingly concentrated in cities, which makes consumption very dense at certain points. For this reason, the original structure of the grid may not be optimal, since supplying energy to these population concentrations can cause grid congestion and supply problems. Hence, it is now increasingly common to see generation facilities located near the points of consumption, known as distributed generation. These distributed resources will change the traditional vertical management of the grid, encouraging it to evolve into a smart distributed system as shown in Figure 1.

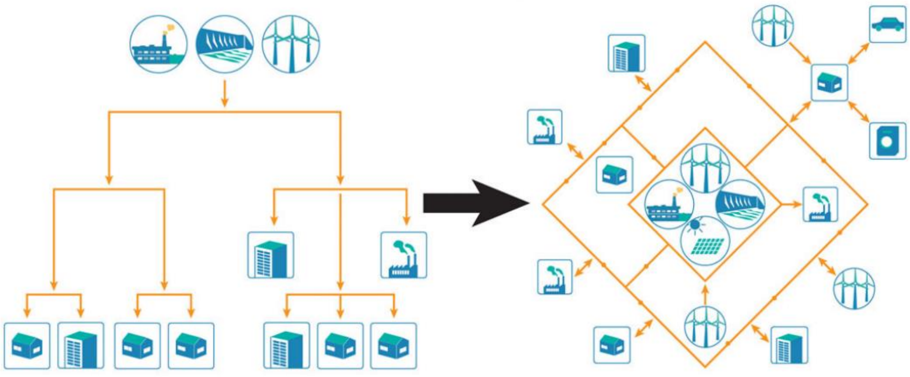


Figure 1. Traditional System VS. Distributed System

This change in management of the power system promoting distributed generation has several benefits compared to the traditional system:

- **Benefits in the electrical grid**: this structure produces a reduction of losses in the grid. Generating electricity close to the consumption points means that less electricity has to be transported from the large power plants, which means that the transmission and distribution lines are less loaded, and their electrical losses are reduced, which for the end consumer are estimated at around 15-20% [1].
- **Possibility of postponing investments in network infrastructure**: since the energy is generated directly at the points of consumption, there is no need for an infrastructure as large as the ones needed to transport large amounts of energy from the power plants that are far from the demand points.
- **Providing greater resilience to the grid**: this implies an improvement in the quality and reliability of the system, although it is true that the latter is highly dependent on the generation technology and whether or not it includes batteries for storage.
- **Economic benefits**: DERs have the ability to reduce the wholesale electricity market price, since in the eyes of the system it behaves as a decrease in total energy demand. In addition, since most of the distributed resources are solar generation, the peaks in peak demand hours can be reduced very significantly, helping to reduce the high prices of these hours.

However, managing DERs with the traditional vertical structure can present serious difficulties. In this context, traditionally a Feed-in-Tariff (FIT) or Net Energy Metering (NEM) have been used to compensate prosumers for the excess generation from their rooftop solar installations. With these methods, prosumers would sell their excess generation to the grid at the preestablished compensation rates, and in the same manner they would buy any needed power supply from the grid. But managing DERs in this manner has created several problems, both for the consumer and the utilities. On the one hand, consumers participating in programs offering FIT have been shown to have little to no incentivize to invest in DERs given the low compensation rates they obtain. On the other hand, methods like NEM have been shown to create problems in the utilities cost recovery mechanisms, generating customer cross subsidization and increasing overall costs for the utility on the long term, with larger DER adoption in the system.

This presents a need to find an optimal way of managing these resources to fully exploit the benefits of this innovative way of generation. Consequently, this form of generation proposes a new model for energy markets, where the owners of these distributed resources, called prosumers, can play an active role in the energy market. Therefore, new forms of energy markets can emerge where energy is traded locally among the different participants, instead of the traditional way where the distribution companies had complete control over these transactions. This form of trading is referred to as peer-to-peer (P2P) trading, and it can present numerous benefits to both participants and the energy sector as a whole. These benefits can come as increased and more accurate compensation to the consumers, and as reduced peak demand and improved power reliability, what would lower infrastructure investments for the grid.

However, participating in energy trading within a P2P network also present many challenges. Firstly, prosumers are expected to autonomously exchange energy among them without the influence of a third party, what creates a trustless system in these platforms. Therefore, it is needed to find technologies that encourage consumers to cooperate in such environment. Moreover, modelling the decision-making process can be very complicated, because it not only has to consider the energy trading parameters and preferences from all the rational users in the network, but it also has to take into account that these consumers are part of an electric network. This last part is the main difficulty for P2P energy trading in grid-connected systems, since these transactions must follow strict constraints to maintain the security and balance of the grid. Therefore, P2P trading must be able to allow these transactions without affecting the network's normal operation.

In this context, numerous approaches have been taken to develop these platforms, and diverse pilot projects have been deployed all around the world to test the potential of these technology. As a result, this thesis will explore how these distributed energy trading platforms work, and analyze the strengths and weaknesses that they present, to further propose solutions that can optimize the performance and integration of these platforms in the power grid.

Chapter 2. DESCRIPTION OF THE TECHNOLOGIES

This project will study P2P Energy Trading platforms, so before diving further into the topic, it is important to understand the different components of these platform, how they work, and interact with each other.

2.1 LAYERS OF P2P ENERGY TRADING PLATFORMS

The Global observatory on Peer-to-Peer Energy Trading [2] states that P2P platforms consist of 5 different layers with different implementation challenges. And before the grid can successfully accommodate DERs to the system using P2P trading, all these challenges must be addressed to optimize the implementation of these platforms. The 5 layers that make up P2P platforms are the physical, ICT, Market, Economic and Regulation layers, as it can be seen in Figure 2. However, this project will focus on the challenges presented in the physical layer and will analyze how current platforms address these challenges and propose approaches that will better encourage the implementation of these platforms.

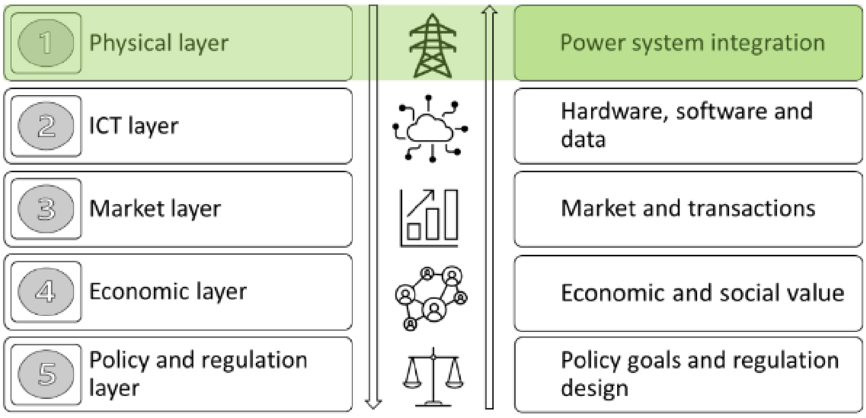


Figure 2. Layers of P2P Energy Trading platforms

2.2 ELEMENTS OF P2P ENERGY TRADING PLATFORMS

To understand how these platforms operate, it is important to comprehend the different elements that they are composed of. These elements can be divided into two layers, the physical and the virtual layer.

The virtual layer ensures a secure connection among the participants, allowing a mean for consumers to interchange diverse types of information, to create trading orders and to utilize a market mechanism to execute the transactions. Alternatively, the physical layer is the infrastructure that enables the real energy trading among prosumers and consumers once the financial transactions are settled in the virtual layer. The physical network could either be the traditional grid, or it could include and additional microgrid that allows the system to operate independently from the grid.

Figure 3 shows the different elements in both the physical and virtual layer, displaying how they interact with each other. In this section, all these elements will be described in detail to further understand the operation of these platforms.

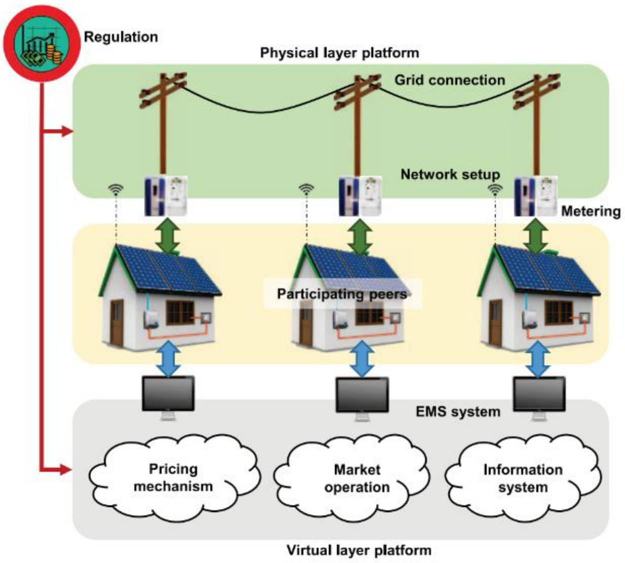


Figure 3. Elements of a P2P platform in the physical and virtual layer

It is important to mention that the transactions among participants are purely financial and conducted in the virtual layer, and at no point that means that the actual energy will flow from one participant to another once the transactions are settled. Instead, the payment guarantees that the prosumer involved in the transaction will inject into the physical grid the amount of energy stablished, for it to be accounted in the balancing of supply and demand.

2.2.1 ELEMENTS IN THE PHYSICAL LAYER

- **DERs**: The first thing these systems need to operate is distributed energy resources. The vast majority of these resources are solar panels, although other systems such as fuel cells, small wind turbines and reciprocating engines are beginning to be developed.

- **Grid connection**: to enable P2P trading the participants must be connected by a physical electrical network. The normal functioning of these systems is with connection to the grid, to balance supply and demand in the network with the help of the utility when the DERs don't provide sufficient generation. The system must stablish the connection points with the grid and implement metering systems in those points to interact with the grid. Moreover, some systems have an additional microgrid/although this is not completely necessary for these projects. However, it is useful to provide greater resilience to the system as it allows the microgrid to operate in island mode, thus being able to operate separately from the grid in the event of a grid failure. Although, the usual way of operation is to be connected to the grid in order to be able to exchange energy with it and better regulate the balance between generation and demand.

- **Smart meters**: these devices measure the energy demand and generation, and in the case of having a storage battery, also its charge level. These measurements allow the system to know the amount of energy available for trading. In addition, Smart meters have a user interface through which users can set their preferences in the prices of energy purchase and sale, and see in real time the consumption and export that is being made. Although these are the basic functionalities of the Smart meters, there are more advanced systems that allow for the optimization of electricity trading and consumption. For this, the system indicates the user the most appropriate times to connect certain demands and makes suggestions on the optimal price for the energy exchange depending on the parameters of the rest of the system. However, all this requires a lot of interaction from the users, so a total automation of these systems must be achieved. In this manner, through previous preferences indicated by the users, the system should automatically manage in the most efficient way the different demands, batteries, and exchanges.

2.2.2 ELEMENTS IN THE VIRTUAL LAYER

- **The information system**: a secure and fast performing system is a key element in ensuring the peer-to-peer trading in these platforms. This information system needs to enable communication among all the participants, allowing equal access to the market to all of them. It also needs to integrate the market mechanism ensuring its correct operation by supervising and securing the transactions. Lastly, it needs to be able to implement the necessary constraints to ensure the reliability of the grid. To this day, the most successful P2P trading platforms utilize Blockchain technology for this matter, given the several benefits that it presents. The Blockchain platform is responsible for containing market applications, users, Smart contracts and managing transactions between users. And although the basis of this technology is the same for the different systems, there are different types and consensus mechanisms that make some chains more appropriate than others for these uses. Although further discussion on this technology will be provided in 2.3.

- **Energy Management System:** the main function of the EMS is to secure the energy supply of the user, whether it is from the peer-to-peer platform or directly from the grid. This element has access to real time supply and demand of the users using the Smart Meter, and it uses this information and set user preferences to participate in the energy market.

- **The market mechanism:** this is basically the price matching algorithm. In the most innovative systems these algorithms use advanced technology working with the EMS and take into account different inputs to decide whether a transaction should be made. These inputs are the prediction of the household demand, prediction of the generation of the solar panels, the parameters set by the users and in systems with batteries it would also take into account the battery data. With this information the system would run the matching algorithm as follows: First the generation and demand of each participant in the next time interval is evaluated, and the prosumer systems communicate the amount of energy they can sell in that interval. Then the prosumer systems evaluate the purchase price of energy from the grid and make a sale offer based on the users' preferences and lower than the grid purchase price. In turn, the consumers’ systems make a purchase offer taking into account the same parameters, and then the matching algorithm is executed. If supply and demand are not matched, the system runs the algorithm again, reducing the prosumers' selling price and increasing the consumers' buying price, until the entire energy is matched. Then a Smart Contract is created that verifies energy transactions and automates payments between users. Although it may not seem beneficial for prosumers to obtain a lower compensation than the purchase price of the network, this is because the network does not buy the surplus energy of these prosumers at the market price at that time, but makes a compensation in the user's tariff through a fixed rate that is not usually very beneficial for the prosumer. Therefore, these markets have benefits for their participants, since consumers get to buy at cheaper prices than the grid, and prosumers get to sell at higher prices than their compensation tariff.

2.3 THE INFORMATION SYSTEM: BLOCKCHAIN TECHNOLOGY

As mentioned above, the information system is a key element in the development of P2P platforms. This element can be described as the “brain” of the platform, as it is the necessary component where all the other elements of the virtual layer will execute their functions and interact with each other. For this purpose, Blockchain technology has been the most utilized information system in the context of P2P trading, and several pilot projects leveraging this technology have already been deployed worldwide.

Blockchain technology has been utilized in the energy sector for far more than peer-to-peer trading. Different companies have leveraged this technology for energy traceability and wholesale energy trading. Moreover, given its automation and security characteristics, companies have also used it for data encryption and contract automation.

However, the focus of this project will not be the study of this technology, above described as the “brain” of the platform, but the study of the elements that form this “brain”. These are the different market mechanisms, pricing strategies and grid constraints that the information system contains. Therefore, in the development of the project these elements will be addressed assuming that the information system consisting of Blockchain technology will enable the interconnection among all of them.

Nevertheless, this section will provide and overview of this technology, considering the benefits and challenges that it presents, so that the reader can better understand the context of the project.

2.3.1 OVERVIEW OF BLOCKCHAIN FOR P2P ENERGY TRADING

When creating market to enable peer-to-peer trading for distributed resources it makes sense to leverage a distributed ledger, for which most of the existing platforms utilize a blockchain based model, due to the different characteristics of this technology. These characteristics are its decentralization, immutability, and security. Decentralization means that there is no central authority controlling the network and transactions are recorded on multiple computers, making the system more resilient to failures. Immutability means that once a transaction is recorded on the blockchain, it cannot be altered or deleted. Security is ensured through the use of cryptographic methods such as Hash algorithms, digital signatures and consensus mechanisms [3], which makes it very difficult to tamper with the data stored on the blockchain.

Several blockchain based energy trading platforms have been deployed in the past years, and while all of them utilize the same technology, each project has different characteristics. In this context, conventional models that allow for the creation of local energy markets with double auction bidding systems have been the most adopted, with platforms such as Power Ledger and LO3 Energy. These platforms enable the sale and purchase of renewable energy between individuals and organizations, using a peer2peer trading model, which eliminates the need for intermediaries and reduces transaction costs. They also use smart contracts to automate the trading process and ensure that all transactions are secure and transparent.

However, while these models have worked to a certain extent, they are far from being optimal since they are too simple to consider all the different characteristics and constraints of the physical grid. For this reason, in the following sections the results and characteristics of some of these models will be analyzed and discussed, to understand what they are lacking to be an optimal model.

2.3.2 CHALLENGES OF BLOCKCHAIN FOR P2P ENERGY TRADING

Although blockchain has many benefits, it also presents a number of challenges.

2.3.2.1 High energy consumption

The first thing that is said about this type of platform is its high energy consumption when carrying out transactions. However, this is mostly attributed to the consensus mechanisms used by the blockchains of the most well-known cryptocurrencies. This mechanism would be the Proof of Work, which requires a large computational capacity to create and validate blocks. But there are other consensus mechanisms just as efficient and with much lower energy consumption, such as Proof of Stake, which is used by most blockchain applications in the energy sector. Moreover, in [4] researchers have proposed more advanced solutions such as using a second layer on the chain to stablish the transactions among specific participants to optimize the energy usage of the platforms.

2.3.2.2 Grouping transactions

Another challenge presented by blockchain platforms is how to group transactions into blocks. When a node validates a transaction, it adds it to a group of pending transactions known as a "transaction pool", until there are enough transactions in the pool to create a block and add it to the chain to be approved by the rest of the validating nodes. This characteristic can present two challenges.

The first is that in each time interval in which the market mechanism is executed to calculate new transactions between prosumers and consumers, it is necessary to close a block so that it can be validated by the rest of the nodes, and so that an energy exchange that ensures the balance between demand and generation can be correctly executed. However, blocks tend to group a large number of transactions in order to make efficient use of the amount of energy involved in verifying a block. But it is possible that in this time interval there are not enough transactions, so it would not be using efficiently the energy required to validate these blocks; unless we have a system with many participants that ensures a large number of transactions.

The second challenge it poses is the management of exchanges with the network, as these would not be done on the same blockchain network as the local market. Although, a possible solution for this could be to use a network with Tendermint protocol, which consists of a blockchain with a two-layer architecture. In one layer the transactions and validations of the blocks would be managed, and in the other layer designated for applications, the market applications would be carried out, which establish the amounts of energy to be traded in the local market, and those to be extracted to the network. In this way, communication can be maintained with the grid to manage the community's surplus energy. With this method, the application layer can have the information of all the energy that is not going to be sold in the community. This information can be grouped to send it as a single package to the network of all the surplus energy of the community, and thus manage the generation-demand balances in a simpler way. In this manner the application would be performing the function of a local aggregator, grouping the net generation/demand required by the community from the grid.

2.3.2.3 Value of the tokens

Finally, there is the problem of the real value of the tokens. To participate in these projects, it is necessary to acquire tokens that will later be used to acquire a certain amount of energy. And this implies a main question, which is: how to establish and fluctuate, both the monetary and energy value of the tokens, in order to create a real and efficient market?

2.3.3 CONCLUSIONS ON BLOCKCHAIN TECHNOLOGY

Therefore, the question arises as to whether blockchain is the most efficient solution for these systems. Given the complexity of P2P energy markets, a centralized solution where participants trust the operator may be a good alternative.

In summary, the important matter is not the technology used, but to enable new interactions between users that give value to the network and put consumers and prosumers at the center of the system, helping in turn to create a more efficient energy system. However, it is true that one of the main advantages of the blockchain system is the capacity it gives users to decide on the different aspects of the platform in a democratic way, thus allowing users to decide the most efficient way to manage their network, whether in the type of market application or in the prices of transactions.

Therefore, while this project will study distributed platforms based on blockchain technology, it will focus on the benefits of distributed energy trading by itself, since the idea of enabling this type of market does not necessarily require blockchain technology.

Chapter 3. STATE OF THE ART ANALYSIS

Up to date several peer-to-peer energy trading platforms have been deployed globally, mostly in pilot projects to analyze the potential benefits of these platforms. The projects have diverse characteristics that make them unique, but the majority of them are focused on local energy markets and leverage blockchain technology to unleash the potential of P2P.

In her master's thesis [5], Carmen Domínguez studies the most well-known projects that have been deployed and provides an overview of the context of these pilot projects. Moreover, she gives insights on the state of the energy sector, the importance of digitalization to efficiently manage DERs, and the role that Blockchain plays in the energy sector, with a more in-depth description of this technology. Therefore, as an introduction to this thesis it is recommended to read her project to better understand the concept of blockchain in the energy sector.

However, the project above mentioned focuses on describing the context of several projects and comparing the approach of different platforms. But this project will focus on analyzing the challenges these platforms face, mainly on the physical layer, and will propose solutions to optimize the performance of these platforms. Therefore, in this section four existing pilot projects of different nature will be analyzed, to understand the challenges and potential of each one of them.

3.1 QUARTIERSTROM

This project allowed prosumers with extra generation to sell their surplus to their neighbors directly [6]. Participants could select the pricing they would be willing to pay or charge for locally produced solar energy using the user application. Additionally, transactions on the blockchain were automatically calculated, completed, and immediately stored. Moreover, the project utilized numerous energy storage batteries for two purposes at different times. The first is to determine whether it is technically feasible to operate them as community batteries connected to the rest of the Quartierstrom system rather than as storage systems for individual homes. And second, based on the circumstances of the community, to determine the degree to which their availability could boost community self-sufficiency.

3.1.1 BATTERY STORAGE

This project is of particular interest given their use of battery storage. In the context of DERs, residential solar is always the main focus, however excess penetration of residential PV can present several problems. Firstly, if the solar capacity exceeds the demand of the community in the hours of peak solar generation, this excess electricity will need to be sold back to the grid. This not only brings back the NEM and FIT that peer-to-peer trading is trying to change, but it also creates instabilities and frequency harmonics in the distribution level of the grid. Secondly, one of the main benefits of DERs is their potential to reduce or postpone the investments on the electrical infrastructure by bringing the generation closer to the points of demand. However, for this to happen it is important to reduce the peak demand of the community, that occurs commonly in the afternoon and does not coincide with the peak of solar generation.

The issues above mentioned can be solved if the distributed solar generation is paired with battery storage, so that the systems are able to dispatch the energy in a more efficient manner. Therefore, the use of batteries in this project is particularly interesting for optimizing the peer-to-peer energy trading platforms.

The batteries in the project were not individual per distributed solar system, but they were community batteries leveraged to manage the total generation and demand of the community. To manage these batteries, the participants were equipped with smart meters that could meter separately the generation, demand and charging level of the batteries. Along with the smart meters, the batteries were controlled by a specific application. This application running on the blockchain was used to keep track of the battery's charge. The community's production and consumption ratios could be read at any moment by this module, which would then determine whether to charge the battery or discharge it depending on whether the community was importing or exporting energy.

3.1.2 CONCLUSIONS ON QUARTIERSTROM

From the Quartierstrom pilot project two main features can be extracted to help develop an optimal model for P2P trading platforms. These features are the use of battery storage and the automation of price matching.

3.1.2.1 Price automation

At first the project utilized the typical method for P2P energy trading, and iterative double auction mechanism were users set limits for the price of energy they want to buy or sell on the local energy market, and then the blockchain platform iterates the sell and buy orders until all the energy is matched for its transaction. However, for a short period of time, the price capping function was temporarily deactivated during the project with advance notification and a uniform price mechanism was implemented. With this system, rates were uniform for all participants and local energy distribution was based on local supply and demand.

The results from this project showed that participants are not willing to pay higher price for locally produced energy, therefore an economic incentive is needed in these platforms. Moreover, a small economic incentive for the participants was not enough for them to go through the burden of having to set their prices manually, and customers would rather have their prices set automatically by the market mechanism. This was observed after the period of time where the uniform price mechanism was implemented, because once this period finalized, the majority of the participants preferred to continue with that type of model, stating that the manual model was difficult to understand and took an extra effort that they were not willing to make.

3.1.2.2 Use of batteries

In this project we can also identify another main characteristic for an optimal platform of this type, the use of battery storage. As it was mentioned above leveraging batteries can help manage the supply and demand of the community without the necessary interaction of the grid to supply or buy electricity when the generation and demand in the community are not balanced. Moreover, this project shows the alternative of using batteries as a community element, rather than an individual battery that tries to maximize each customer's interest. Later, it will be discussed how batteries can help efficiently manage the generation of a community, and if utilizing batteries for a community efficiency, rather than an individual one, is the best option.

3.2 VERV'S HACKNEY PROJECT

This project focuses on a community of 17 blocks of buildings in which 14 of them have rooftop solar PV installations [7]. The community services in the buildings were all powered by these solar panels, with any extra energy being put into the grid at the feed-in tariff rate. In order to benefit from the solar installations, the project distributed part of the installations among the various community members. As a result, a community of neighbors who traded energy was stablished, allowing them to trade energy at reduced cost compared to that of the grid.

3.2.1 ADVANCED DEMAND FORECASTING

The main focus of attention for this project is the specific device they use for demand forecasting. This device is the Verv Home Hub (VHH), which is used to sample the participants' consumption values. Real-time data on consumption, the status of appliances (i.e., on or off), and their energy efficiency are collected by installing it on the conventional electricity meter or smart meter by placing an ammeter clamp on the circuit. The device measures current and voltage values to later utilize machine learning to separate the profiles of various appliances. This allows to create consumption patterns in houses using all this data to forecast future demand more accurately, then with the forecast stablished the participants can participate in peer-to-peer trading in a more secure and efficient manner.

3.2.2 USER PREFERENCE AND AUTOMATION

This project not only leverages innovative technology for demand forecasting, but it also uses it for the trading process in itself. The matching algorithm utilizes artificial intelligence along with the following inputs to determine whether or not a transaction should be made: forecasts of household demand, forecasts of solar panel generation, the parameters set by the users, and in the future, forecasts of battery data. The VTP platform uses all this data to run the matching algorithm through an iterative double auction process. Therefore, through the app developed by Verv, users can set specific preferences on price limits, and once that is set the system will run automatically thanks to the advanced demand forecasting and the AI matching algorithm.

3.2.3 CONCLUSIONS ON VERV

From this project the main characteristic that can help towards the development of an optimal platform, is the extensive use of advanced technology.

3.2.3.1 Advanced technology for demand forecasting and automation

As it has been mentioned in the previous section, automation of the trading process is one of the most important parameters for the users' acceptance of the platform. Therefore, the optimal platform must include devices that allow for this automation. In that way, a device that provides advanced demand forecasting is needed to accurately manage the supply and demand of a local energy market. Moreover, pairing set device with AI in the matching algorithm will allow the platforms to run automatically without excessive user interference.

3.3 BROOKLYN MICROGRID

This project is the first of its kind to be developed in the United States [8], and it shows potential to be a good model for these platforms since it has recently been studied to be authorized to operate in the New York city energy system as an energy retailer.

In the Brooklyn Microgrid system, residents of NYC who prefer to use renewable energy to buy excess solar generation from consumers on their community. Participants in the project can interact with the system through an app where they set their preferences on prices and source of energy (local or grid) to then participate in the energy trading.

To enable and manage the trading among the participants, the Brooklyn microgrid utilizes a similar system to the ones described in the previous sections, therefore no deeper focus will be set on it I this section. As so, it uses an Energy Management Trading System (EMTS) to set specific consumer preferences and automatically manage the energy supply. Then the market mechanism manages the buy and sell orders using a double auction pricing mechanism.

3.3.1 MICROGRID

The first characteristic of interest of this project is the use of a microgrid additional to the traditional grid. Brooklyn's outdated grid is close to its electric capacity utilization limit, what makes it vulnerable to grid failures. Moreover, the grid is already struggling to accommodate the characteristics of new technologies such as residential PV, energy storage or electric vehicles. Therefore, leveraging a physical microgrid allows participants to minimize the impacts of grid issues and allows for a better management of the local energy supply. However, this system still relies on Con Edison, NYC Distribution System Operator (DSO), to manage load balancing and demand response, when supply and demand do not match within the community.

3.3.2 ELECTRIC VEHICLES

An innovative characteristic that this platform has implemented is including electric vehicles into their platform. In this manner, users can include charging stations and EVs in the market to make their surplus energy available for purchase in the local energy market. For this, the system utilizes bidirectional chargers that allow EVs to receive and send energy to the grid. Then, on agreement with the DSO these vehicles can send energy back to the grid during peak demand periods.

3.3.3 CONCLUSIONS ON BMG

This project has been proven to be successful in NYC's energy system, since the number of participants is growing, and it is on its path to becoming an energy retailer. While it would be interesting to further analyze the tariffs and agreements the system has with the grid operators, unfortunately no information could be found on this matter. However, some of its above-mentioned characteristics can aid towards the development of an optimal platform.

3.3.3.1 Location

The main characteristics of the platform were very similar to the ones described in the previous platforms. However, there is an element in particular that makes this platform more successful than the others. This element is its location.

The BMG was developed in NYC, a densely populated area in which the grid already struggled to manage a network that was close to its capacity limits. Therefore, creating local energy markets that relieved the congested traditional grid through the utilization of DERs can help the traditional system, especially in densely populated areas.

3.3.3.2 Reliability

The implementation of an additional microgrid ensures that the system will function when traditional grid doesn’t. This is useful for systems where the grid is outdated and for areas that experience harsh weather conditions that usually end up electricity blackouts.

3.3.3.3 Electric Vehicles

With the increasing number of EVs that has been seen in the recent years, leveraging them as batteries for the distributed energy system can optimize the performance the energy system. In this manner, EVs can be included in these platforms to act as batteries to absorb excess solar generation, and if paired with bidirectional chargers, to act as demand response.

3.4 RENEW NEXUS

This project was developed by Power Ledger a leading global company in blockchain technology applied to the energy sector. Further study and analysis is carried out for this project given the impact of Power Ledger in the energy sector and the availability of detailed reports that help produce a more in depth analysis of the optimality of this platform.

If the reader wants a better understanding of the background of the project, in [5] Carmen provides a more detailed description of its context and elements. However, this section will directly analyze the results provided by Power Ledger and evaluate the elements that can be utilized to develop an optimal model platform.

The projects that will be studied are Freo48 and Loco1, two projects developed inside the Renew Nexus context, which focused on P2P trading and the use of batteries to form Virtual Power Plants (VPP).

3.4.1 FREO 48

3.4.1.1 Methodology

In this part of the project participants set their own price for the energy traded in peer-to-peer platform in dynamic market where prices were set in a double auction method. This allowed for the creation of a localized energy market where participants would be incentivized by the energy price to balance demand and supply.

The idea of this market is to function between the price of the FIT and the retail energy price from the grid, allowing participants in the LEM to benefit from a reduced price of energy. In that way, consumers will bid at a price lower than the retail one and prosumers will make offers at a price higher than the FIT and lower than the retail price. Depending on the supply and demand of the community at any given interval of time the market competition for the local energy will regulate itself. In that manner, in periods were the community has excess energy, the prosumers with the highest offers will have to sell to the grid at the FIT. And, in periods of excess demand, consumers with the lowest bids will have to purchase energy from the grid.

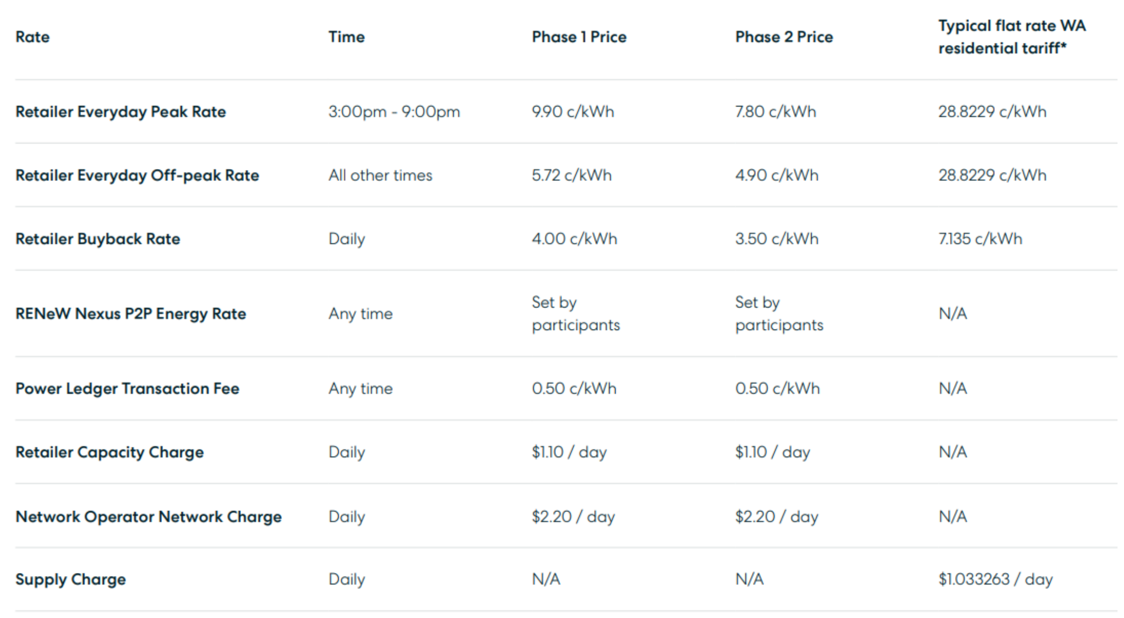
3.4.1.2 Pricing schemes

The tariffs utilized in the project reflected the various charges that typical electricity tariffs underly, which comprise the network cost, capacity cost and retailer energy cost. These costs were the divided into fixed and variable to allow for the P2P trading. For this, the capacity and network cost were fixed for each participant, and the energy retailer cost was set on a Time of Use (ToU) rate if purchased from the grid, or by the P2P market if participating in it. The exact cost of each item can be observed on Figure 1 extracted from Power Ledger's report on the project [9].

The fixed prices were based on the following assumptions:

- Average per-customer charge required to recover network and fixed capacity costs over the entire residential customer base.
- A 9% discount on the network charge component was applied to participants in the project.

To encourage P2P trading among the community the buyback rates form the grid were set at a much lower rate than the current FIT tariff in the context of the project (7.135 c/kWh).



Rate	Time	Phase 1 Price	Phase 2 Price	Typical flat rate WA residential tariff*
Retailer Everyday Peak Rate	3:00pm - 9:00pm	9.90 c/kWh	7.80 c/kWh	28.8229 c/kWh
Retailer Everyday Off-peak Rate	All other times	5.72 c/kWh	4.90 c/kWh	28.8229 c/kWh
Retailer Buyback Rate	Daily	4.00 c/kWh	3.50 c/kWh	7.135 c/kWh
RENeW Nexus P2P Energy Rate	Any time	Set by participants	Set by participants	N/A
Power Ledger Transaction Fee	Any time	0.50 c/kWh	0.50 c/kWh	N/A
Retailer Capacity Charge	Daily	$1.10 / day	$1.10 / day	N/A
Network Operator Network Charge	Daily	$2.20 / day	$2.20 / day	N/A
Supply Charge	Daily	N/A	N/A	$1.033263 / day

Figure 4. Tariffs for the Renew Nexus Freo 48 project.

3.4.1.3 Results on Freo 48

3.4.1.3.1 Phase 1

In this phase of the project 94% paid higher prices for their energy usage than they would have on a standard tariff. This can be attributed to the following factors:

- **Fixed cost components**: the network and capacity costs for normal utility customers are usually recovered through both variable and fixed costs. However, for this project, these charges were based on the average consumers tariff, with a demand 11.5 kWh per day. Then a fixed charge was created for every participant independent of their energy usage, what led to losses in every participant that had a lower consumption than the average and favored the higher consuming participants.
- **Ratio consumer-prosumer**: the project consisted of 70% of prosumers, what led to limited demand on the local energy market, and more energy sold to the grid than in the P2P, and at a lower rate than the usual FIT (7.3125 c/kWh). In Figure 5 it can be observed the excessive solar generation that had to be purchased from the grid.

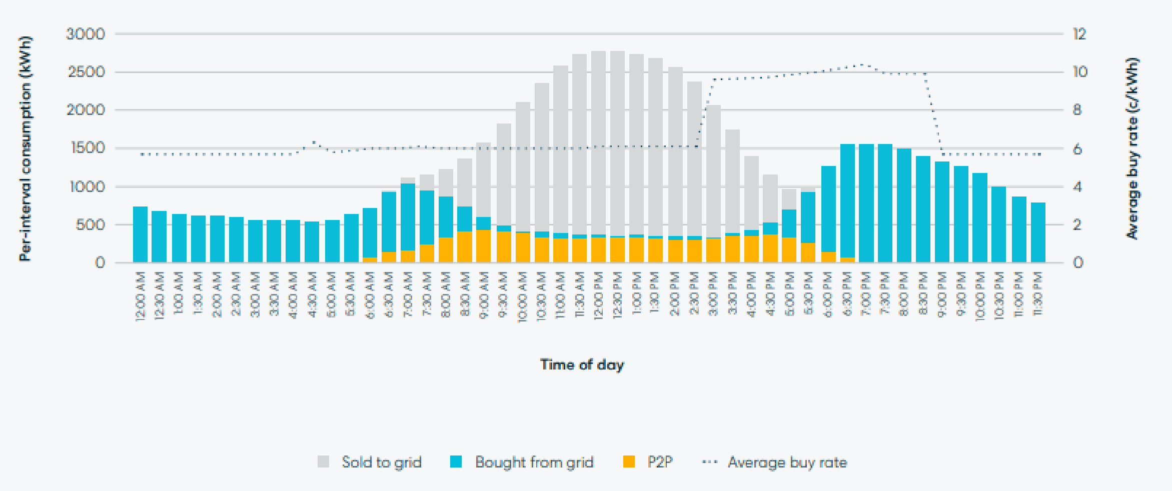


Figure 5. Transactions on the Freo 48 phase 1 project

3.4.1.3.2 Phase 2

With the learnings from phase 1 some changes were implemented for phase 2. The prosumer to consumer ratio was changed to 2:1 (consumer - prosumer) and the chosen participants had an average daily consumption of 11-16 kWh, to overcome the outcomes of high fixed charges.

- **Fixed cost components**: The changes made in this phase resulted in better outcomes than in the previous one with 62% of participants paying lower costs for their energy than in a normal tariff. However, this was largely due to the larger consumption of the participants, since 80% of the participants with a daily consumption lower than 11kWh still experienced losses, reaffirming the effect of high fixed charges.
- **Ratio prosumer-consumer**: the ratio prosumer-consumer was not enough since the energy sold to the grid compared to the energy traded in the P2P was 62%.

Figure 6 reflects the transactions of the project in the different intervals.

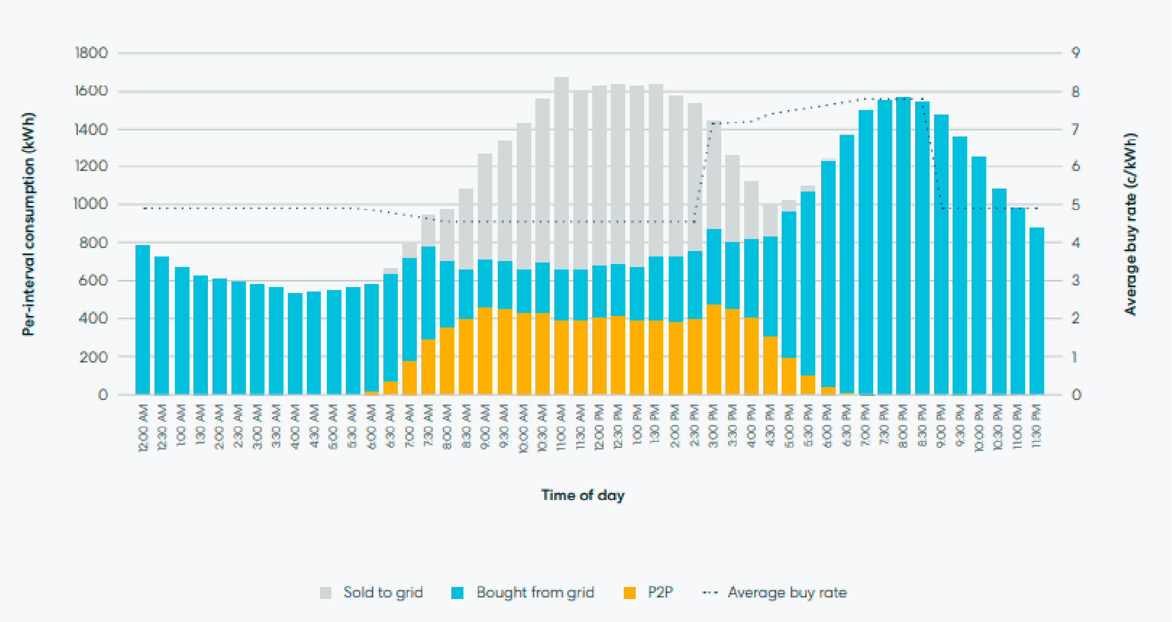


Figure 6. Transactions on the Freo 48 phase 2 project

3.4.1.4 Conclusions on Freo 48

- **Consumer-prosumer ratio**: a local energy market needs the correct prosumer-consumer ratio to not export its excess generation at the peak solar intervals to the grid, causing instability and frequency harmonics. Or, enough battery storage to allow to serve the excess generation that occurs at midday in different time periods.

- **Fixed charges**: the way that operators charge for the network use needs to better reflect the actual use of infrastructure, since it benefits users with larger energy consumption and discourages energy efficiency initiatives.
- **Buyback rate**: the price at which the grid buys the excess energy from this local energy market is set excessively lower than the usual buyback rate, what makes participants reduce their revenue when energy is exported at peak solar generation. This rate should be revised.
- **Energy usage shift**: even though results were not favorable for many participants, the creation of LEM does encourage users to shift their energy demand to periods where there is P2P tradeable energy incentivized by the lower prices.
- **Excess solar not traded in P2P (automation)**: it can be observed in Figure 7 that in phase 2 of the project, some participants didn't trade energy in the P2P market efficiently when there was enough solar generation in the community. Analyzing the prices set for phase 2, retail grid off-peak rate of 4.9 c/kWh, and buyback rate of 3.5 c/kWh, there is local market interval that could benefit both consumer and prosumers that is not being used. Considering the price per transaction in the P2P of 0.5 c/kWh, consumers should be willing to pay anything lower than 4.4 c/kWh and prosumers should be willing to sell at any price higher than 4 c/kWh. This leaves an interval of which consumers do not take advantage given their scarce knowledge on energy trading, and this highlights the need for automation in this process, since consumers will not always make the smarter choices.

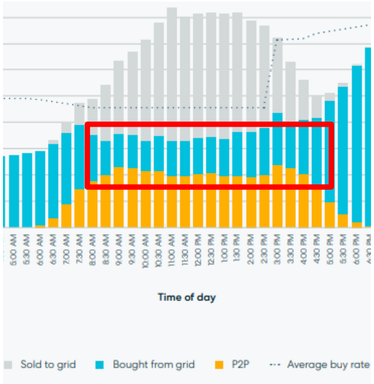


Figure 7. Energy not traded in P2P market in phase 2 of the Freo 48 project

3.4.2 LOCO 1

In Loco 1, as an extension of the project, a model was created to determine the average return on invest from 10-15 kWh batteries for their typical use, with the objective of evaluating if the integration of set batteries in a Virtual Power Plant (VPP) would minimize the payback period.

The idea was to allow prosumers with battery storage to participate either on the P2P market or as a VPP in each interval, but not both in the same period of exchange. In this manner, participants in the network could buy energy from the batteries when there was no solar energy available in the community, and the prosumers with battery storage could offer reliability services to the grid to help with grid stability.

3.4.2.1 VPP pricing

Since the project was developed in Australia, the pricing was based on Western Australia's Energy Market (WEM), however this market operates in a similar manner to most energy markets in Europe or the United States.

The WEM comprises two markets, the capacity market, and the energy market. In the capacity market utilities are compensated for the availability of providing energy, whether this energy is generated or not. And the energy market, consists of the energy that is actually generated, and is made up of three different markets. The first one consists of Power Purchase Agreements (PPA), long term contracts between buyers and sellers that allocate a certain generation. The second one, is the Short-Term Energy Market (STEM), that is cleared a day ahead of the actual demand and supply balancing, and allows participants to make a more accurate forecast of their actual energy needs. And lastly, the Balancing Market, in charge of balancing real time demand and supply mismatches.

For this project, the pricing was stablished based on historical data of the STEM market. In this manner, in each time interval of the P2P market, the users with the batteries could choose to participate in P2P, consume their energy or participate in the VPP based on that specific interval STEM price. Even though it would make more sense to set the VPP prices based on the Balancing Market, this was not possible due to the lack of price forecasting for it, therefore STEM prices could serve as a guide for the analysis.

The model developed for this project utilized the following considerations:

- Implemented residential tariffs, STEM and ancillary services prices from the markets of the area of the project.
- Average user consumption: 20 kWh per day
- DERs: 5 kW PV paired with 3.3kW/10kWh battery or 10 kW PV paired with 5kW/15kWh battery.
- P2P trading price: 7.8485 c/kWh (based on grid buyback rate + 10%)
- Size of the VPP: 10 MW
- Reliability compensations: the batteries also received compensation for participating as ancillary services in the grid, each with a 2.5 kW and 3 kW capacity respectively.

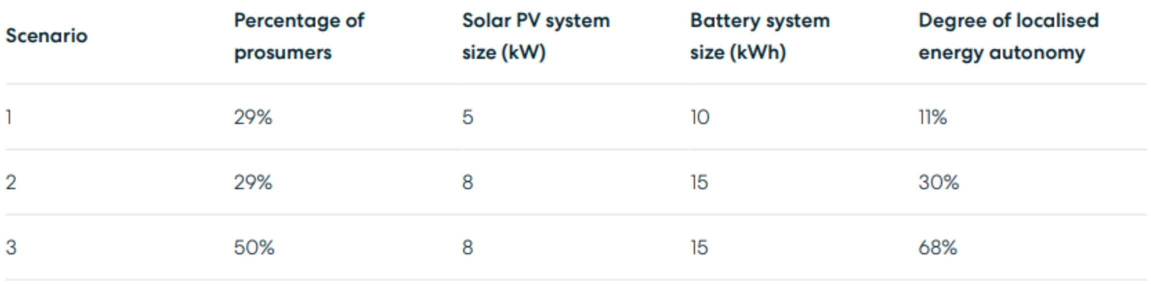
3.4.2.2 Results on Loco 1

3.4.2.2.1 Phase 1

The results from Loco 1 concluded on higher benefits for the owners of battery and PV systems. They calculated the total revenue comprised of self-consumption savings, P2P trading, STEM prices, ancillary service prices and capacity markets. When comparing the payback periods for the batteries with the usual payback period with only self-consumption, this resulted in payback periods 40% to 50% shorter depending on the adopted system size. Moreover, the analyzed the dependence on the grid of these customers and the results showed that 86% to 90% of their energy would come from self-consumption.

3.4.2.2.2 Phase 2

In phase 2 of the project, they attempted to study the energy autonomy of a community with these models and systems installed. The considerations for the trading and pricing were the same as in phase 1, but the average daily consumption was changed to 13.436 kWh, a more realistic value based on the average of the project's area. Then they analyzed the degree of autonomy for the community based on the three scenarios described on Figure 8.



Scenario	Percentage of prosumers	Solar PV system size (kW)	Battery system size (kWh)	Degree of localised energy autonomy
1	29%	5	10	11%
2	29%	8	15	30%
3	50%	8	15	68%

Figure 8. Reslust for phase of Loco 1

The results obtained show that a high degree of energy autonomy can be obtained from implementing projects that leverage this type of model.

3.4.2.3 Conclusions on Loco 1

- **Consumer-prosumer ratio**: the project Freo 48 showed the importance of the prosumer-consumer ratio in systems that only consist of PV panels, by showing that excess prosumers would lead to an excessive amount of generation being exported to the grid. However, in Loco 1 it was shown that by pairing battery storage with PV panels the excess energy produced at midday could be used to supply the community in other moments. Further, it showed that an increased prosumer-consumer ratio could benefit the community by allowing them to increase their energy independency form the grid, helping the grid in the same manner too.
- **Increased ROI:** by creating VPP this project allowed prosumers to participate on new markets, allowing them to increase their financial benefits and further encouraging the acquisition of battery storage to counter the excess solar generation midday. Moreover, participants were creating value for the grid too, by providing services to it when it was needed, thus helping avoid or reduce new infrastructure investments.

3.4.2.4 Inquiries on Loco 1

The project obtained beneficial results for customers, providing financial incentives to invest in systems with PV and battery storage. However, some elements of the project related to the pricing for the VPP do not align with the objectives of P2P trading.

- **STEM pricing**: the pricing stablished for the energy that the VPP would trade with the grid was based on STEM prices. However, the idea of enabling localized energy trading is to bring the generation closer to the points of demand, and stablish a more localized pricing of energy. Therefore, compensating the VPP based on STEM prices does not align with the purpose of creating a localized market. A possible alternative for this would be to compensate this VPP based on Locational Marginal Pricing (LMP) within the distribution system. LMP is already utilized in energy markets to account for transmission losses and grid congestion, therefore, utilizing a similar model based on the distribution system would be a better way to allocate the energy that VPP can provide.
- **P2P trading price**: the P2P trading price was set at the fixed FIT from the grid. While this allows for an easier calculation of the results, it defeats the purpose of creating a local energy market. Therefore, the results from this project actually show the operation of a VPP under grid management in a FIT. Even though the results are beneficial for battery owners, they do not represent the actual case of a P2P trading platform. For this to happen, the pricing should be based on a P2P average clearing price from the first project (Freo 48). However, Power Ledger does not provide further information on the prices set in Freo 48, therefore there is no possibility of evaluating the differences if an actual P2P platform was studied.

Chapter 4. P2P ON THE PHYSICAL LAYER

Energy trading is different from other types of trading due to its unique characteristics. Firstly, it cannot be stored in large quantities in an efficient and economical way, and secondly, demand must match supply at every moment to ensure the adequate frequency is maintained. Therefore, all the elements that form part of this system must attain to certain technical constraints in order to maintain the correct operation of the overall grid, and this includes customers and DERs in the distribution network.

Hence, if Localized Energy Markets (LEMs) want to be deployed at scale throughout the grid they need to ensure the implementation of these network constraints in their models. This represents the main challenge for implementing DERs in the grid, and therefore the impact of this implementation in P2P platforms should be studied.

Up to date, the electricity network has been operated in a centralized manner, meaning that the Energy was generated in big power generation plants and then flowed in one direction to the consumers. In the same way, the transmission grid was designed to handle high voltage electricity and to transport it for long distances until it reached the points of demand. Then, after transforming the voltage in a substation or transformer, the electricity would be circulated to the final customers along the distribution grid. This distribution grid is designed radially, meaning that electricity flows in one direction from substation to final customers, in the same way as the branches of a tree. These “branches” or power lines are designed to handle the highest demand in the feeders that represent the end of the line into the final customer.

The challenge in this outdated distribution system arises when there is large number of DERs and LEMs being connected to the low voltage system, since the grid is not designed to handle this type of generation. So, even though DERs present multiple benefits for the power system, they need to be implemented in a way that the addresses all the challenges that they present to the physical grid. Therefore, for P2P platforms to be implemented successfully they need to be designed in a way that they consider these network constraints in their operations.

4.1 VOLTAGE

Voltage variation is a key challenge when implementing P2P communities. This phenomenon occurs when the voltage levels vary from the specified levels of 0.9 to 1.1 p.u. and is mainly due to a high penetration of DERs in a feeder. A large amount of energy being transacted in a community can elevate the voltage levels of the nodes causing instability in the grid. However, this can be managed in several ways:

- **Inverters equipped with voltage controllers**: with this included into the participant's systems, the limits could be included as constraints in the P2P platforms, and therefore curtail the transactions to the stablished voltage limits [10].
- **Accurate demand forecast**: voltage levels are primarily affected by the flow of energy coming in or out of the total community, as in across the feeder from the distribution grid [11]. Therefore, a more accurate supply and demand balance from the total energy for the community with the substations will lead to more controlled voltage levels.
- **Including physical constraints on market mechanisms (Transactive Energy)**: this represents an advance from P2P platforms to a model referred to as Transactive Energy (TE). With this model the market mechanism includes optimization constraints for the community that consider the power flow equations and voltage constraints of the community, what avoids the voltage problems since transactions among peers are limited by the physical network [12].

4.2 PHASE

The balance of the three phases in necessary for an adequate energy supply, both in current and voltage, to ensure that the power values of these phases are also balanced. P2P platforms need to consider the phases to which the households are connected, since higher voltage imbalances and losses occur when there is a network imbalance. Therefore, platforms should include ways to deal with these phase imbalances.

- **Dynamic phase switching**: with this method the limits of certain lines can be adjusted to better match the actual condition in each moment and allow for a larger utilization of its capacity. By including dynamic phase switching with the system operator, the impact of DER installations on voltage unbalance can be effectively reduced, by altering the lines capacity when it is needed. This method can help increase the power transfer capability of existing infrastructure, reduce transmission losses, and improve grid reliability. Furthermore, using dynamic phase switching can help with the integration of renewable energy sources by maximizing the utilization of existing transmission and distribution networks [13].

However, phase imbalance has not been widely studied in the context of P2P platforms, since most projects and research papers assume a balance between the phases to which the participants are connected. Some studies propose that a larger inclusion of DERs in the system could lead to higher voltage and line losses, due to imbalance between phases. Hence, further research should be directed to the effect of P2P platforms on this matter and how it can be solved.

4.3 CONGESTION AND INCREASED POWER PEAKS

With P2P platforms the number of DERs in the grid could potentially increase, and this could impede the matching of available transmission infrastructure capacity and generation, causing increased congestion in the lines. To manage congestion, it is important to consider the power peaks on such system, and how different approaches to developing the P2P platform will affect this.

- **Price distribution**: the way the market mechanism is designed has an impact in the outcome of the amount energy traded and when it is traded, which is directly correlated with causing congestion in the lines. [14] found that uniform mechanisms inside the community reduce the utilization of certain lines.

- **Network tariffs**: rate structures stablished for these P2P communities by the grid have a large impact on when and the amount of energy that is exported or imported from the community. These rates can be uniform or include capacity or time of use characteristics, incentivizing participants to use their energy in a way that is efficient for the trading with the grid. In [15] the effect of Capacity and ToU tariffs was studied, finding that both reduced peak demand in the P2P community, with capacity tariffs having the largest impact in reducing the energy imported from the grid.
- **P2P platform operation (TE)**: these platforms can be operated in several ways depending on their market operation mechanism. This mechanism is usually centered in obtaining each participant's highest benefit with methods such as iterative double auctions like it has been described in previous sections. However, this mechanism could also be designed to optimize the energy efficiency of the community, rather than the maximum benefit of each participant. This would be a manner of implementing Transactive Energy characteristics, what can help the P2P platform to operate in more efficient way when interacting with the grid. In this manner [16] found that if the DERs of a P2P community worked in an aggregated manner and offering service to the centralized system, a substantial peak reduction could be obtained.
- **Interaction with DSOs**: as it was observed in the Renew Nexus project, allowing battery storage to participate as VPP has benefits for the participants. Moreover, in [17] it was found that allowing the DSO control of these flexible distribute energy resources by letting them participate in reliability markets, can effectively reduce peak demand in the community.

In conclusion, the reduction of peak demand and congestion is mainly affected by the participants choices on when and how much energy they consume. Therefore, the only way to control this is to develop market mechanisms that incentivizes participants to consume in periods of lower demand. However, if batteries are included in the P2P platform this peak demand can be further reduced. Moreover, by implementing a market mechanism that aims to maximize the energy efficiency of the community, further peak reduction can be obtained.

4.4 DISTRIBUTION GRID PLANNING

Network operators need to plan the investments on new infrastructure according to the growth in demand, but with the growth of DERs this planning needs to change to adapt to this new way of generation.

One of the most well-known benefits from DERs is their ability to reduce the investments in the network infrastructure. However, to realize this benefit DERs have to be managed in the correct manner, this meaning being able to reduce peak demand, since this is the main driver of infrastructure investments. Here is where P2P platforms come to play, since they have the potential of shifting the energy demand of a community to times were there is excess solar generation and away from peak demand, incentivized by the lower energy prices at set times. In [18] studied how P2P communities affect the investment plans of infrastructure and showed that creating P2P systems to manage DERs effectively results in consuming less electricity in periods of peak demand, therefore aiding in reducing network investment.

4.5 INTEGRATION OF GRID CONSTRAINTS IN P2P

Network constraints present a challenge for Local Energy Markets, and they need to be accounted for to ensure P2P communities don’t create a negative impact on the physical grid. To do this, platforms can implement different approaches. Firstly, they can incentivize prosumers to respect network constraints by providing dynamic price signal in the market. Or alternatively, market mechanisms can directly reflect the constraints of the network by implementing branch flow equations in them.

Branch flow equations, or power flow equations, are the equations used in power system analysis to model the flow of power and determine the operating conditions of an electrical network. They represent the balance of power at various nodes and branches in the network considering the electrical characteristics and constraints of the system components. To integrate these equations and constraints in the P2P platforms several approaches have been followed.

- **Market mechanism with constraint equations:** including branch equations directly in the market mechanism will ensure that technical constraints are respected, since the only bids that will be cleared would be the technically feasible bids. In [19] researchers utilized an Optimal Power Flow solution with bilateral trading to create a platform that aimed to maximize social welfare of the community. This approach included grid import costs and trading costs while considering the grid constraints and was tested with data from an existing P2P community. The results showed that including these equations in the market mechanism resulted in less energy being imported from the grid during peak hours, due to higher prices but also to congestion issues that could occur.
- **DSO operation:** other alternative is to model the branch equations as capacity and equality constraints. Then when the transactions were going to be cleared in the P2P platformed, the DSO intervened and curtailed any transactions that did not comply with the stablished constraints. Moreover, the DSO guided the transactions for the following trading period by providing information on how to participants could clear the market without overloading already congested lines [20].

4.6 NETWORK TARIFFS

Up to date, network usage fees consisting of volumetric charges are the prime method to ensure cost recovery of the distribution network. However, a larger penetration of DERs in this traditional grid present a challenge to the use of volumetric network charges. In this manner, utilities are implementing fixed, capacity or demand charges along with NEM for customers with residential solar PV, to try and avoid customer subsidization in the recovery of their distribution costs. In a similar way, system operators have implemented fixed costs for the P2P platforms that are connected to the grid, even though as it was seen in 3.4.1.2 these fixed costs do not accurately represent the grid usage of the P2P participants.

For Local Energy Markets, the network fees should allow the system operator to recover the infrastructure costs but adequately representing the usage of the network that the P2P community represents. Moreover, this network fees should also aim to reduce congestion risk by including price signals from the operator that can allow participants to behave in a certain way. Given the nature of a P2P community, and the ability and incentives they already have to shift their energy usage in respond to price signals within the community, the use of **dynamic network tariffs** could be a successful approach for these projects. With dynamics network tariffs P2P communities could be charged for a more accurate part of the infrastructure that they actually use, and be incentivized to adapt their behavior in a way that favors the distribution grid.

4.7 POWER LOSSES

The traditional system estimated power losses at the highest demand and then utilized the loss factor identified to predict total energy losses. However, with P2P platforms there is an opportunity to allocate power losses by using more accurate and advanced methods, as well as to assign power losses to the different transactions in the system.

Since there is no connection between the virtual and physical layer of a P2P network, it is difficult to allocate power losses to each transaction in the community. However, researchers have found several methods that could implement this feature.

- **Proportional Sharing Rule (PSR)**: in [21] power losses are established from prosumer to consumer in shared manner. The losses between the point of generation and the point of demand are calculated, and then they are attributed in an equal manner to both the prosumer and the consumer.
- **Day ahead scheduling for LEM**: in [22] they considered the power losses in the Low Voltage network with the optimization goal of minimizing energy purchase costs for the community. In doing so, the prosumers and consumers participating in trading were allocated with internal network losses, either between the consumer and prosumer if the trading was done within the grid, or with external losses if the exchange was done with the grid. In their results they found that by considering this power losses, participants reduced their cost by taking part in P2P trading rather than only being able to transact with the grid.

Chapter 5. OPTIMAL CHARACTERISTICS

As it has been seen on the previous sections, P2P energy trading platforms have already been implemented and studied across the world in pilot projects, models, and research, with different approaches and results. However, if these platforms want to be implemented at scale across the grid, they need to be equipped with the necessary elements to address the challenges that the inclusion of DERs presents. These elements need to adequately include these systems in the physical layer and ensure that participants obtain a fair pricing for their energy usage. Moreover, they need to be able include innovative initiatives that allow to maximize the benefits that this type of generation can present to the energy sector.

Therefore, in this section the main drivers of success for these platforms will be evaluated along with the areas that require further research and changes.

5.1 AUTOMATION

From the results from the previous projects, automation in the trading process appeared to be a necessity for the successful implementation of P2P trading. The conclusions obtained from the research show that automation was essential for mainly two reasons.

5.1.1 CONSUMERS' LACK OF PARTICIPATION

While P2P platforms aim to empower consumers by making them active participants of the energy sector, they need to consider that the average consumer cannot be on top of bidding in the market on his daily life. Results from several of the projects show that participants are not willing to be bidding actively in the energy market due to a lack of time. Therefore, platforms need to have specific preferences set by the consumers, but hen operate autonomously aiming to optimize both consumer benefit and energy efficiency in thew community. As some participants stated in [9] "the platform knows better than me when and how to bid". However, this consumer preferences should not always be respected given their lack of knowledge while setting them, what brings about the next reason.

5.1.2 CONSUMERS' LACK OF KNOWLEDGE

The average consumer barely understands the basics of energy trading, and the complexity of it can lead to make poor decisions in the trading process. This was seen in 3.4.1.4 where excess solar generation in the community was left untraded in the P2P market when there was actual demand for it, due to a mismatch between consumer and prosumer offers. This shows that even though participants' preferences should be taken into account, the platform should automatically allocate supply and demand in certain occasions if the decisions made by the participants do not support the optimality of the trading process.

5.2 ADVANCED DEMAND FORECASTING

Demand forecasting is highly paired with automation and studied right in the next section because they can provide the maximum benefit for the overall community if they work together. The benefits of advanced demand forecasting can be labeled as the following.

5.2.1 CONSUMER ENGAGEMENT

One of the main objectives of P2P energy trading platforms is to incentivize consumers to make a more efficient use of their energy, making them aware through dynamic price signals, and allowing them to actively participate in improving the overall operation of the grid. Energy efficiency is obtained by shifting demand to the periods where there is excess generation in the community, by aiding the community in reducing the amount of energy exported to the grid and reducing peak periods of demand from the grid. For this, real time and advance demand forecasting play a very important role at informing when and how to this. With devices such as the VHH from [7] consumers can know what the demand of their different appliances is in real time to make more informed decisions on their energy usage. Moreover, with advanced forecasting of the community's generation and demand of the next periods or days, consumers can be informed by set devices on when it is better to schedule their connection, for both the benefit of the consumer and the community.

5.2.2 ADVANCED FORECASTING AND AUTOMATION

Pairing these elements together can create a truly autonomous energy efficiency schedule that acts as a local demand-response for the community. With new appliances that include features such as operation scheduling and smart connectivity, a connection can be made between the demand and generation leveraging the platform. In this manner, users can set certain preferences for the connection of their appliances (time period restrictions), and then the platform can automatically use these preferences and connect the appliances when it is most beneficial both for the consumer and the community.

5.3 LOCATION

DERs have the capacity of bringing the generation close to the demand points, opening the possibility to reduce transmission losses and network infrastructure investments. However, these benefits can be better observed in certain areas than others, that is why the location of the projects plays a key role in determining these benefits.

One of the main drivers for success of the Brooklyn Microgrid project analyzed in 3.3 is its location. This project was developed in a part of NYC grid that was very close to its capacity limits, and that regularly suffered outages due to weather conditions and mismatches in generation and supply. By implementing a P2P trading platform and a microgrid in this context, the project was able to alleviate the grid and to provide consumers a more reliable source of generation.

Therefore, prior to developing these projects it is smart to perform a Hosting Capacity Analysis of the grid, to better understand the potential benefits that DERs can present in set location.

5.3.1 HOSTING CAPACITY ANALYSIS

A hosting capacity analysis (HCA) consists of an evaluation of the grid's capacity to securely accommodate DERs without threatening the grids stability, reliability or quality of service. With this analysis utilities can determine the threshold for the maximum capacity of DERs that can be installed in a certain point or feeder.

The HCA considers the following factors to determine the degree of availability for Der penetration in a certain territory:

- **Grid infrastructure**: analysis of the existing grid infrastructure considering distribution lines, substations and transformers, to evaluate how additional DERs will affect voltage levels, loading regulation and fault protection.
- **Voltage levels**: ensuring additional DERs do not cause voltage levels to violate the stablished limits affecting the quality of supply.
- **Power quality**: it evaluates the impacts on harmonics and frequency stability that can endanger power quality.
- **Grid stability**: assesses impacts on frequency control, voltage stability, and system resilience.

5.3.2 LOCATION INCENTIVES

With the HCA performed DERs can help the overall grid infrastructure in the areas where this is needed. To encourage further DER adoption, utilities currently use Performance Based Incentives (PBIs) and Capacity Based Incentives (CBIs) on their FIT and NEM tariffs, that provide additional benefits to users who install new DERs. These incentives usually represent rebates on equipment or extra revenue on energy sent back the grid.

In the context of P2P platforms this could be utilized to encourage the development of these projects in the areas where they are needed. In this manner, it has been observed in this project that fixed costs from the grid in the P2P platforms are one of the main parameters that will determine the success of a platform. Therefore, reducing these fixed costs in projects that are developed according to the HCA analysis, will act in a similar manner as the PBIs and CBIs based on location. Therefore, helping both the grid and the participants of the P2P market.

5.4 ELECTRIC VEHICLES

The use of electric vehicles has grown rapidly in the past years, and it is set to continue this path for the coming years. While these vehicles allow for a carbon emission free transportation, they have a high energy consumption from the grid, that if not managed properly can create undesired peaks in demand, specially with Direct Current Fast Chargers (DCFC). However, if managed in an efficient manner leveraging P2P platforms, they can provide benefits to overall grid stability and be used as demand response.

5.4.1 CHARGING SCHEDULE

While it seems obvious that if EVs are connected to the P2P platform they could help absorb the excess solar generation that occurs at midday, this does not align with consumer preferences related on when to charge their vehicles, especially when focused on a residential community.

In residential communities the majority of EV owners utilize these vehicles during the day for day-to-day commutes and then charge them at night. This schedule also aligns with the objective of flattening the demand curve by shifting this high energy usage at night when the demand is at its lowest. Moreso, utilities already incentivize this behavior by offering nighttime discounted rates for EV charging like SMUD is doing in California [23].

Therefore, when it comes to P2P platforms focused on a residential community, including EVs in the P2P platform will not have a noticeable impact in the outcome of the project. However, if developing the project in the correct context, the inclusion of EV could make an impact in the overall energy efficiency usage. In [24] researchers studied the effect of consumer behavior on EV charging and how it will affect the grid. As we have mentioned before, they found that EV owners prefer and a are incentivized to charge their vehicles during nighttime, flattening the demand curve. However, another part of their study focused on daytime charging found that a large percentage of EV owners could also charge their EVs wherever they are stationed during the day (e.g. their workplace) if they were incentivized to do so in comparison with charging them at night. Moreover, they found that this type of behavior could help absorb a large part of the excess solar energy that occurs during peak solar time.

Hence, analyzing the results from this paper, it is seen that EVs could efficiently be included in P2P platforms if the projects were developed in the adequate locations. In this manner, it is proposed that to include EVs as elements of the P2P platform, these projects must be developed in places with EV charging stations that are utilized during the day, such as those in the workplace or public parking in the center of a city where customers could station their EVs during the day. Then leveraging a P2P platform developed in set area, the EV owners could take advantage of the cheap excess solar generation of the community, taking part as active participants in that community for the time that the car is going to be stationed in set charger.

A good example for this, is BMG studied previously in this project, what brings about again the importance of location for the development of the projects. As mentioned before BMG took advantage of developing its project in a grid context where it was needed, but set location is also beneficial for the inclusion of EV charging. By developing the P2P community in the heart of Brooklyn they can include participants from residential, commercial, and public backgrounds. And, in this context, this would allow for the excess solar generation from residential participants to be absorbed by the EV chargers from commercial participants or public street chargers.

5.4.2 DCFC

Direct Current Fast Chargers (DCFCs) allow EV owners to charge their vehicles relatively quickly, what makes this technology very attractive since it solves the issue of charging time when it comes to EVs. However, with the fast charge comes a high energy usage in a short period of time, what creates a high peak of demand for a reduced time. When scaled up to a larger number of DCFCs this can present a problem to grid stability if not scheduled accordingly.

In this manner, P2P trading platforms could aid in including and scheduling these demands. The use of DCFC occurs primarily during daytime at commercial or public locations with these chargers available, since at nighttime EV owners charge their vehicles at their homes with normal chargers as mentioned before. Therefore, leveraging the daytime connection of these DCFCs, they could be included as part of a P2P community focused in these areas, helping to schedule the peaks of demand that they create in periods of peak solar generation.

5.4.3 VEHICLE-TO-GRID

Along with EV chargers and DCFCs, Vehicle-to-Grid (V2G) technologies have been developed to allow Electric Vehicles to reverse their energy flow and discharge their batteries into the grid. This presents a potential use of electric vehicles to be serve as demand response in these platforms.

In the previous sections the potential of including EVs as demand response in the correct locations was studied, but V2G technology could allow these vehicles to act as generators in the same context. With these technology in place, EVs could be implemented into a P2P platform with the characteristics previously mentioned and used to serve the community in periods of peaks demand. However, very specific consumer preferences need to be considered in terms of what percentage of the battery should be left- for the EV owner to be able to use it safely.

In [23] they are studying pilot projects to include this technology as a low-cost alternative to battery storage and looking at the possibility of including them in a VPP. However, one of the main challenges these projects face is how to consider each customers' preference on the amount of battery storage that needs to be left for the EV owner to be able utilize its vehicle safely. In this context, a P2P platform could be a potential easier solution, since each participant of the platform can stablish its preference that will be recorded and considered in the ledger at the time of scheduling the transactions.

5.5 PROSUMER - CONSUMER RATIO

5.5.1 ENERGY AUTONOMY

The prosumer-consumer ratio is a parameter that will play an important role in defining the energy autonomy of a P2P community. When the P2P community consists solely of solar PV, the prosumer-consumer ratio should not be very high to avoid exporting excess energy to the grid during hour of peak solar generation. However, if the community has sufficient battery storage a high prosumer-consumer ratio can improve the energy autonomy of the community, allowing prosumers to power the batteries leveraging the excess generation at midday, and provide energy to the other participants at peak demand time when there is no solar generation available.

5.5.2 REVERSE FLOWS

In addition, when implementing a P2P community or any type of system that includes DERs in residential areas, it is important to consider the total demand that is connected to the feeder of that area. When a prosumer has excess solar generation, it will pour it to the grid so that it is absorbed by rest of consumers connected in that area, but if this generation and demand is not managed properly it can create reverse flows in the grid that can be difficult to manage and even dangerous for grid stability and reliability. The main parameter needed to consider is the total DER generation and consumer demand behind the feeder, since the main problems for the grid arise when the reverse flows go beyond the feeder for the community. Therefore, for the community to be safe on the grid it needs to consider that the peak solar generation should roughly equal the total demand at that moment accounting for all the DERs and consumer connected to the same feeder.

5.5.3 RATIO ANALYSIS

5.5.3.1 PV capacity study

To stablish the optimal prosumer-consumer ratio in a P2P community the peak solar generation should be roughly equal to the total demand at that moment, accounting for all the DERs and consumers that are connected on the same feeder.

To analyze this parameter, this section will focus on the state of Florida, and will analyze the correct prosumer-consumer ratio that a P2P community with only solar PV must have in this area.

To conduct this study several residential roof top models have been developed on Helioscope to observe the daily generation of these systems, along with the daily average residential demand curves in Florida that were obtained from [25]. The models developed on Helioscope were 5 kW DC systems composed of 305 W panels, and a further description of the parameters and models is given in ANEX I: HelioScope modeling.

In Figure 9 the monthly generation of this solar system can be observed, and along with Figure 10, the months chosen for the study can be selected. Therefore, considering these two sets of data, the months selected for the study are January, March, May, and July, since they are considered representative periods of the year given both their solar generation and daily demand curves.

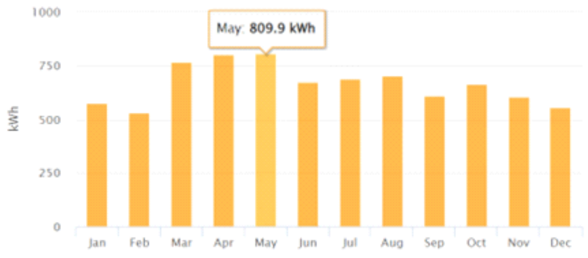


Figure 9. Monthly generation of a 5kW DC solar system

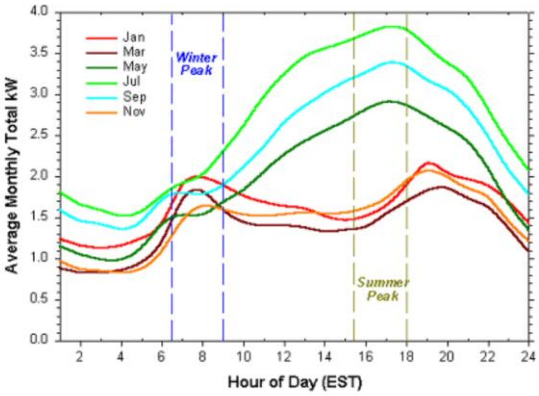
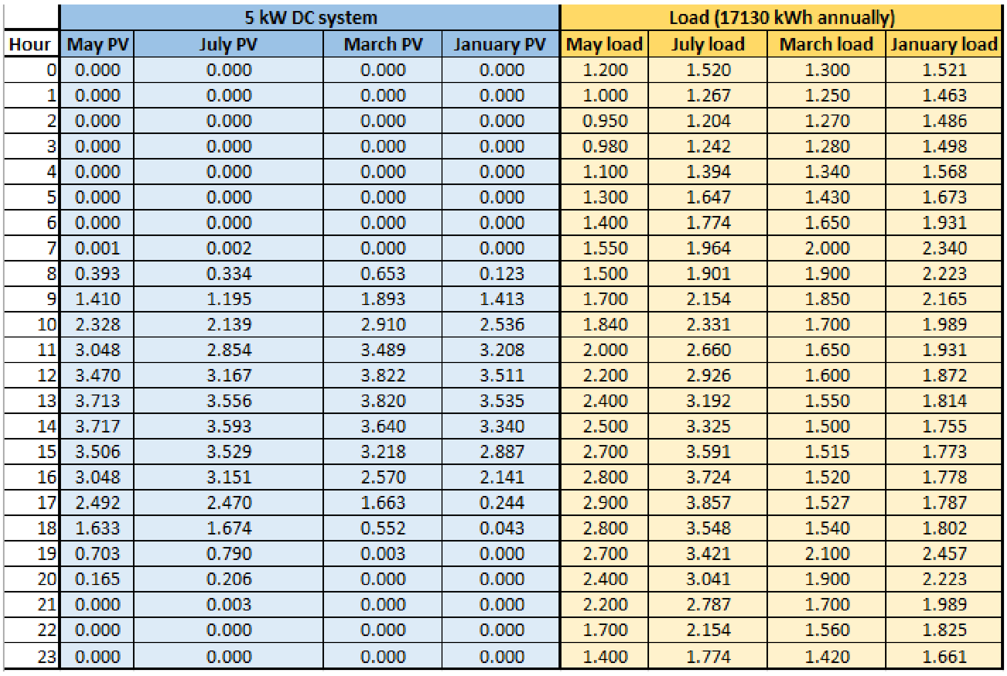


Figure 10. Daily average residential demand curve in Florida

To analyze the difference between daily solar generation and daily demand, the hourly models on Figure 11 were developed using Helioscope and the information from [25].



	5 kW DC system				Load (17130 kWh annually)			
Hour	May PV	July PV	March PV	January PV	May load	July load	March load	January load
0	0.000	0.000	0.000	0.000	1.200	1.520	1.300	1.521
1	0.000	0.000	0.000	0.000	1.000	1.267	1.250	1.463
2	0.000	0.000	0.000	0.000	0.950	1.204	1.270	1.486
3	0.000	0.000	0.000	0.000	0.980	1.242	1.280	1.498
4	0.000	0.000	0.000	0.000	1.100	1.394	1.340	1.568
5	0.000	0.000	0.000	0.000	1.300	1.647	1.430	1.673
6	0.000	0.000	0.000	0.000	1.400	1.774	1.650	1.931
7	0.001	0.002	0.000	0.000	1.550	1.964	2.000	2.340
8	0.393	0.334	0.653	0.123	1.500	1.901	1.900	2.223
9	1.410	1.195	1.893	1.413	1.700	2.154	1.850	2.165
10	2.328	2.139	2.910	2.536	1.840	2.331	1.700	1.989
11	3.048	2.854	3.489	3.208	2.000	2.660	1.650	1.931
12	3.470	3.167	3.822	3.511	2.200	2.926	1.600	1.872
13	3.713	3.556	3.820	3.535	2.400	3.192	1.550	1.814
14	3.717	3.593	3.640	3.340	2.500	3.325	1.500	1.755
15	3.506	3.529	3.218	2.887	2.700	3.591	1.515	1.773
16	3.048	3.151	2.570	2.141	2.800	3.724	1.520	1.778
17	2.492	2.470	1.663	0.244	2.900	3.857	1.527	1.787
18	1.633	1.674	0.552	0.043	2.800	3.548	1.540	1.802
19	0.703	0.790	0.003	0.000	2.700	3.421	2.100	2.457
20	0.165	0.206	0.000	0.000	2.400	3.041	1.900	2.223
21	0.000	0.003	0.000	0.000	2.200	2.787	1.700	1.989
22	0.000	0.000	0.000	0.000	1.700	2.154	1.560	1.825
23	0.000	0.000	0.000	0.000	1.400	1.774	1.420	1.661

Figure 11. Hourly models for daily solar generation and demand

Using Excel with the hourly data obtained the graphs from Figure 12 and Figure 13 were plotted to visualize the generation and demand during summer and winter seasons.

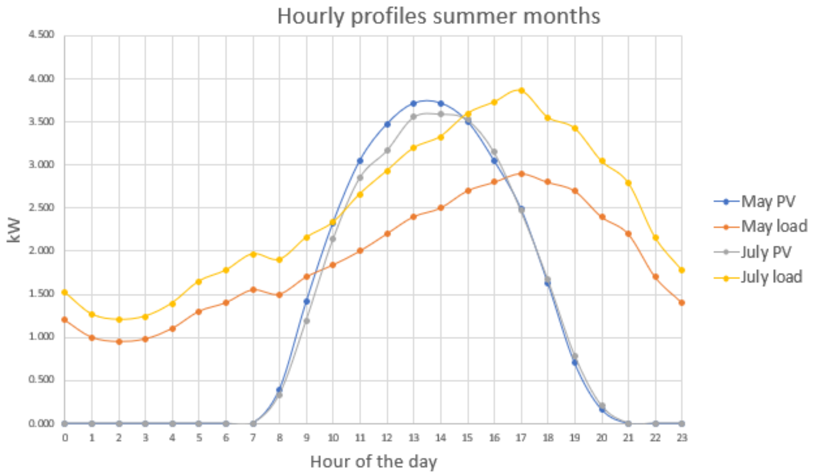


Figure 12. Hourly solar generation and demand curves in summer

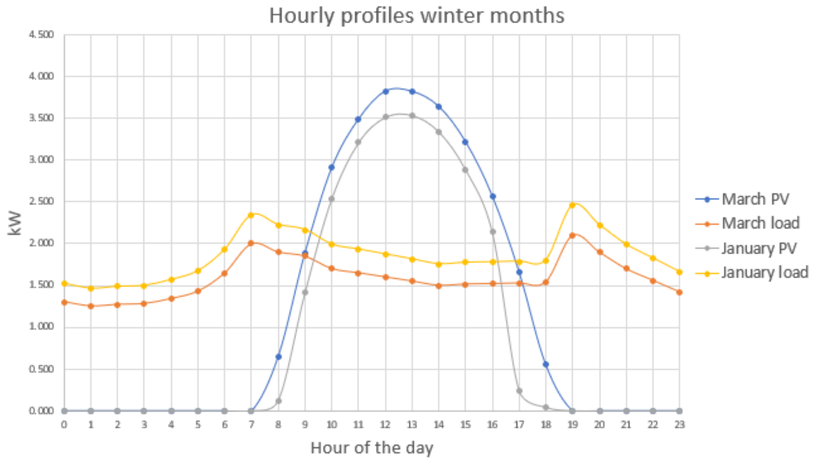


Figure 13. Hourly solar generation and demand curves in winter

The analysis shows that the excess solar generation is more critical in the winter, since it coincides with a period a low demand, and the demand from the consumers is much lower in general. On the other hand, in the summer the excess solar generation is not that noticeable given the higher demand and the fact that the peak demand is more coincident with this time.

Therefore, this shows that the prosumer-consumer ratio should be stablished for the winter season if the goal is to avoid excess solar generation to be absorbed by the grid. However, even though this would avoid reverse flows of energy, the community would be less energy autonomous during the summer months, where the peak demand better coincides with the peak solar generation. Therefore, when stablishing this parameter, these contradicting views should be considered, and a further study should be carried on how to handle these reverse flows of energy in the winter season, if the systems are sized to leverage all the energy during the summer season.

This said, with the information from the graphs it is deducted that to avoid excess solar generation the P2P community should install 2.5 kW DC of solar per participant. It is important to note that this refers to the ratio that must be respected prior to the feeder, so if a P2P community expands across customers connected to different feeders, this should be taken into consideration.

5.5.3.2 PV orientation study

Another important parameter to consider is the panel orientation. PV panels are usually installed in south configuration to yield the maximum annual production. However, even though installing the panels in a south configuration yields a slightly lower total annual generation it can have several benefits.

Firstly, the monthly generation of south facing panels is more evenly distributed during the year, while with west facing panels, the generation in the winter months is reduced as it can be observed in Figure 14. This helps with the critical excess generation that happens in this season, as it was seen on the previous section.

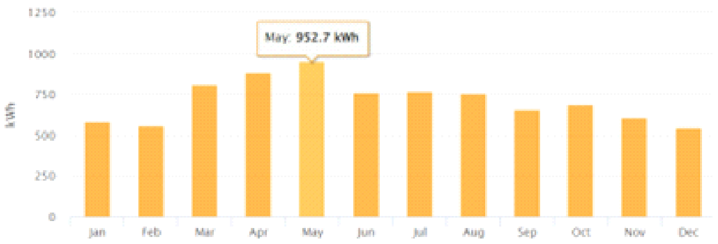


Figure 14. Monthly generation of west PV configuration

Secondly, west facing panels move the daily generation slightly to the right, causing more generation in the later hours of the day and less in the earlier ones. While this does not matter for the traditional Feed in Tariffs, since they do not consider the time value of energy and compensate all generation at the same price, it is important for a P2P system. As it can be seen on Figure 15 and Figure 16, the daily generation curve for the west orientation is better aligned with the demand peak in the summer, although it does have any effect in the winter. And this is important for the following reason:

- **Reverse energy flows**: by aligning better the peak solar generation with the peak demand it is ensured that the solar generation is better utilized.
- **Demand shifting**: P2P platforms aim to encourage consumers to shift their demand to periods where there is P2P trading available (solar generation) incentivized by lower prices. Therefore, even though the time of peak generation will still not coincide with the time of peak demand, it will require a smaller effort from consumers to shift demand to these periods since there are closer to their usual peak demand time.

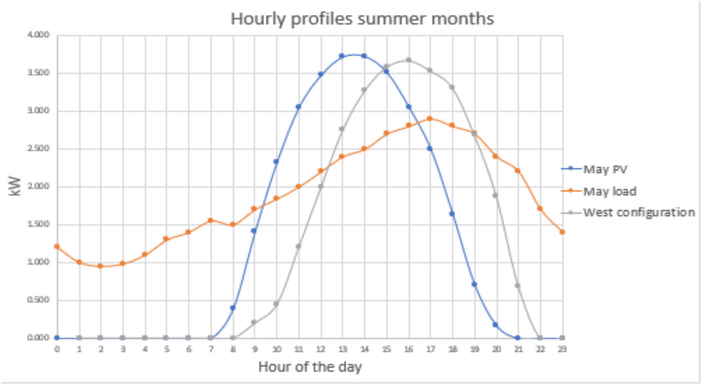


Figure 15. Hourly curves for west PV configuration in summer

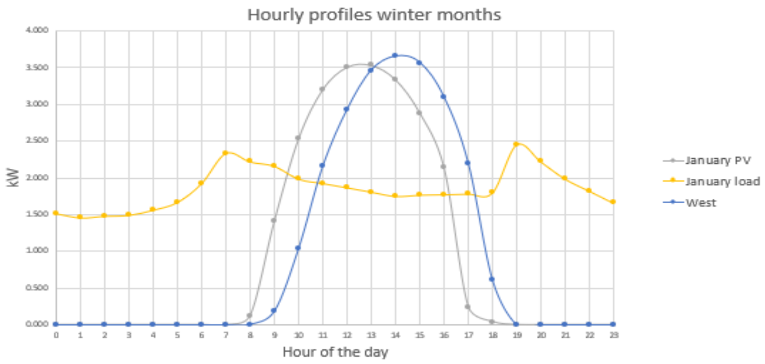


Figure 16. Hourly curves for west PV configuration in Winter

5.5.3.3 Battery capacity analysis

To increase the prosumer-consumer ratio avoiding reverse flows across the feeder, the most critical period should be studied. This occurs in March, where the difference between load and peak solar generation is the largest. Therefore, to increase the prosumer-consumer ratio ensuring no excess solar energy is exported outside the community during any period of the year, the battery should be sized to be able to absorb the energy represented on the striped area in Figure 17. These calculations are done considering a 5 kW DC PV system, and would be for a solely prosumer community, however the size of the solar systems and the percentage of the prosumers will vary with the characteristics of the community, but his results can be used as a base calculation. Considering the curves represented below, the parameters for the battery should be the following:

- 2.5 kW peak battery per 5 kW DC system installed prior to the feeder.
- 13 kWh of storage capacity per 5 kW DC system installed.

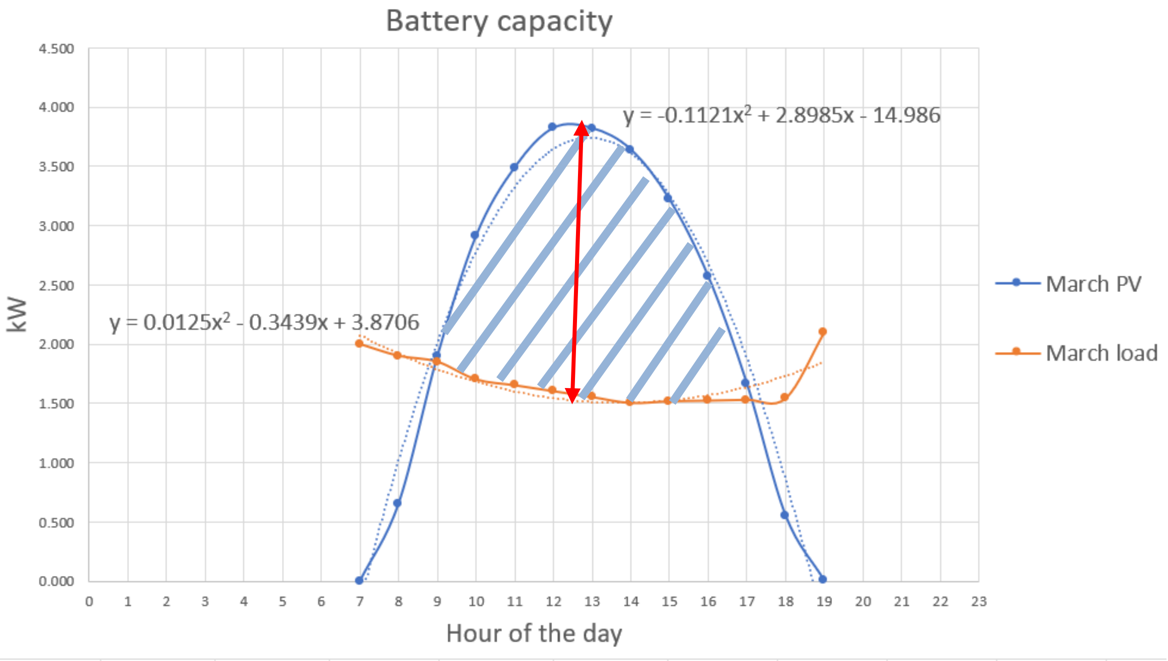


Figure 17. Battery capacity analysis

It is important to note that these calculations are done to avoid any type of reverse of flows across the feeder during any season of the year. However, sizing the systems in this manner will lead for them to be underutilized during the summer season, what in turn leads to lower ROI on the PV and battery. Therefore, the systems should be sized taking into account all of these considerations.

5.6 VIRTUAL POWER PLANTS

The prosumer-consumer ratio is an important parameter in the implementation of this projects to ensure that there is not an excessive solar generation at midday compared to the demand of the community. A potential solution to this prosumer-consumer is to provide the community with battery storage to absorb the excess generation at midday and provide it at periods where it is needed. However, battery storage is not cheap, and the payback periods are often long when the consumer is aiming to maximize his own benefit and energy efficiency. Thus, the concept of Virtual Power Plants is introduced to incentivize the use fo battery storage.

Virtual Power Plants and their implementation in P2P systems will be studied in further detail in 6.1, but in summary, VPPs are a way of providing battery storage owners and additional source of revenue by operating their batteries to serve the communities efficiency, rather than the owner's efficiency. In this manner, battery owners are said to increase their revenues in comparison with the normal operation, what reduces the payback periods and incentivizes consumer to acquire these devices.

In [9] a simulation using battery storage in a community as a VPP was carried out and found that the additional source of revenue provided to the battery owners incentivized the adoption of this technology as well as the energy autonomy of the community. In this next section, the return on investment of these systems will be studied to analyze the economic impacts on the individual consumers.

5.6.1 ROI OF A VPP: CASE STUDY – RENEW NEXUS

The report from [9] offers details and information on the different parameters of the study. However, this section will focus on the economic impact that the VPP implementation has on an individual battery owner. For this, the participants that owned a 5 kW PV system and 10kWh battery storage system will be considered, and the data on the revenue and pricing will be taken from the project's report.

The project report provides information on the benefits and costs of investing in a battery to store the energy generated by the PV modules. An investment feasibility study will be developed by calculating the ROI, the Payback and the Net Present Value of the investment.

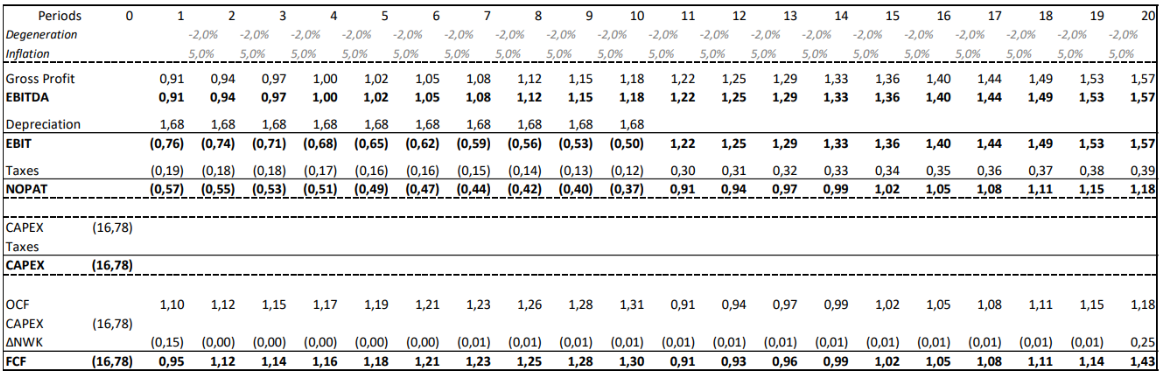
The report provides the following information:

- Cost of the battery: $11,775
- Profit in year 1 from the sale of the energy, and savings compared to what was paid in the pool under market conditions: $1470.

The following assumptions have been made:

- 5% inflation is expected.
- The investment is expected to at least match inflation. Therefore, the WACC will be 5%.
- The annual energy cost increase will be proportional to inflation.
- The lifetime of the battery and panel is 20 years.
- There is a degradation of the modules and battery of 2% per year.
- Cost of the modules: $5,000
- 25% tax, 10-year project payback

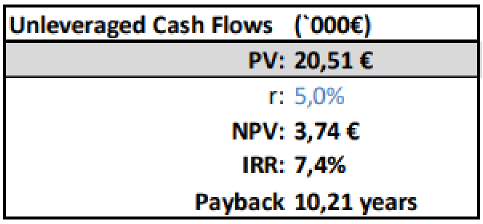
The analysis was done using a DCF (Discounted Cash Flow) model in Excel. A screenshot of the model can be seen in Figure 18.



Periods	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Degeneration		*-2,0%*	*-2,0%*	*-2,0%*	*-2,0%*	*-2,0%*	*-2,0%*	*-2,0%*	*-2,0%*	*-2,0%*	*-2,0%*	*-2,0%*	*-2,0%*	*-2,0%*	*-2,0%*	*-2,0%*	*-2,0%*	*-2,0%*	*-2,0%*	*-2,0%*	*-2,0%*
Inflation		*5,0%*	*5,0%*	*5,0%*	*5,0%*	*5,0%*	*5,0%*	*5,0%*	*5,0%*	*5,0%*	*5,0%*	*5,0%*	*5,0%*	*5,0%*	*5,0%*	*5,0%*	*5,0%*	*5,0%*	*5,0%*	*5,0%*	*5,0%*
Gross Profit		0,91	0,94	0,97	1,00	1,02	1,05	1,08	1,12	1,15	1,18	1,22	1,25	1,29	1,33	1,36	1,40	1,44	1,49	1,53	1,57
EBITDA		**0,91**	**0,94**	**0,97**	**1,00**	**1,02**	**1,05**	**1,08**	**1,12**	**1,15**	**1,18**	**1,22**	**1,25**	**1,29**	**1,33**	**1,36**	**1,40**	**1,44**	**1,49**	**1,53**	**1,57**
Depreciation		1,68	1,68	1,68	1,68	1,68	1,68	1,68	1,68	1,68	1,68										
EBIT		**(0,76)**	**(0,74)**	**(0,71)**	**(0,68)**	**(0,65)**	**(0,62)**	**(0,59)**	**(0,56)**	**(0,53)**	**(0,50)**	**1,22**	**1,25**	**1,29**	**1,33**	**1,36**	**1,40**	**1,44**	**1,49**	**1,53**	**1,57**
Taxes		(0,19)	(0,18)	(0,18)	(0,17)	(0,16)	(0,16)	(0,15)	(0,14)	(0,13)	(0,12)	0,30	0,31	0,32	0,33	0,34	0,35	0,36	0,37	0,38	0,39
NOPAT		**(0,57)**	**(0,55)**	**(0,53)**	**(0,51)**	**(0,49)**	**(0,47)**	**(0,44)**	**(0,42)**	**(0,40)**	**(0,37)**	**0,91**	**0,94**	**0,97**	**0,99**	**1,02**	**1,05**	**1,08**	**1,11**	**1,15**	**1,18**
CAPEX	(16,78)																				
Taxes																					
CAPEX	**(16,78)**																				
OCF		1,10	1,12	1,15	1,17	1,19	1,21	1,23	1,26	1,28	1,31	0,91	0,94	0,97	0,99	1,02	1,05	1,08	1,11	1,15	1,18
CAPEX	(16,78)																				
ΔNWK		(0,15)	(0,00)	(0,00)	(0,00)	(0,00)	(0,00)	(0,01)	(0,01)	(0,01)	(0,01)	(0,01)	(0,01)	(0,01)	(0,01)	(0,01)	(0,01)	(0,01)	(0,01)	(0,01)	0,25
FCF	**(16,78)**	**0,95**	**1,12**	**1,14**	**1,16**	**1,18**	**1,21**	**1,23**	**1,25**	**1,28**	**1,30**	**0,91**	**0,93**	**0,96**	**0,99**	**1,02**	**1,05**	**1,08**	**1,11**	**1,14**	**1,43**

Figure 18. DCF analysis of the ROI of a PV and battery storage participating in a VPP

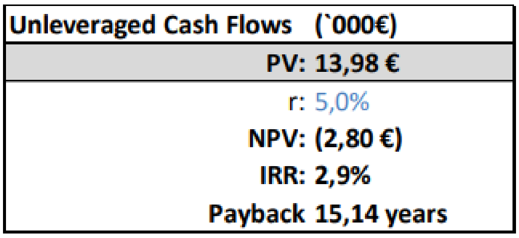
The results of participating in the VPP are the following:



Unleveraged Cash Flows (`000€)	
PV:	**20,51 €**
r:	5,0%
NPV:	**3,74 €**
IRR:	**7,4%**
Payback	**10,21 years**

Figure 19. Results of DCF (VPP participation)

Analyzing the results obtained, it is clear that the investment would be clearly profitable. However, in the case of not counting on the income provided by the energy exchange with the VPP, only a profit of $913.86 per year would be achieved. Thus, the following results would be obtained:



Unleveraged Cash Flows (`000€)	
PV:	**13,98 €**
r:	5,0%
NPV:	**(2,80 €)**
IRR:	**2,9%**
Payback	**15,14 years**

Figure 20. Results of DCF (no VPP participation)

From this analysis, it can be observed that the participation in the VPP provides an additional source of revenue for the PV and battery storage owners, what in turn provides a higher ROI on the system, what will further incentivize the investment on them.

5.7 RATE STRUCTURES

The main challenge for P2P communities is their interaction with the grid. These communities aim to empower prosumers and provide a more autonomous operation of the energy in the community. However, in most projects these communities still strongly rely on the grid on the grid for demand and supply balancing, what in turn, requires a network tariff for this service. How this network tariff is set will have a huge impact in the outcome of the P2P, and finding the correct rate structure for this project is still a matter in need for a solution.

5.7.1 FIXED COSTS

In 3.4.1.2 the effect of setting high fixed costs was observed. This resulted in consumers not being incentivized to use energy efficiently and made the project profitable only for the participants with a very high energy usage. If this is carefully analyzed, the fact that the users with the highest energy demand were the only ones that could profit from the platform, shows that the transaction costs of the Blockchain were not the drivers of failure, but the fixed costs were.

The fixed costs were set based on the average consumer of the SWIS system with a demand 11.5 kWh per day. Then a fixed charge was created for every participant independent of their energy usage, what led to losses in every participant that had a lower consumption than the average and favored the higher consuming participants. This shows that there is a need to find a way of setting network and capacity costs that better reflect the actual usage of the participants of these P2P platforms. For this matter, it is proposed that these fixed network tariffs are changed to dynamic network tariffs that account for the time and locational value of energy.

5.7.2 INCENTIVIZING DEMAND SHIFT

Dynamic network tariffs that account for the time value of energy have been widely implemented by utilities to incentivize users to use energy in periods of low demand, and some have obtained impressive results in shifting demand to off-peak periods. Moreover, research done by the EPA [26] found that when pairing this type of tariffs with information/technology the effects on peak reduction are noticeably increased, as it can be observed in Figure 21. This shows a great opportunity for P2P, since by participating in these communities, consumers already possess the technology and information necessary in the P2P platform. Moreover, with advanced demand forecasting and automation technologies such as the ones seen in 5.2, these benefits can be easily achieved.

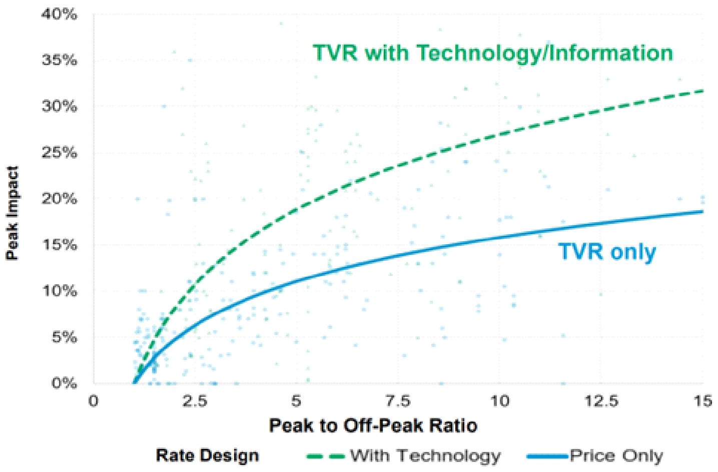


Figure 21. Effect of TVR rates on peak demand

5.7.3 INCENTIVIZING SOLAR CONSUMPTION

While TVRs have the capacity to move demand to off-peak periods, in the context of DERs it is important to consider the periods where there is excess solar energy, and the need of moving the demand to these specific periods.

Utilities currently use NEM or FIT to compensate solar generation, what does not correctly incentivize customers to shift their energy usage to these periods, since they are not able to take advantage of the cheap solar generation that occurs at this moment. On the other hand, P2P communities incentivize customers to shift their energy usage to these periods due to the cheap price of P2P traded energy. This promotes two benefits, soaking up excess solar generation and reducing peak demand.

In {Renew Nexus} a survey was conducted to ask participants if the shifted their energy usage to periods of excess solar generation, and it found that more than 50% of them did, Figure 22. This shows that P2P promotes consumer engagement through price signals. However, even though they are compensated for this effort with cheaper generation at those moments, they are still charged by the grid at the same price as the participants that did not shift their demand, what does not show the actual usage of the grid that these participants make. Therefore, there is a need to quantify and compensate this behavior, for what demand charges are proposed in the next section.

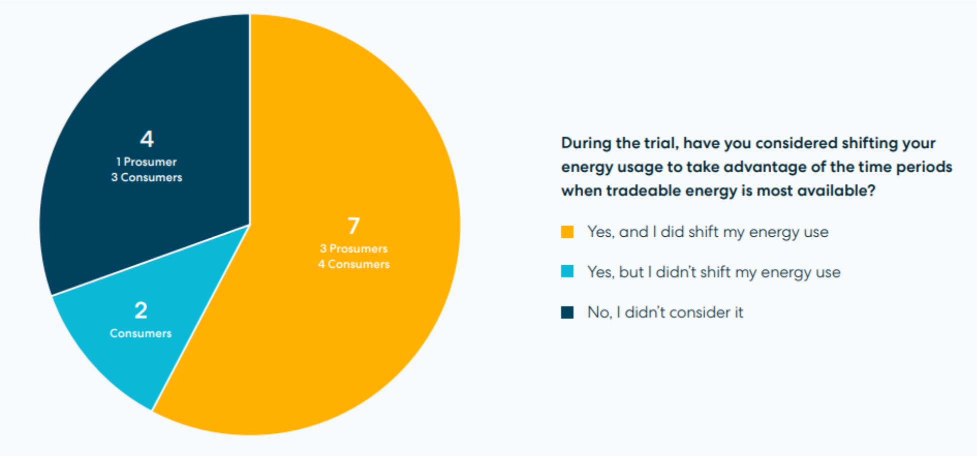


Figure 22. Renew Nexus: energy shift survey.

5.7.4 DEMAND CHARGES

The main benefit of DERs and P2P communities is their potential to reduce infrastructure investment by bringing the generation closer to the consumption. However, if these technologies are not managed and compensated accordingly these benefits will not be realized, and DERs will just result in adding more strain to the grid.

It was seen in the previous sections that using high fixed charges hindered the performance of these projects. However, if these projects need the grid for balancing and supply when there is no local generation, they need to be charged accordingly. Therefore, to charge these customers accordingly and to help realize the benefits of DERs mentioned in the previous paragraph, a Demand Charge rate structure is proposed.

Demand charge rate structures implement a specific charge proportional to the highest demand of the customers at the time of peak demand, and then charge the rest of energy used on base tariff. This can be beneficial for P2P platforms in several ways.

Firstly, it will encourage users to shift their energy usage off the peak period due to these charges, and on to the times were there is excess solar generation incentivized by the low price in those moments. By doing this, consumer will actually reduce the total peak demand from the community, what is said to be one the main benefits of P2P platforms.

Secondly, they will be charged based on their actual usage of the grid. The electric network is designed to meet the largest demand that occurs at the end of the line, therefore if this demand is reduced, the need for network upgrades will be avoided or postponed. So, charging customers with demand charges will effectively represent the part of the electrical infrastructure that they utilize.

In summary, utilizing Demand Charges incentivizes P2P participants to reduce peak demand, what in turn realizes the main benefit of P2P communities and charges customers according to their actual usage of the network.

5.7.5 LOCATION INCENTIVES

The benefit of DERs is that they bring generation close to the demand, and P2P communities incentivize the local energy consumption. The grid has parts that are more constrained than others, what can be studied using a HCA as it was seen in 5.3.

Chapter 6. ADDITIONAL STRATEGIES TO P2P

In this project the potential and challenges that P2P platforms present have been analyzed, and it has been seen that although these systems can benefit the grid in different manners, they still need to be optimized if they want to be implemented at scale. Furthermore, the importance of battery storage in these projects has been identified as an essential element to solve the prosumer-consumer ratio problem and avoid creating an excess solar generation peak at midday. Moreover, in this context the concept of VPP was briefly introduced in some of the projects to allow prosumers to realize an additional value stream for the battery and PV systems. Consequently, in this section the concept of creating a Federated Power Plant (FPP) will be analyzed and proposed as an additional strategy to help existing P2P platforms maximize their benefits. Therefore, the concept of unifying a VPP and P2P will be studied to create a FPP as a more optimal model of these platforms.

6.1 FEDERATED POWER PLANTS

The coordination of DERs at the local level can yield substantial benefits, such as enhancing network efficiency and improving energy security. This coordination can be achieved through the concept of virtual power plants (VPPs). A VPP is a platform where multiple DERs are organized to have quantifiable and manageable effects on the power grid's transmission level, by incorporating demand response aggregators, which concentrate on optimizing flexible loads.

However, in the context of VPPs, important institutional and economic problems are still unresolved. Existing VPP coordination solutions need a top-down design and implementation that is managed by a single organization that establishes the guidelines for VPP functioning. Conversely, as it would conflict with their current operating models, the electrical market participants who are best positioned to implement these platforms may not be motivated to set up a socially optimal degree of DER involvement, since individual prosumers are the participants that have the strongest incentives to maximize the value of the DERs they currently possess.

Therefore, to efficiently aggregate DERs so that they can participate as whole in the grid, the concept of Federated Power Plants (FPPs) is proposed, which consists of a VPP made up of P2P transactions between individual prosumers.

6.1.1 VPP COORDINATION

The type of DERs that may be included, their operation, and the services they can deliver depend on the approach used to coordinate them into a VPP, what directly affects the capabilities and worth of the VPP. In general, there are two types of VPP coordination strategies. Direct strategies that regulate individual DERs and indirect strategies that use incentive signals to alter prosumer consumption and generation decisions.

- **Direct coordination strategies**: DERs are under control of a VPP operator, who decided when and how much generation to dispatch from these DERs, but always within the limits of their owner's preferences and their operating parameters. This strategy allows DERs to provide frequency regulation services by giving the VPP operator certainty of the response and capacity of these elements.
- **Indirect coordination strategies**: prosumers are provided with price incentive signals, which they evaluate and then chose to consume or generate according to their preferences. This type of strategy allows prosumers to decide on the flexibility of their loads while incentivizing to do the correct thing for the overall grid. A direct illustration of this concept is time-of-use pricing. ToU is a strategy that encourages prosumers to adjust their energy consumption away from peak demand periods, aiming to decrease the need for excessive upstream capacity. Moreover, some other strategies include day-ahead hourly pricing and location-based pricing within distribution networks. With this approach, DERs can be coordinated based on their geographical location, and then consider situations where groups of distributed generation or the introduction of significant loads like electric vehicles or heat pumps might present challenges to grid management.

In order to get the required aggregate response, a VPP operator may put limitations on the net power consumption of subscribing prosumers at specific periods. This approach would be an intermediate point between direct and indirect coordination. In this context, when the costs of the communications and processing infrastructure outweigh the benefits of direct control, or when prosumers are hesitant to give a VPP operator direct access and control, indirect coordination solutions are the best approach.

6.1.2 VPP SERVICES

Along with coordination with the Distribution System Operator (DSO), VPPs with oversight over numerous DERs can offer grid-related services, encompassing participation in wholesale energy markets, transmission rights transactions, and ancillary services such as reserves or frequency regulation. Moreover, VPPs equipped with knowledge about the specific locations of their DERs within a distribution network can offer valuable grid services to DSOs for active management of the distribution network. And, by realizing a coordinated control of DERs, these services can effectively minimize energy losses, enhance voltage regulation, and prevent any breaches of thermal limits that might occur.

6.1.3 VALUE ADDED OF P2P

Coordinated deployment of complementing DERs might boost overall welfare by lowering upstream generation and transmission needs and lowering losses. Storage systems and flexible loads, in particular, can boost the local usage of fluctuating renewable sources. However, because retail power contracts individually meter prosumers, they are solely driven to alter their own demand to minimize their energy costs. As a result, DERs are used inefficiently, and prosumers do not fully benefit from the value of their DERs as a source of capacity.

- **Energy coordination**: due to the variability of load and renewable generation, active coordination is essential for scheduling storage systems and flexible loads to minimize the need for additional upstream capacity. In this manner, DERs that are owned by a single entity can be scheduled using an energy management system, but if they are owned by different prosumers, a direct application of an energy management system is not feasible. In such cases, to encourage prosumers to operate their DERs in a coordinated manner, there is a need for the development of a market mechanism that considers the individual preferences and resource characteristics of the prosumers. This is where P2P platforms can play a key role by enabling prosumers with surplus energy to negotiate mutually beneficial energy transactions with those who have complementary demand. Moreso, these platforms will account for DER capacity, flexibility, uncertainty, and network location to ensure efficient and optimal energy exchanges.

- **Minimization of uncertainty**: smaller loads and sources of renewable energy are frequently unpredictable, but when users are treated collectively, the fluctuation of electric load is considerably decreased. The generation of one kind of renewable energy will be associated with meteorological conditions in a specific location, but aggregated DERs have substantially less unpredictability if they are spatially scattered or comprise a variety of technologies.

Retail suppliers have traditionally undertaken the role of managing the risks associated with variable load-serving obligations due to the absence of smart meters. This role involves sharing the costs of uncertainty, capacity investments, and reserves, in an even manner among consumers. However, the emergence of P2P trading platforms offers a promising avenue to add value since it enables prosumers to form cooperative groups, and therefore fosters information and risk-sharing. In a particular case, research demonstrated that collective action by groups of wind power producers in wholesale energy markets can lead to increased profits due to their collaborative contracting and risk-sharing practices. And on the same way, prosumers can leverage these platforms to exchange information, what would lead to more effective group contracts with their suppliers. The benefit of P2P transactions is their ability to account for the unique contributions of each prosumer to the group's variability and their individual preferences. This can include elements such as risk aversion or desired financial returns, among many other considerations that shape the choices that prosumers make in the dynamic and adaptive environment of P2P markets.

6.1.4 OPERATION OF A FPP

The concept of the Federated Power Plant (FPP) is proposed as a way to create a Virtual Power Plant (VPP) formed through Peer-to-Peer (P2P) transactions among self-organizing prosumers. While the traditional VPPs rely on top-down institutional arrangements to harness their value, these arrangements often clash with socially optimal investment outcomes. Therefore, P2P energy-trading platforms are introduced to provide a bottom-up approach that can further evolve to facilitate transactions for grid services; with groups of prosumers forming the FPP and interacting with wholesale markets, Transmission System Operators (TSOs), generators, retail suppliers, or Distribution System Operators (DSOs).

To understand the concept of a FPP, the operation and combination of a VPP and P2P must be described. Firstly, for a VPP the prosumers would be subscribed by the VPP operator, allowing to interact with wholesale energy markets and DSOs to provide the different services that can be observed in Figure 23.

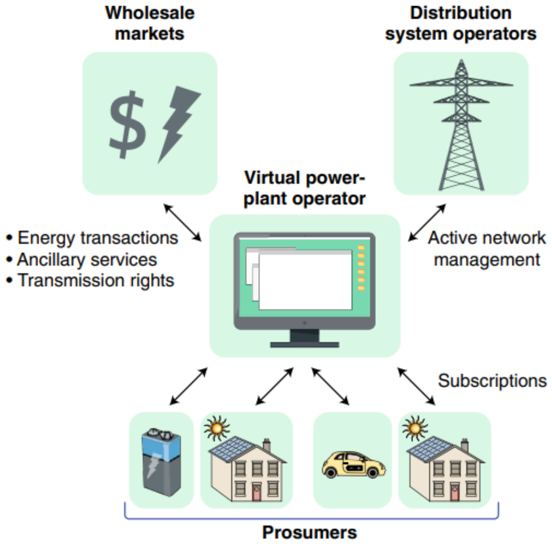


Figure 23. Transactions to form a VPP.

In addition to this VPP, the FPP must include a P2P platform so that prosumers can perform the energy trading among the community to efficiently manage their DERs and group them in a coalition to interact with a retail supplier, as it can be seen on Figure 24.

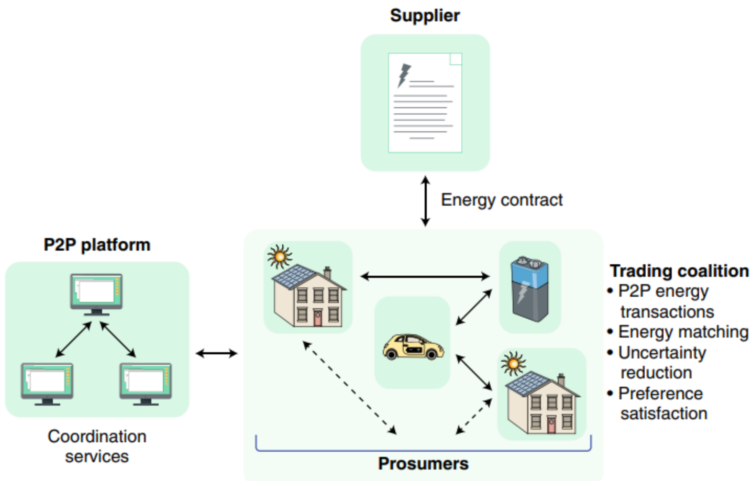


Figure 24. P2P transactions to form coalition

Then, a FPP would combine these two concepts to more efficiently manage the whole system. It would include P2P so that prosumers can trade the energy in the community, and it will encourage these P2P transactions to form a coalition to function as a FPP to interact with wholesale energy markets and DSOs.

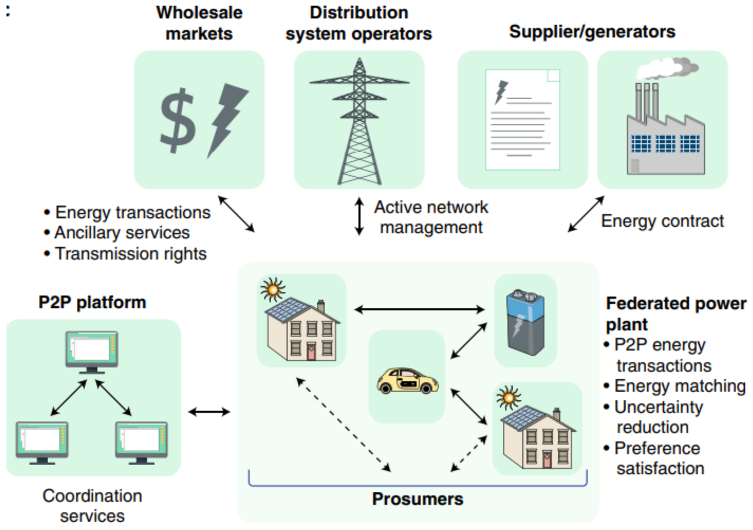


Figure 25. Operation of a FPP

In a FPP the opportunity for participants to act as a VPP is identified directly by the P2P platform that offers contracts to the prosumers so they can choose to provide grid services. Then, through the different transactions in the P2P platform the prosumers would be organized and incentivized by these contracts to provide the required grid services. The interactions of these elements can be observed on Figure 26.

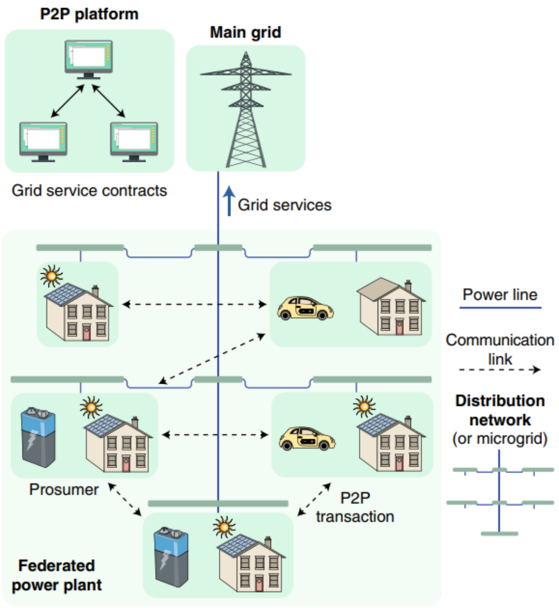


Figure 26. Interactions in the FPP

In summary, instead utilizing the traditional approaches of directly exerting control over these DERs or incentivizing individual prosumers separately, the P2P platform operates as a market facilitator. In this manner, it enables energy transactions between participating prosumers, what leads to mutually beneficial exchanges and allows the platform to identify opportunities for grid services and present them as contracts that groups of prosumers may undertake. As a result, coalitions of prosumers naturally form to fulfill these contracts.

The primary goal of the P2P market is to establish a transparent mechanism that prosumers can rely on to fairly balance their preferences and requirements, fostering trust among participants, and ensuring a system where energy exchanges are conducted in an equitable and dependable manner.

6.1.5 VALUE OF A FPP

- **Additional value for prosumers:** in the P2P energy-trading platform prosumers have the chance to create a FPP, which enables them to participate in grid service transactions similar to VPP, empowering them to enhance the allocation of their DERs effectively. This would provide new sources of revenue stream for prosumers while helping with reliability of the grid.

- **Ease the coalition formation**: utilizing P2P platforms is key in the formation of a FPP for identifying opportunities for grid services and arranging contracts for these services between groups of prosumers and upstream market participants. Moreover, P2P platforms enable the participation of prosumer groups in wholesale electricity markets, which includes both energy and ancillary services markets. It does so by advertising contracts for grid services, which can be fulfilled by coalitions of prosumers, instead of imposing top-down control on these interactions. Additionally, the platform provides the necessary communication infrastructure to facilitate these transactions and allow prosumers to naturally form trading coalitions that possess the appropriate combination of DERs to meet capacity and controllability requirements.

- **Reduce risk**: P2P informational transactions offer prosumers the means to decrease uncertainty related to their energy loads and renewable sources, and also gives them the opportunity to cooperate, allowing them to share risks. By participating in the FPP, prosumers have the opportunity to engage in long-term bilateral contracts with generators and suppliers, securing more advantageous terms compared to negotiating individually. In this process, the P2P platform assumes an essential role by providing monitoring services and establishing mechanisms for prosumers to join or leave these long-term arrangements.

- **Location and time independent service**: FPPs have the potential to offer valuable services to DSOs, by contributing in essential services required by them, like voltage regulation. However, the effectiveness of these services depends significantly on the prosumers' network location, and it may fluctuate over time due to changes in network power flows. This variability makes FPPs particularly appealing since they have the flexibility to adapt and address these changing demands effectively.

6.1.6 IMPROVEMENTS VERSUS A VPP

FPPs encompass various characteristics that tackle social, institutional, and economic challenges that have hindered the successful adoption of VPPs.

- **Easy and automated DER aggregation**: to enable the establishment of FPPs, the P2P platform promotes grid service contracts that prosumers can fulfill by forming trading coalitions. The process of creating this coalitions is envisioned as highly automated and conducted by prosumer energy management systems that utilize user preferences and information from connected DERs. To create these trading coalitions several methods have been proposed, and the next section 6.2 will analyze an energy sharing scheme that allows for the formation of these coalitions, along with the benefits and consequences of this aggregation.

- **Reduced complexity in DER coordination**: when functioning within the FPP, prosumers maintain full autonomy over their DERs and have the authority to determine their level of involvement in energy transactions. This is where P2P negotiations play a vital role. Firstly, in identifying a cohesive group of prosumers that is capable of efficiently providing grid services. And then, determining the appropriate pricing incentives to motivate their active participation. Moreover, the P2P platforms allows for the individual preferences and resource capacities of each prosumer to be considered in the decision-making. These preferences present a challenge for VPPs, since their success relies on the acquisition of this essential information from prosumers, which often incurs certain costs and requires a computationally feasible control strategy to effectively accommodate and integrate this gathered data. Meanwhile, a P2P energy-trading platform streamlines the process compared to direct VPP coordination by eliminating the necessity of designing a top-down control strategy to cater to individual prosumers' unique preferences. And, unlike an indirect VPP coordination strategy, the P2P platform doesn't require predicting prosumers' demand elasticities to determine pricing structures that will elicit the desired response from participants, since participants would do so solely by taking part in these platforms.

- **Reduced investment and barriers in coalition formation**: unlike the complex and resource-intensive setup involved in traditional VPPs, FPPs represent a more progressive phase in the evolution of P2P energy-trading platforms. In this manner, while conventional VPPs rely on assembling a large pool of prosumers to meet wholesale electricity market requirements, FPPs offer a more flexible approach by allowing for value creation even at smaller scales through direct prosumer-to-prosumer energy transactions. The lack of necessity for this upfront large coalition allows P2P energy-trading platforms to initiate its operations in a localized community by collaborating with just one retail supplier and DSO and gradually expanding its services as new subscribers join the platform. Then, as the P2P energy-trading platform grows, it can extend its capabilities to include FPP operation and eventually achieve the operational scale of a traditional VPP. Therefore, the lack of a minimum size lowers entry barriers for DER services coordinated within the FPP, what enables easier participation and fosters a gradual process of building trust and experience among prosumers. The benefit of embracing FPPs as an intermediary step in the development of P2P energy-trading platforms is that the energy market can witness more inclusive and accessible growth opportunities, facilitating a smoother transition of DERs to larger-scale VPP operations.

In conclusion, the significance of organizing DERs into VPPs is widely acknowledged as it enables the realization of their value within power systems. Simultaneously, the appeal of P2P transactions for prosumers has sparked the emergence of bottom-up P2P energy-trading platforms that offer the potential to leverage these transactions to incentivize prosumers to come together in coalitions capable of providing grid services. The FPP model exemplifies a solution that addresses these specific challenges encountered by top-down strategies in coordinating prosumer DERs into VPPs. Furthermore, it unlocks additional value for P2P energy trading by creating a synergy between the two approaches, fostering a more inclusive and efficient energy landscape, empowering prosumers to actively participate in grid services and optimizing their energy interactions within the system.

6.2 ENERGY SHARING MECHANISM FOR DER AGGREGATION

In the previous section the concept of a Federated Power Plant was introduced as a combination of a Virtual Power Plant and a P2P platform. The benefits of sharing DERs to improve grid reliability and stability were mentioned and proposed as an additional revenue stream for DER owners. Yet, creating a VPP was envisioned as complicated due to requiring a large upfront participation, and therefore, the concept of creating these VPPs through P2P platforms was introduced, as a natural way of developing these P2P systems for grid participation.

However, how to efficiently create and manage this DER coalitions remained unstudied. Hence, this section will try to answer this question and analyze the benefits that this can provide to DER owners and the grid. To do so, the focus will be on a study proposed in [27] on how DERs could form coalitions with the aggregator to provide these services and further incentivize DER adoption. Even though, the research was done involving the participation of an aggregator, the sharing scheme and compensation could be implemented into a P2P platform, and the results are valid for overall DER adoption and grid benefit. Therefore, this is proposed as incentive mechanism to encourage prosumers to share DERs for grid services, and as a way of identifying the contribution of each user for its adequate compensation.

6.2.1 ENERGY SHARING DEVELOPMENT

An innovative energy sharing scheme that assesses the advantages of sharing DERs is proposed to achieve local power balance and peak shaving. This energy sharing scheme consists of an aggregator that optimizes the utilization of shared DERs for both peak shaving and local load balance. The model created incorporates the aggregator's reliability charge, what allows to quantify the benefits derived from peak shaving.

In the model, users are considered agents making strategic investments in DERs (PV and storage), while also contemplating the option of sharing their invested DERs. This user work along with the aggregator to participate in energy and capacity markets, and the benefits of energy sharing are evaluated by comparing this scenario with another in which DERs would not be shared.

To ensure that all users have a rational incentive to invest in and share DERs, an incentive mechanism is designed leveraging a sharing contribution rate (SCR) that quantifies each user's contribution towards grid service, considering load balancing a peak reduction.

6.2.1.1 Market framework

The focus of the study is on a distribution grid scenario featuring an aggregator serving N energy users, where each one is treated as a price-taker when participating in both energy and capacity markets. To address long-term resource adequacy challenges, capacity markets have been implemented in various regions and operate alongside the energy market and conduct annual auctions.

These capacity markets are structured with a series of auctions aimed at securing resources to effectively balance the region's long-term load requirements. The process begins with a base residual auction (BRA) held three years ahead of the delivery year, and then three incremental auctions are conducted to procure additional resources that more accurately match the predicted load. In the delivery year the aggregator would first participate in the capacity market which incurs a daily reliability charge, that is calculated based on the aggregator's peak load for the day. On top of this, the aggregator need to satisfy the users' hourly loads for what he would also participate in the day ahead market.

Based, on the charges from the aggregator it can be seen that sharing DERs could decrease cost by reducing capacity charges through peak shaving and energy charges through locally produced energy. This study solely concentrates on the aggregator's involvement in the BRA and examines the decision-making process of both the aggregator and users before the delivery year. At the moment of the BRA each user strategically invests in DERs to minimize their annualized individual costs, and the aggregator implements an energy sharing scheme and an incentive mechanism to motivate users to share these DERs among the community.

6.2.1.2 Energy sharing scheme

In the absence of energy sharing, the users in this system act as price-takers, conducting their transactions solely with the aggregator, by purchasing electricity from at a predetermined retail rate and selling any surplus energy at the net metering rate (NMR). Users operates with limited knowledge about the demand or surplus of their neighbors' DERs and optimization efforts are focused on minimizing individual costs. For the aggregator, the net cost is computed by calculating the difference between the price charged for the energy provided form the grid and the total revenues obtained from the different participants.

In the case of energy sharing, a pool-based sharing platform is established, that allows users to buy or sell shared energy with a price determined by the aggregator. Prior to the delivery year users sign sharing contracts with the aggregator, defining rules for benefit allocation and each user optimizes their DER sizing and scheduling. The aggregator gathers information on users' demands and surpluses, facilitating DER sharing among them, and optimizes their operation to reduce peak demand on the community, therefore reducing reliability charges.

In this energy sharing scheme users deviate from their individual optimum to maximize the efficiency of the community and they are provided with an incentive mechanism that can identify the diverse contributions of each individual user. They are charged for net load at retail rates and compensated for surplus net energy at NMR, and then with the shared payments calculated based on their contribution to the efficiency of the community.

6.2.1.3 Incentive mechanism

In [27] the optimization problem for this energy sharing model is formulated in detail for both cases with and without energy sharing, using Lagrange optimization, asymmetric Nash Bargaining and alternating direct method of multipliers. In this section the different equations and optimization methods used will not be discussed in further detail since it escapes the scope of the project. However, this section will provide an overview of how to develop the model so that the results can be analyzed later.

The main difference between the optimization problem in both cases, is that in the energy sharing scheme the equations and constraints are focused on optimizing the overall cost of the community, while in the case without energy sharing the optimization focuses on each user's individual optimum. However, treating all users as a group to minimize total cost does not reveal the contribution of each user, and therefore and incentive mechanism needs to be designed to identify each contribution and compensate each user accordingly.

The incentive mechanism is designed based on a sharing contribution rate that can identify the contribution of each participant towards peak reduction and energy sharing. These contributions are identified in two ways, first it accounts for the user's choice of deviating from its individual optimum to consume or generate shared energy, helping reduce the overall energy cost. Then, it accounts for the user's choice of reducing load or increasing DER generation to reduce reliability charges during peak hours. In summary, this sharing contribution rate which identify the user's participation in the overall contribution to the problem optimization. To allocate these individual participations to the community benefit, they leveraged an Asymmetric Nash Bargaining model that allows to quantify the contributions and compensate them accordingly.

6.2.1.4 Decentralized solution algorithm

One of the most interesting elements of this approach is its decentralized approach in its solution algorithm, since it allows for P2P individual implementation, and aids in answering the question previously asked on how to create and manage coalitions of DERs in a P2P platform.

As it was seen with VPP, as the number of DERs continues to increase, efficiently scheduling energy sharing and fairly distributing sharing benefits among a substantial user base becomes increasingly challenging, primarily due to privacy concerns and to the fact that, unlike generators in wholesale markets, electricity users may be hesitant to engage in frequent bidding. Therefore, to address these challenges and safeguard users' privacy, this method opted for a decentralized approach and employed the alternating direction method of multipliers for this decentralized implementation. This approach ensures that energy sharing, and settlement processes are conducted in a distributed manner, promoting user privacy and mitigating the need for frequent bidding. Moreover, solving the algorithm in this individual manner allows the platform to easily accommodate new DERs in its operations, what was previously seen to be one of the main benefits of FPP compared to VPP.

This approach allows for the energy sharing optimization problem to be decomposed into a local program for the aggregator and individual programs for each user, what enables this decentralization that is sought through P2P. Then, this model can be solved in an iterative manner by coordinating all these programs, as it is show on Figure 27.

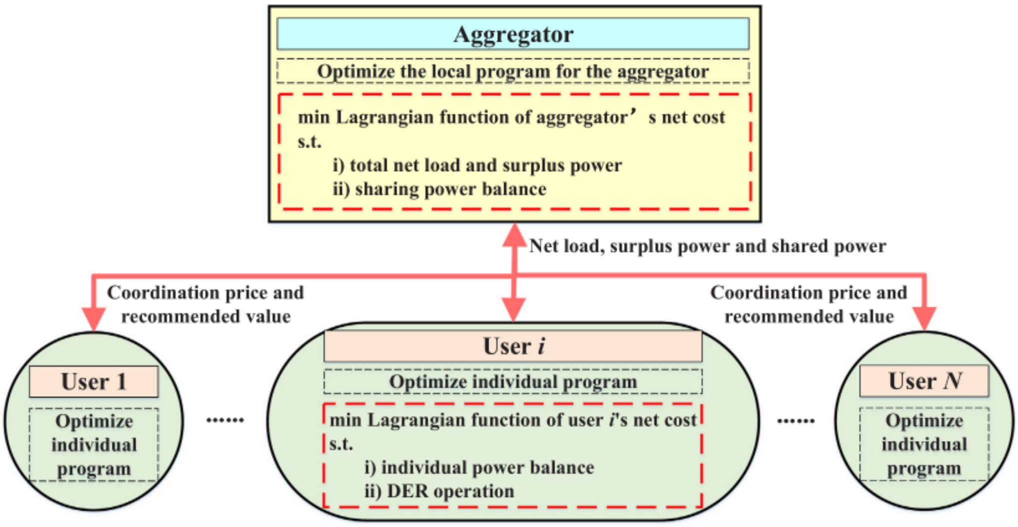


Figure 27. Energy sharing scheme decentralized solution.

6.2.2 RESULTS

Simulations of this model implementing the energy sharing scheme were carried out, utilizing real data from consumer loads, PV and storage prices, solar generation, rate structures, and energy market prices including LMPs and capacity markets from PJM.

Figure 28 illustrates the optimal capacities for solar and battery storage in both cases, with and without energy sharing. When energy sharing is implemented, the optimal capacities for solar and storage experience substantial increases, rising by more than 3 and 4 times respectively. These findings highlight the effectiveness of the proposed energy sharing scheme, since it successfully incentivizes users to invest in DERs, what results in significantly larger capacities for solar and storage compared to the case without energy sharing.

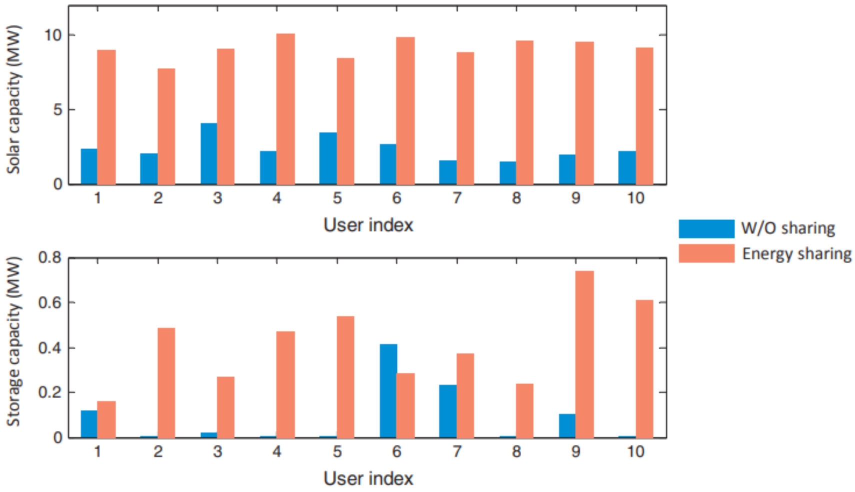


Figure 28. Optimal PV and battery capacity with the proposed energy sharing scheme

Figure 29 presents a comparison of an energy user's average power curves in the two scenarios evaluated. In the case without energy sharing, the user lacks sufficient motivation to invest in solar and storage resources due to the inability to recover the investment costs. However, in the case with energy sharing, users not only achieve self-sufficiency through their own DERs but also benefit from sharing DERs with the aggregator and neighboring users, what incentivizes a notable increase in investment in solar and storage, leading to improved DER utilization.

Due to this increase in DER adoption, the aggregator can effectively utilize the shared power to respond to the connected power grid. This can be observed in Figure 30, that illustrates the aggregator's average net power curves in both cases, showing that with the integration of more solar and storage resources, the aggregator's peak load experiences a reduction of 17.65%, what results in a reduction in the annual reliability charges for the aggregator. Additionally, with a greater number of solar resources installed, the aggregator can supply the power grid with net power during peak hours.

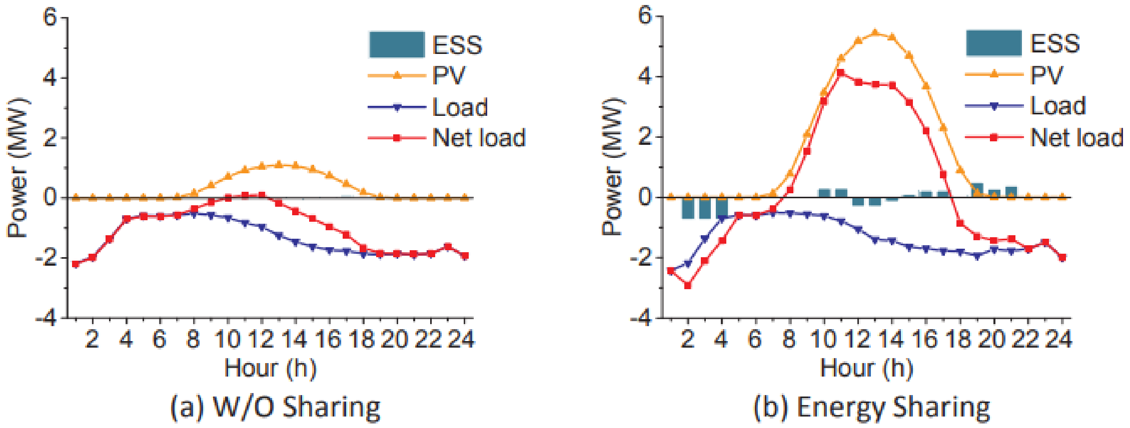


Figure 29. User's power curves with the prposed energy sharing scheme

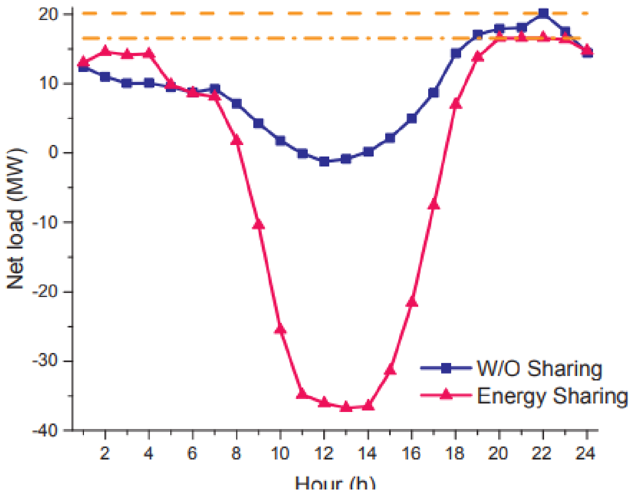


Figure 30. Aggregators net load in the proposed energy sharing scheme

6.2.3 P2P INTEGRATION

The proposed energy scheme that has been studied in this section provides the necessary tools to implement and manage the trading coalitions necessary for Federated Power Plants. By proposing a decentralized solution to the optimization problem, the platform allows to easily include new users that do not have to be accounted for in advanced, as they would be in a VPP. Moreover, it aligns with the benefits of FPPs versus VPPs regarding DER coordination and user privacy, since by solving the optimization problem for each individual user it leverages the information contained for each individual user of a P2P platform.

While the method studied was developed for interaction with an aggregator, it can be utilized for a P2P platform without the need for this third party. The P2P platform in a community could act as the aggregator, being the entity in charge of balancing total supply and demand for the community, while implementing all the trading above mentioned and interacting with the external agents that represent the grid, such as DSOs.

This methodology in P2P platforms deviates from finding each user's individual optimum in the market mechanism, and instead focuses on optimizing the efficiency of the community, what can also lead to more benefits for the participants if implemented adequately. This introduces the concept of Transactive Energy in P2P platforms, a methodology that can maximize overall efficiency and aim to better consider the physical constraints of the grid.

6.2.4 INQUIRIES ON THE ENERGY SHARING SCHEME

The results show that the energy sharing scheme has potential to incentivize DER growth, reduce peak demand, maximize the efficiency of DERs, and provide users with better compensation for their DERs. However, Figure 30 shows that even though peak demand is reduced, the generation from the aggregated DERs at midday is very large. This excessive generation can present two issues:

6.2.4.1 Reverse flows

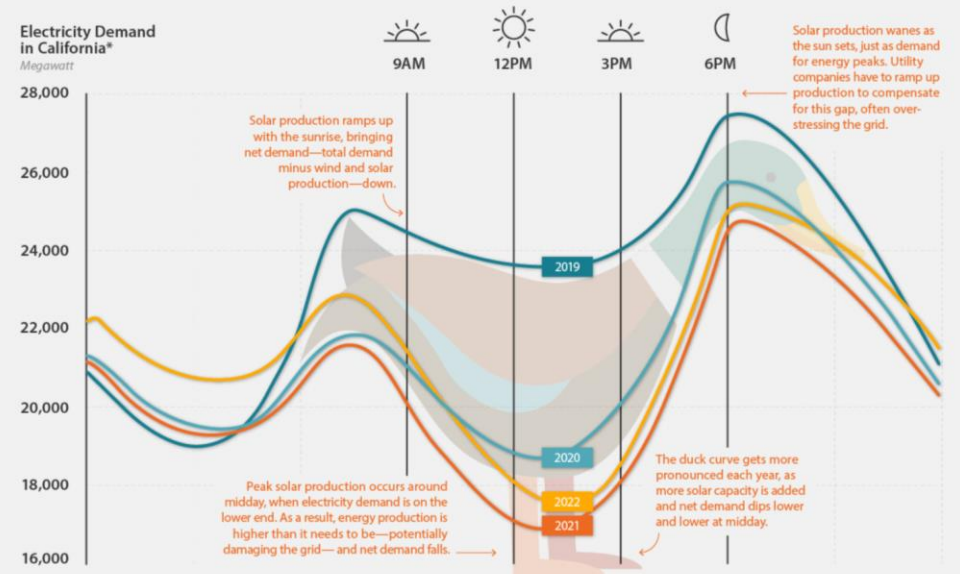
Even though it seems beneficial for the aggregator and the system to promote this renewable generation, the revers flows created can cause several issues in the grid such as voltage and frequency instability, if not handled properly. Therefore, if this initiative is implemented it needs to consider what areas the excess generation comes from.

If there is excess generation in a specific community connected to the grid, this can present issues for the grid if this generation is higher than the demand in the area prior to the feeder. Once this generation goes further than the feeder at that certain point, the reverse flows can be difficult to manage and cause instabilities in the grid. Therefore, the aggregator that groups all of these DERs to act as VPP needs to consider the location of all of them to avoid this from happening and stablish a limit on the number of DERs that should be installed per feeder, ensuring that the generation in set area will not exceed the overall consumption.

When implementing this for a P2P community, the same considerations should be made, ensuring that the generation of the community at midday is not excessive and will cause these harmful reverse flows in the grid.

6.2.4.2 Duck curve

Another problem that this approach presents is the creation of the “duck curve” that is depicted in Figure 31. Even though, the approach slightly reduces peak demand, it creates a very high peak of solar generation at midday, what reduces the generation required from other sources at this time. But, when this excess generation at midday starts to decline the other resources need to be powered, and when the difference between the peak demand at the evening and the demand not provided by solar at midday is very large, this would require a very large ramping capacity from the generators in the grid. This phenomenon is already taking place in states such as California and Texas, that have a very large solar penetration in their systems.



Solar production ramps up with the sunrise, bringing net demand—total demand minus wind and solar production—down.

Solar production wanes as the sun sets, just as demand for energy peaks. Utility companies have to ramp up production to compensate for this gap, often over-stressing the grid.

Peak solar production occurs around midday, when electricity demand is on the lower end. As a result, energy production is higher than it needs to be—potentially damaging the grid— and net demand falls.

The duck curve gets more pronounced each year, as more solar capacity is added and net demand dips lower and lower at midday.

Figure 31. The Duck Curve

Chapter 7. OPTIMAL PLATFORM DESIGN

The objective of this chapter is to summarize all the previous concepts and aim to provide some clarity into what the optimal characteristics are for a P2P platform, along with the objectives and requirements for the implementation of these elements.

From previous research and analysis, the following objectives for an optimal design have been identified:

- Economic benefit for participants: network tariffs, adequate buyback tariffs, additional sources of revenue and incentives.
- Consumer engagement: demand shifting, automation and ease of operation, advanced demand forecasting.
- Providing services to the grid: peak reduction, locational system relief, demand response.
- Grid interaction: avoiding revers flows, respecting network constraints, prosumer-consumer ratio.
- DER aggregation for maximized efficiency: FPPs.

Therefore, when designing a P2P it is important to consider the accomplishment of these objectives, and how the design of the elements that comprise the platforms will aid in this achievement. To do so, this section will summarize the previous findings of this project based on how they aim to achieve these objectives.

7.1 ECONOMIC BENEFIT FOR PARTICIPANTS

It has been seen that allowing the users of these platforms to realize an economic benefit by their participation is essential for the development of the project. And to achieve this, the following elements are considered to be of major importance.

7.1.1 RATE STRUCTURES

Since these platforms still rely on the grid for energy supply and demand balance when there is not enough energy available from P2P trading, they need to be charged accordingly to their usage of the grid. For this, it has been found that the traditional way of using fixed charges for these customers is not optimal to allow them to realize an economic benefit form the project. And therefore, the following considerations should be considered when designing these rate structures for a more fair and adequate compensation.

- Dynamic network tariffs: rates that account for the time value of energy will encourage customers to shift their demand to utilize the available energy from the P2P community, reducing the energy usage in peak periods.
- Demand charges: instead of a fixed network usage charge, this structure can be implemented to effectively charge customers solely for the part of the electrical infrastructure that they utilize.

7.1.2 BUYBACK TARIFFS

When the demand from the community is not enough, the excess solar energy needs to be sold to the grid, and the compensation provided by the grid for this energy can have a big impact in the outcome of the project. For this, it is proposed to use a VDER (Value of Distributed Energy Resources) tariff, as the one the NY PSC is using in [28]. This buyback tariff will provide the adequate incentives to consumers by accounting for the locational and time value of energy. This will compensate energy exported top the grid in peak periods at a higher rate, promoting battery storage and west oriented panels. Moreover, it will compensate the energy produced in highly congested areas at higher rate, what will encourage the development of projects in the areas of the grid where they are needed.

7.1.3 ADDITIONAL SOURCES OF REVENUE

As well as the normal operation of these platform in a P2P trading manner, the potential of VPP has been analyzed in this project. By allowing customers to realize an additional source of revenue through their batteries, the ROI on these batteries is reduced, what will further encourage battery storage, aiding in the energy autonomy of the community.

7.2 CONSUMER ENGAGEMENT

One of the main benefits of these platforms is the potential they have to encourage consumers to shift their demand to the hours where tradeable P2P energy is available, incentivized by the low prices of this energy. However, even though in the previous sections and projects analyzed it was found that P2P does encourage this behavior, there is still a need to optimize the operation of the platforms to achieve a higher degree of consumer engagement.

Through the analysis of the existing projects the need for automation in the trading and price establishment process is realized due to the participants' lack of knowledge and participation. Moreover, it is found that having devices that provide advanced demand forecasting helps consumers know how to better engage in practices that aid int their energy efficiency. Lastly, the idea of pairing advanced demand forecasting with demand automation is found to be an additional way of adding value to these platforms, by automatically providing demand response to the P2P community, in the same manner as DSOs are doing with HVACS, pool pumps and water heaters in pilot projects in Florida and California.

7.3 PROVIDING SERVICES TO THE GRID

P2P platforms are said to be able to help better manage the integration of DERs to the grid, by providing peak demand reduction, locational system relief and grid stability services. However, it is important to quantify these benefits and to design the platforms in a way that ensure the achievement of set benefits.

To incentivize peak demand reduction, it is important to consider the appropriate network tariffs previously mentioned to incentivize the usage of the P2P traded energy. However, the concept of a FPP was studied in this project and found that managing DERs in this manner can have a big impact in peak reduction and allow customers to maximize the benefits of their excess generation.

In addition, the principal characteristic of DERs is their capability of providing energy close top the points of demand, and this benefit can be better observed in certain locations than others. It was seen in the example of Brooklyn Microgrid that the location was one of the most important factors of success of the project due to the relief it provided to a highly congested area. Therefore, considering the locational value of energy when designing the rate structures for the projects it is important to optimize the locations where the are developed. Moreover, adequate location will enable to include additional technologies to the platform, such as EVs that can aid in absorbing the excess solar generation of the community.

Lastly, the concept of providing services to the grid in the form of demand response is achieved through the development of VPPs and FPPs that allow the participants to aggregate their resources to interact with the grid, and in this manner achieve additional sources of revenue while providing value to the network.

7.4 GRID INTERACTION

While P2P platforms present many benefits to the grid, they can also affect grid operation negatively if they are not managed in the correct manner. To ensure a correct integration of DERs in the grid it is important to ensure that the network constraints are accounted for and respected, and that reverse flows are managed accordingly or avoided.

To ensure that network constraints are respected, the P2P platform needs to account for a set of parameters that will ensure that demand and supply are correctly managed at all times, and that the voltage and frequency values of the grid are maintained within the established limits. For this, several studies have been reviewed in Chapter 4. that consider the physical constraints of P2P trading. There are various ways to ensure that each of the constraints is respected, but a “one fit for all” solution would be to include the network constraints in the market mechanism modeling them as branch equations, so that the P2P platform would only allow the transactions that respected these constraints. However, the computational burden of including all these parameters for every transaction need to be studied to find a feasible option for its implementation.

Lastly, an important concern of DERs is how to deal with the reverse flows they create due to excess solar generation. A way to solve this is to ensure the correct prosumer to consumer ratio is established, not in the P2P community, but in the participants connected to the same feeder. That will ensure that exceeds generation does not go upstream in the grid creating instability and endangering the reliability of the supply. However, sizing the communities in this manner is not optimal to maximize the benefit of PV and battery installations, therefore there is a need to study a way of how to better deal with reverse flows in the grid.

7.5 DER AGGREGATION: FPPS

As an additional strategy to P2P, the concept of FPPs was studied in this project, as a way to manage DERs more efficiently in and aggregated manner. The studies analyzed show a reduced peak demand reduction from the community, as well as a higher DER adoption from the consumers incentivized by higher compensation.

However, even though these alternatives increase the adoption of DERs and can reduce peak demand, they can also create an excess of solar generation midday that would be difficult to manage for the grid. So, their at-scale implementation can generate very high solar generation peaks, what will require to shift the demand to those periods. This further realizes the necessity for consumer engagement through incentives that encourage this demand shifting.

Creating FPPs is hard in an individual community due to the excess generation at midday that would go across the feeder, but this can be used as a way of expanding the P2P system across different communities in the same area but with different feeders. The P2P could act as the aggregator of all these DERs from different communities (and feeders) and help them participate in DR or LMPs for that area. By doing this across communities, it can be ensured that the power flows in each feeder are respected, and that excess solar generation does not present a problem.

Also, by doing this, the excess generation from DERs can be bid on the long-term market, since it reduces uncertainty of production. A problem in general with solar generation is its unpredictability due to the specific weather conditions in a certain area at a certain moment, due to clouds and shading of the panels. But, by aggregating the DERs this uncertainty can be reduced and more accurate to weather conditions in an area, what nowadays is easily forecasted.

Chapter 8. CONCLUSIONS AND FUTURE WORK

8.1 CONCLUSIONS

The objective of this project was to analyze the operation of P2P platforms that leverage blockchain technology to function, as well as provide insights on how the optimal design of these platforms could be achieved. To do so, the project has focused on the concept of P2P trading in itself, rather than on the blockchain technology, since it is important to understand the elements that P2P trading requires prior to optimizing the technology it uses.

Therefore, this project has studied the main elements and characteristics that P2P platforms need to have to operate in the most efficient manner with the grid, as well as to ensure that the implementation of these platforms aligns with the objectives of incentivizing DER technology. Chapter 7. provides a summary of the objectives of P2P platforms and how the elements identified help achieve these objectives. Moreover, an additional energy sharing scheme defined as a Federated Power Plant is proposed as a way of aggregating DER operation and P2P transactions, to realize the maximum benefit of DERs by coordinating their operation.

Hence, the project concludes that blockchain is not the most important element for P2P platforms to operate in the most way, and it is rather seen as the information system that can bring an optimal P2P platform to live. Therefore, the conclusion of the project is that, to optimize a P2P platform, the first step is to design it according to the elements described in this project, and then, once this is established, any technology or information system that allows to implement all these characteristics correctly will be the correct way of creating an optimal P2P platform.

8.2 FUTURE WORK

In line with the conclusion of the project a possible line for future work is the study of a technology, such as blockchain, and the possibility of implementing all these elements together in the same information system.

As well, throughout the project there have two matters that have remained unresolved and that can aid in creating these optimal platforms. The first one, is to study how to deal with reverse flows of energy coming from these communities, so that the consumer prosumer ratio was not limited by this parameter. And the second one is to study the computational burden of adding all the network constraints to the market mechanism, so that these platforms directly operate in a way that does not affect the normal grid operation.

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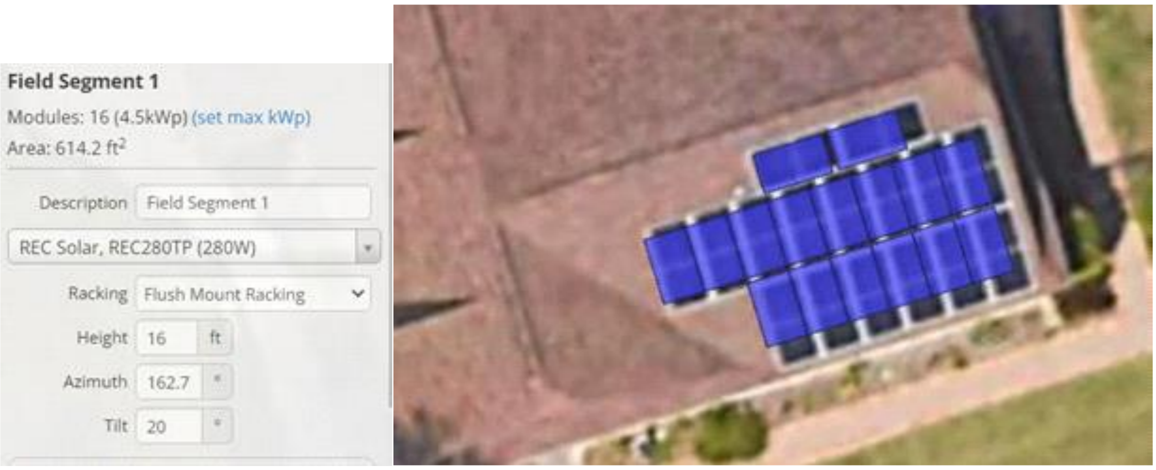
ANEX I: HELIOSCOPE MODELING

The software used for the hourly solar generation analysis in 5.5.3.1 is Helioscope. This software allows users to create solar rooftop systems and analyze the annual, monthly and hourly generation.

The study was based in Lakeland, Florida, in an average residential house with the following considerations:

- Azimuth: 167 degrees (south facing)
- Tilt: 20 degrees
- Weather conditions: NREL TMY, 10km Grid (28.05,-81.95)
- Load ratio: 1.19 DC/AC
- Panels: 350 W
- System size: 5.2 kW DC

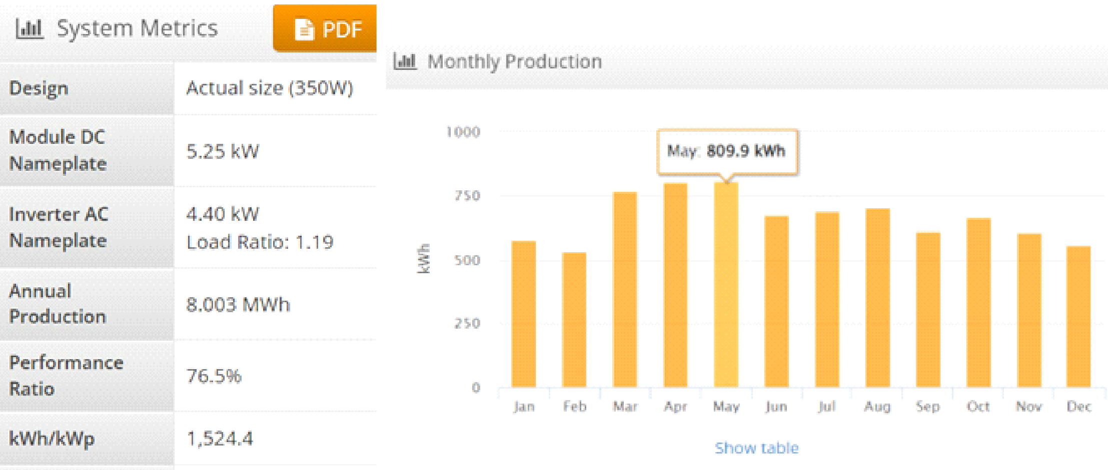
Figure 32. Top vie of the solar array



Field Segment 1
Modules: 16 (4.5kWp) (set max kWp)
Area: 614.2 ft²

Description: Field Segment 1
REC Solar, REC280TP (280W)
Racking: Flush Mount Racking
Height: 16 ft
Azimuth: 162.7 °
Tilt: 20 °

Figure 33. Modelling parameters for Helioscope

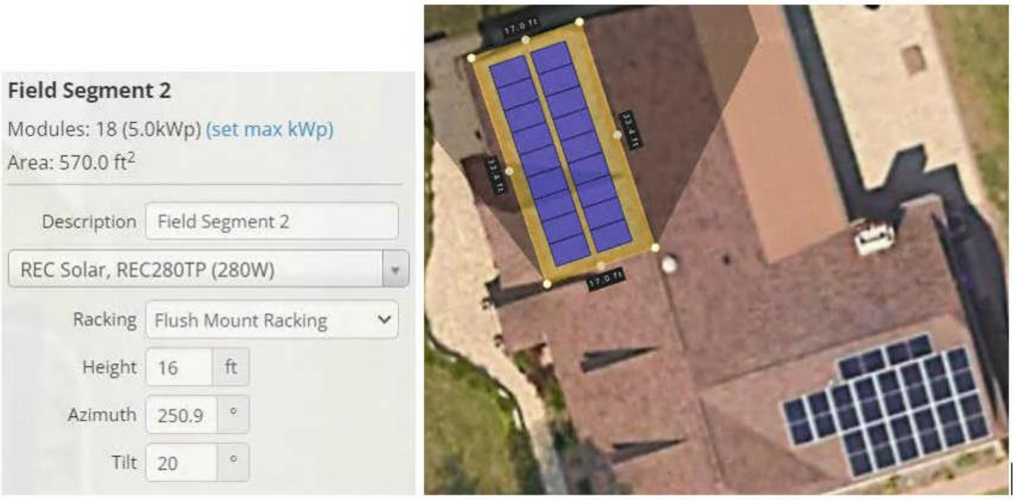


Design	Actual size (350W)
Module DC Nameplate	5.25 kW
Inverter AC Nameplate	4.40 kW Load Ratio: 1.19
Annual Production	8.003 MWh
Performance Ratio	76.5%
kWh/kWp	1,524.4

Figure 34. Helioscope results

The same modeling was carried out for the west facing configuration.

- Azimuth: 251 degrees (south facing)
- Tilt: 20 degrees
- Weather conditions: NREL TMY, 10km Grid (28.05,-81.95)
- Load ratio: 1.19 DC/AC
- Panels: 350 W
- System size: 5.2 kW DC



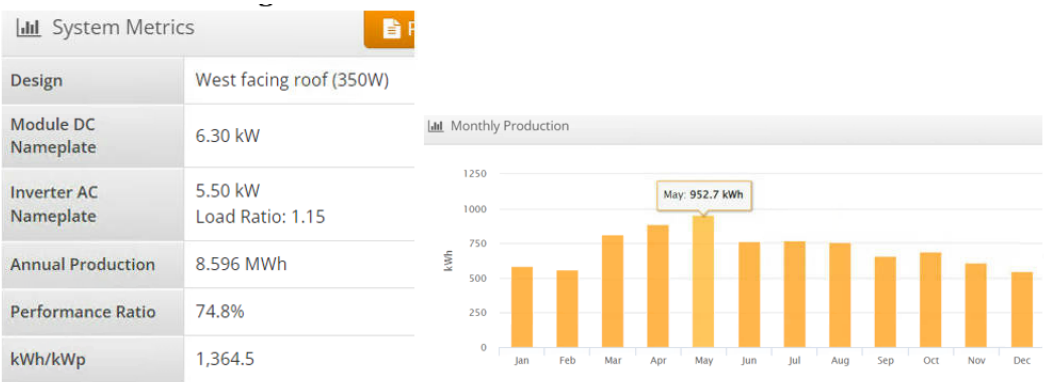
Field Segment 2

Modules: 18 (5.0kWp) (set max kWp)

Area: 570.0 ft²

Description	Field Segment 2
	REC Solar, REC280TP (280W)
Racking	Flush Mount Racking
Height	16 ft
Azimuth	250.9 °
Tilt	20 °

Figure 35. Modellig parameters Helioscope (West)



System Metrics

Design	West facing roof (350W)
Module DC Nameplate	6.30 kW
Inverter AC Nameplate	5.50 kW Load Ratio: 1.15
Annual Production	8.596 MWh
Performance Ratio	74.8%
kWh/kWp	1,364.5

Figure 36. Helioscope results (West)

ANEX II: SDGs

On September 25, 2015, world leaders adopted a set of global goals to eradicate poverty, protect the planet and ensure prosperity for all as part of a new sustainable development agenda.

Figure 37. Sustainable Developement Goals

- **Goal 7**: Ensure access to affordable, reliable, sustainable and modern energy for all.

  This project aids in the creation of communities that utilize distributed energy resources, encouraging the use of these renewable energy sources.
- **Goal 9**: Building resilient infrastructures, promoting sustainable industrialization and fostering innovation.

  Leveraging distributed energy systems can present several benefits towards sustainable industrialization, since it can bring about important savings in electrical infrastructure as well as aiding in the creation of a more resilient power infrastructure.
- **Goal 11**: Make cities and human settlements inclusive, safe, resilient and sustainable.

These platforms can help create more sustainable communities by promoting the exchange of locally produced energy. Moreover, it makes users more aware of their energy consumption, what can aid towards a more efficient use of electricity.