UNIVERSIDAD TÉCNICA FEDERICO SANTA MARÍA

DEPARTAMENT OF ELECTRONICS

VALPARAÍSO - CHILE

TOWARDS SOLAR PEER-TO-PEER ENERGY TRADING AS A SERVICE IN A COMMUNITY MICROGRID

Submitted by

FRANCISCA SOTO ASTORGA

In partial fulfillment of the requirements for the award of the degree of

MASTER OF SCIENCE IN ELECTRONICS ENGINEERING

THESIS SUPERVISOR: PHD. MOHAMED ABDELHAMID

EVALUATION COMMITTEE: PHD. JOSÉ MANUEL MARTÍNEZ

EVALUATION COMMITTEE: PHD. RODRIGO CARVAJAL

JULY - 2025

CONSTANCIA DE VALIDACIÓN Y CONFIDENCIALIDAD DE MONOGRAFÍA A REPOSITORIO ACADÉMICO

1.- IDENTIFICACIÓN DEL TRABAJO ACADÉMICO

Tipo de monografía (marcar una opción): ☐ Memoria o trabajo de título; ☒ Tesis de Postgrado;

Título del trabajo: Towards Solar Peer-to-Peer Energy Trading as a Service in a Community Microgrid

Nombre del candidato(a): Francisca Valentina Soto Astorga

Carrera / Grado: Magíster en Ciencias de la Ingeniería Electronica, mención Telemática e Ingeniería Civil Telemática

Campus: Casa Central Valparaiso ; **Departamento**: Electrónica

2.- VALIDACIÓN DEL PROFESOR GUÍA/DIRECTOR DE TESIS

Yo, Mohamed Abdelhamid, en mi calidad de profesor(a) guía/director(a) del trabajo académico mencionado anteriormente **DEJO CONSTANCIA** que:

- He revisado esta versión del documento y corresponde a la versión final aprobada del trabajo.
- El trabajo cumple con los requisitos académicos y de formato establecidos por la institución

3.- EVALUACIÓN DE CONFIDENCIALIDAD POR PROPIEDAD INDUSTRIAL

☒ El trabajo **NO contiene información que amerite confidencialidad** y puede ser publicado de inmediato en repositorio con acceso abierto.

☐ El trabajo **CONTIENE** información con potenciales implicancias de propiedad industrial o intelectual y requiere un periodo de confidencialidad (embargo) por:

☐ 6 meses; ☐ 12 meses; ☐ 2 años; ☐ 3 años; ☐ 5 años; ☐ 10 años

Fundamentación de la necesidad de confidencialidad (obligatorio si se solicita embargo):

4.- FIRMAS

Profesor(a) guía o director(a) de memoria o tesis:
Fecha: 25-07-2025 ; **Firma:** M.Abdelhamid

Estudiante o Candidato(a):
Fecha: 25-07-2025 ; **Firma:** Fran S

Este formulario debe ser insertado como página 2 de la memoria o tesis, completado y firmado por estudiante y profesor(a) antes de la entrega en portal PRISMA de Biblioteca USM.

Life can be heavy, especially if you try to carry it all at once. Part of growing up and moving into new chapters of your life is about catch and release. What I mean by that is, knowing what things to keep, and what things to release. Decide what is yours to hold and let the rest go. Oftentimes the good things in your life are lighter anyway, so there's more room for them.

And I know it can be really overwhelming figuring out who to be, and when. Who you are now and how to act in order to get where you want to go. I have some good news: It's totally up to you. I also have some terrifying news: It's totally up to you.

Sometimes the right thing to do is to throw out the old schools of thought in the name of progress and reform. Sometimes the right thing to do is to listen to the wisdom of those who have come before us. How will you know what the right choice is in these crucial moments? You won't.

How do I give advice to this many people about their life choices? I won't.

Scary news is: You're on your own now.

Cool news is: You're on your own now.

- Taylor Swift

Agradecimientos

En primer lugar quiero agradecer a mi familia, papá, mamá y Nita, que siempre estuvieron ahí para mí, apoyándome y acompañándome en los mejores y peores momentos de mi vida universitaria, por entregarme tantos valores y la oportunidad de estudiar, impulsarme y acompañarme a cumplir mis sueños. A mis amigos y amigas que me acompañaron en este proceso de penas y alegrías, a Karolain y Francisco por apoyarme y ser los compañeros de carrera que siempre estuvieron ahí; Sofía, Deborah, Victoria, Pablo, y con quienes compartí gracias al fútbol, por todos esos buenos momentos deportivos y de ocio donde más de una vez tuvimos una grata conversación. A mi compañero de viaje todos estos años y partner, Nacho, por aconsejarme y animarme en el momento en que todo se vió gris, por su compañía en todos esos momentos lindos, de estudio y de risa que vivimos dentro y fuera de la universidad.

Agradezco especialmente al profesor Mohamed por todo el tiempo que hemos compartido, guiándome tanto como alumna, ayudante y persona, por ser una inspiración para continuar con el postgrado y por su apoyo absoluto en este último proceso de la carrera. A Patricia Franco por todos los consejos y apoyo que me brindó en la etapa de Magister y que sin duda ha sido una inspiración para mí. Finalmente agradecer a todos los profesores y cuerpo docente con los que tuve la experiencia de compartir y adquirir sus conocimientos y consejos.

Gracias a todos por el apoyo que me brindaron en estos años de universidad.

Abstract

Solar peer-to-peer (P2P) energy trading is a promising approach that allows participants, prosumers with local energy generation and consumers, to exchange energy directly, which reduces dependence on the centralized power grid and opens new opportunities for a local decentralized energy market. However, implementing such a P2P energy trading system requires careful consideration of hardware, software, and communication networks to ensure smooth and secure energy transactions between participants. Most of the previous research works have addressed P2P energy trading from different perspectives such as market models, communication networks, Blockchain, smart contracts, and simulations, while few works have presented the technical implementations of such a P2P energy market. Furthermore, there are no comparisons between different energy trading architectures and/or configurations.

To address this gap, this work aims to design and implement a Solar P2P energy trading platform (hardware/software) that allows local energy trading among prosumers and consumers in a community microgrid, aiming at maximizing the utilization of distributed energy resources. The proposed platform will benefit from recent advances in the Internet of Things (IoT), communication networks, cloud services, and blockchain technologies. A decentralized market architecture has been developed and implemented in a laboratory environment, together with a comparative analysis with respect to system scalability, and communication network performance, considering different wired/wireless communication technologies. This work contributes towards a decentralized energy market, facilitating the adoption of renewable energy sources and empowering local communities.

Keywords: Solar Energy, Peer-to-Peer Energy Trading, IoT, Blockchain, Communication Network, Community Microgrid

Resumen

El comercio de energía solar entre pares (P2P) es un enfoque prometedor que permite a los participantes, prosumidores con generación de energía local y consumidores, intercambiar energía directamente, lo que reduce la dependencia de la red eléctrica centralizada y abre una nueva oportunidad para un mercado energético descentralizado. Este enfoque promueve la sostenibilidad, la autosuficiencia energética, el ahorro de costos y el impacto medioambiental. Sin embargo, la implementación de un sistema de comercio de energía P2P de este tipo requiere una cuidadosa consideración del hardware, software y las redes de comunicación para garantizar transacciones de energía fluidas y seguras entre los participantes. La mayoría de los trabajos de investigación anteriores han abordado el comercio de energía P2P desde diferentes perspectivas, tales como modelos de mercado, redes de comunicación, Blockchain, contratos inteligentes y simulaciones, mientras que pocos trabajos han presentado las implementaciones técnicas de comercio de energía P2P. Además, no existen comparaciones entre diferentes arquitecturas y/o configuraciones de comercio de energía.

Para abordar esta brecha, este trabajo pretende diseñar e implementar una plataforma de comercio de energía solar P2P (hardware/software) que permita el comercio local de energía entre prosumidores y consumidores en una microrred, con el objetivo de maximizar la utilización de los recursos energéticos distribuidos. La plataforma propuesta se beneficiará de los recientes avances en IoT, redes de comunicación, servicios basados en la nube y tecnologías blockchain. Se desarrollará una arquitectura descentralizada , en un entorno de laboratorio, junto con un análisis comparativo con respecto a la escalabilidad del sistema y el rendimiento de la red de comunicación (considerando diferentes tecnologías de comunicación cableadas/inalámbricas). Este trabajo contribuye hacia un mercado energético descentralizado, facilitando la adopción de fuentes de energía renovables y empoderando a las comunidades locales.

Contents

List of Figures

List of Tables

Chapter 1

Introduction

Nowadays, Chile has made significant progress in electrification in most of the country's regions. However, there are still many challenges in some rural and remote areas. According to a study conducted in 2019 [1], approximately 24,556 homes do not have an electricity system, of which 6,637 homes are in the process of electrification, representing 0.4% of the total population of the country and 3.5% of the rural population. As can be seen in Figure 1.1, the concentration of homes without electricity is concentrated in regions of the country that are characterized by complex geography and low population density, which often face difficulties in connecting efficiently and reliably to the national electricity grid. This results in limited or discontinuous access to electricity, which negatively affects the quality of life of its inhabitants and limits the economic development of these communities.

In addition, Chile has continued its commitment to the use of clean and renewable energy by formulating public policies that support their implementation. According to the data from the Ministry of Energy and the National Electric Coordinator, non-conventional renewable energies (NCRE) achieved a dominant participation of 93.5% in the National Electric System until October 2023, where 53.3% of solar energy was registered [2]. Furthermore, until April 2024, the NCRE generation reached 41%, where solar energy production increased by 13% during the first 3 months of 2024 [3].

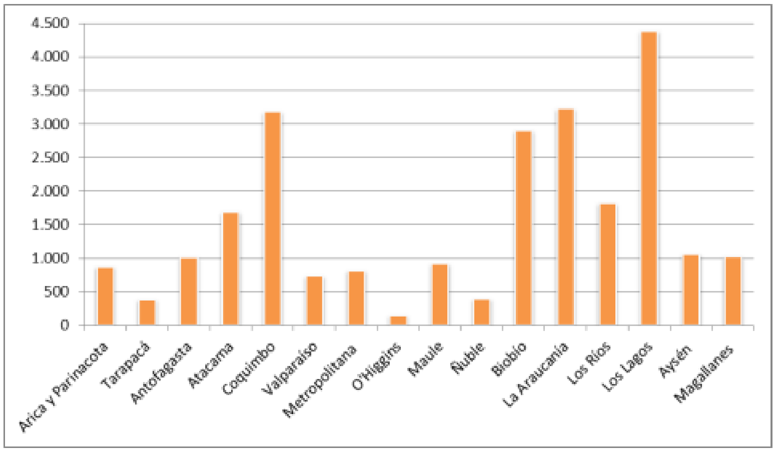


Figure 1.1: Homes without energy by region in Chile.

The peer-to-peer (P2P) energy trading model has emerged as an innovative solution to address the problem of electrification in remote and isolated areas. P2P energy trading will allow consumers and prosumers (who generate their own energy through renewable sources such as solar or wind) to exchange surplus energy with other users, without the need to rely exclusively on large centralized electricity distribution grids. This P2P model has the potential to transform areas where traditional electricity infrastructure is insufficient or unviable. In general, there are three main architectures for P2P energy trading [4]: (a) centralized architecture, (b) decentralized architecture, and (c) hybrid architecture. Figure 1.2 shows a schematic diagram for the P2P energy trading framework.

In order to implement the peer-to-peer energy trading mechanism in Chile, there are multiple challenges that need to be addressed [5]:

- It is necessary to evaluate the existing regulatory framework and its capacity to allow and encourage this type of decentralized energy trading.
- Rural and isolated areas face technological barriers, such as the lack of access to smart grids and digital platforms, which are critical to the effective operation of P2P energy trading.
- The social and economic adoption of this model, in rural communities, raises questions about its long-term viability, given that many of these territories lack basic

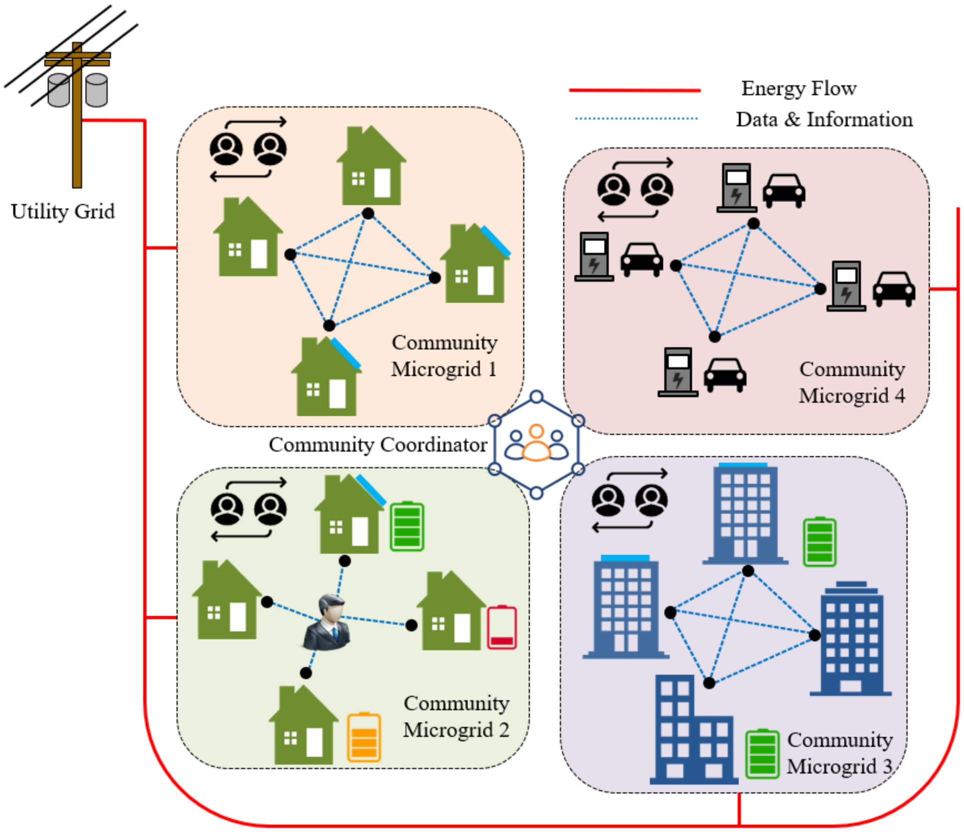


Figure 1.2: Schematic diagram for P2P energy trading framework.

infrastructure and financial resources, and social acceptance by the populations.

The main objective of this work is to design and implement a real IoT-Blockchain platform for Solar P2P energy trading among smart homes in a local community. In order to facilitate energy exchange among different participants, a decentralized market architecture has been developed to support different scenarios and needs. The developed platform supports different wired/wireless communication technologies to send the data collected by the sensors to the Internet, allowing its visualization and interaction in real time by the users. The platform has been implemented, in a laboratory environment, to validate the feasibility and effectiveness of the proposed system.

Future work aims to study the feasibility of implementing this system in a local community, considering technical, economic, and regulatory aspects. This analysis will allow evaluating the potential impact and benefits that the P2P system could offer in real environments, thus contributing to the advancement and development of innovative solutions in the field of renewable energy systems and energy efficiency for local communities.

1.1 Problem Definition

This work aims to design and implement a real solar P2P energy trading platform (hardware/software), in a laboratory environment, which supports the integration of IoT, communication networks, cloud-based systems, and blockchain technologies. The proposed platform should be adapted to support different architectures and/or configurations for local communities.

1.2 Hypotesis

It is possible to develop and implement a Solar P2P energy trading platform (hardware/software) in a community microgrid that allows local energy trading among consumers and consumers. The Solar P2P energy trading platform should consider two main elements: an IoT cloud-based system and a blockchain network that allow data acquisition, energy monitoring, and energy exchange among participants. To do this, the work can be separated into three main focuses:

- It is possible to develop and implement an IoT system to monitor the energy consumption, using smart meters, for a group of consumers in a community grid, where the data obtained can be visualized on a web platform using wired/wireless communication network.
- It is possible to develop and implement an IoT system to monitor the energy generation profile of photovoltaic systems for a group of prosumers in a community grid, in such a way that the data obtained can be visualized on a web platform using wired/wireless communication network.

- It is possible to develop and implement an IoT-Blockchain platform for solar P2P energy trading among houses where the platform will allow users to sell/buy surplus/demand energy through the Web, for which a blockchain and smart contracts will automate the trading transactions securely.

1.3 Objectives

1.3.1 General Objective:

To design and implement an IoT-Blockchain platform (hardware/software) for Solar P2P energy trading in a local community microgrid

1.3.2 Specific Objectives:

1. Study, analyze, and compare the state-of-the-art regarding different case studies, implementation, and testbeds for P2P energy trading in microgrids and P2P markets.
2. Propose an IoT-Blockchain architecture for Solar P2P energy trading considering available technologies for IoT, cloud computing, and Blockchain.
3. Develop and implement a hardware system for data acquisition and data transmission from smart homes (consumers and prosumers) via a wired/wireless communication network to the cloud-based service in a laboratory environment.
4. Develop and implement a blockchain network and smart contracts to ensure security, transparency, and trust in transactions among market participants.
5. Develop and implement a web platform for local energy trading that allows the visualization of data obtained from consumers and prosumers.
6. Analyze the results obtained from the developed decentralized energy trading market, limitations, and the direction for further extension.

1.4 Methodology

- Specific Objective 1
    1. Exhaustive review of the literature and related work on P2P energy trading in smart grid/microgrids in different countries. The focus will be on smart homes with PV systems and the battery energy storage system (BESS).
    2. Perform an analysis and provide comparative tables for relevant related work and available solutions related to the main research topic, considering the main characteristics which contribute to achieve the work proposal.
- Specific Objective 2:
    1. Identify the technologies available for IoT, cloud computing, and blockchain that can be used according to the available resources.
    2. Select the resources available to prosumers and consumers according to the subject and relate the communication system between devices.
    3. Propose an IoT-Blockchain architecture considering the context of the decentralized scenario.
    4. Identify the case study and define the requirements for the local energy market.
- Specific Objective 3:
    1. Implement, by means of a communications simulator, which technology will be used for the case study (wired/wireless communications technologies) before the real implementation.
    2. Select and implement sensor nodes, smart meters, and microcontrollers for monitoring PV systems and loads in smart homes of consumers and prosumers.
    3. Configure the selected microcontroller for sending the real data from Smart homes to the cloud.

- Specific Objective 4:
    1. Study and compare different blockchain implementations for local P2P energy trading.
    2. Adapt the available platforms and blockchain network for the decentralized P2P scenario.
    3. Develop and deploy smart contracts according to the P2P architecture on the platform.
- Specific Objective 5:
    1. Define the framework and configure the environment for the implementation of the Web platform.
    2. Configure the visualization of the data obtained, in a web platform, for both the consumer and the prosumer.
    3. Integrate blockchain development with the web platform.
    4. Expand the Web platform for the decentralized peer-to-peer architecture.
- Specific Objective 6:
    1. Integration and validation of the proposed P2P energy trading platform for the decentralized scenario.
    2. Analyze and validate the results of the developed decentralized architecture, discuss the limitations and direction for further extension.

1.5 General Structure of the Document

This thesis is focused on the design and implementation of solar peer-to-peer energy trading in a local community microgrid. This document is divided into seven chapters:

Chapter 1: introduces the research topic, problem statement, and presents the general and specific objectives, hypothesis, and methodology to follow.

Chapter 2: introduces and explains the Chilean development of energy projects. In addition, it reviews an in-depth analysis of the state-of-the-art of P2P energy trading in various areas such as market types, pricing, blockchain, simulation, projects, and implementations.

Chapter 3: contextualizes the architectures of a smart grid and IoT architectures. Finally, we present and describe the proposed IoT-blockchain architecture.

Chapter 4: presents the modeling of a smart home and their components and functions such as smart meter, PV system, BESS, and home appliances. Then, the communication modeling for P2P energy trading transactions is presented.

Chapter 5: shows the results of communication network simulation, including wireless and wired technologies. The simulation considers smart homes and P2P energy trading.

Chapter 6: presents a testbed implementation of solar peer-to-peer energy trading for a Smart Prosumer and a prototype for a Smart Community.

Chapter 7: presents the conclusions and future work.

Chapter 2

Related Work

P2P energy trading is an innovative model that has emerged to help the electrification in different areas, both urban and rural, and to boost decentralization of the main power grid. This P2P energy trading model defines two main entities: prosumers who generate their own energy through renewable resources and consumers. Prosumers can sell the excess energy generated to consumers, creating a new marketplace for communities where the traditional electricity infrastructure is insufficient or unviable. However, in order to perform P2P energy trading, information from different domains is required such as how to measure the consumer demand and prosumer generation (data acquisition), how communication infrastructure will support data exchange (communication network), how trading market will operate (market place), and what are the current public policies and how it supports P2P energy trading (regulation).

2.1 Energy Digitization in Chile

The digital revolution in different sectors and the use of renewable energies have led to projects that achieve joint progress in two main areas: business strategies and the reduction of carbon emissions generated in the production and consumption of electricity. Although there are many benefits generated with energy digitization and renewable energy integration, there are several challenges to progress in the energy area.

In this regard, the Chilean Ministry of Energy in collaboration with the Germany Federal Ministry and Economic Affairs and Energy have analyzed and presented different use cases for the future smart grid [6]. The study analyzed 30 uses/applications divided into six categories. The following are the main initiatives presented, including the following:

- *Energía 2050 [7]*: It proposes a vision for the energy sector in 2050 that corresponds to being a reliable, sustainable, inclusive, and competitive sector. Guided by a systemic approach, according to the main objective of achieving and maintaining the reliability of the entire energy system, while meeting sustainability and inclusion criteria and contributing to the competitiveness of the country's economy.
- *Casa Solar [8]*: This is a government program that allows the purchase of photovoltaic systems at a lower price with the state co-financing. Its objective is to promote the use of renewable energy through the installation of photovoltaic panels connected to the grid, without batteries, at the residential level. For 2024, about 2,200 new photovoltaic projects were delivered to homes.
- *Ruta de la Luz [9]*: It consists of a public investment project that seeks to electrify rural and remote areas of the country through safe and sustainable solutions. This program is financed by the state budget and is executed by the Regional Governments or Municipalities.

Although the study of the digital revolution in energy system covered various applications and use cases, this section will focus only on the analysis of smart grid, P2P, and prosumers. The study of the digital revolution highlighted the use of prosumers and P2P trading in the smart grid. Among the enabling technologies considered are smart meters, IoT, communication network (LAN/HAN/NAN/WAN), and blockchain technology. Table 2.1 shows the type of institutions, sectors, and applications considered with respect to energy stakeholders.

Table 2.1: Summarizes of potential use cases and applications of P2P work.

Institution type	**Sector**	**Potential use and application(s) under consideration**
Distribution system operators	Energy	Customer domain: Prosumer & P2P trades, Retailing, billing & customer orientation.
Energy generation	Energy	Customer domain: Prosumer & P2P trades, Retailing, billing & customer orientation.
Finance sector	Finance	Customer domain: prosumer & P2P trades.

Digitalization was also highlighted as a key element in the P2P market, as it will support remotely measuring energy production through AMI. The AMI can be used to track the origin of energy generation and consumption through blockchain or can enable peer-to-peer trading through a digital marketplace. It can also enable retail, billing, and customer orientation, which is related to activities in the energy retail market, where digital applications can be leveraged to enhance the customer experience for the retailer. This new P2P market will contribute in terms of flexibility, economic balance, and participation of the population. However, the main barriers identified are:

- With the dependence on communication infrastructure or Internet connection, a high-security system is needed for the type of data transmitted.
- The population needs to know about the trust and use of this type of market.
- It must be taken into account who will have access to the information. Following this perspective, there must be a cybersecurity system for possible attacks.
- Greater participation of the population and agents is necessary to generate a measurable impact.
- The laws must be updated to encourage this participation.

Table 2.2 shows the main barriers and opportunities for prosumers and P2P trades.

For the project ”Energía 2050”, the main objectives are:

Table 2.2: Summarize of barriers and potential opportunities for the National Coordinator.

Uses & Application	**Barriers**	**Opportunities**
Prosumer & P2P trades	Lack of infrastructure to measure and track energy. Reduced types of energy products that prosumers can sell (energy only).	The coordinator is carrying out a pilot program with blockchain technology for certification of cost statements and fuel stocks that are used in the daily operation scheduling. This application could be extended for other types of information that the coordinated companies must declare.

- Emission-free energy: achieve a sustainable, resilient, flexible energy matrix, low in greenhouse gas (GHG) emissions and local pollutants, advance compliance with the goal of carbon neutrality in the most cost-effective manner, and ensure compliance with international climate change commitments.
- Universal and equitable access: ensure universal and equitable access to quality energy services that are safe, reliable, efficient, and sustainable, as well as access to energy-efficient and healthy housing that meets the diverse energy needs of people.
- Energy-sustainable cities: promote an improvement in the quality of life of people in cities, addressing energy efficiency and sustainability in the construction and use of buildings, and especially aiming at decontaminating the air in cities.
- Inclusive economic development: promote the economic development and productivity of the country through energy, with a decentralized, sustainable, and harmonious approach with the environment, guaranteeing the inclusiveness and equity of economic benefits for the entire population.
- Social and environmental sustainability of energy development: to promote and encourage a sustainable, participatory energy development that guarantees fair energy transitions, enabling tools and means that guarantee the protection of the environment and biodiversity.

- Local development and decentralization: promotes the implementation of initiatives and projects to generate shared value, associativity, and improve the quality of life of communities.

Finally, the P2P energy market can help to solve and complement the points described above, but there are many technical and political barriers that need to be addressed.

2.2 Peer-to-Peer Energy Trading

Previous research work have addressed the topic of P2P energy trading from different perspectives such as P2P market, bidding prices, challenges, architectures, physical connections, blockchain, and communication system, among others. Figure 2.1 shows the main topics investigated in the P2P energy trading. This section presents the main studies related to the areas mentioned above.

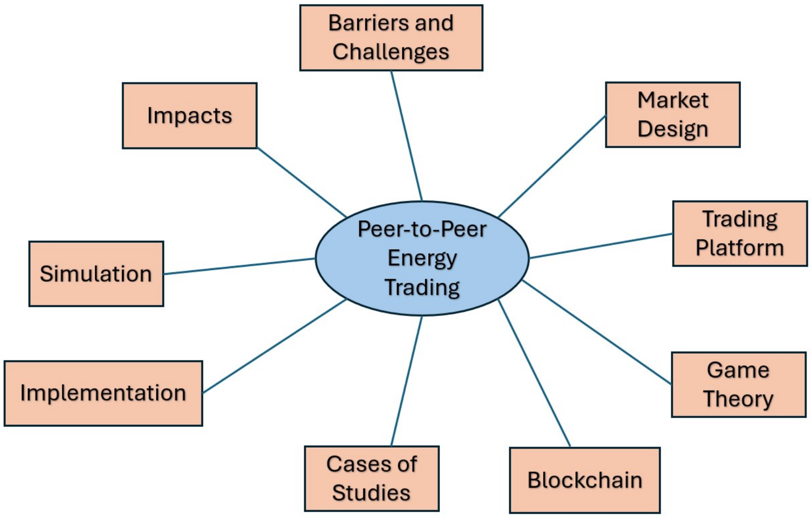


Figure 2.1: Main topics investigated for P2P energy trading.

2.2.1 P2P Market and Bidding Prices

In [5], the authors developed a three-entity architecture model and a decision making algorithm for P2P energy trading. The work performed a sensitive analysis of local P2P PV energy trading in a community microgrid including different scenarios, both with and without the battery energy storage system (BEES), an aggregator, and the utility grid. The results obtained showed that the P2P market could lead to a reduction in annual electricity bills by as much as 1.76% for consumers and an increase in annual income of up to 149% for prosumers. In addition, the work defined algorithms in different situations for HEMS with and without BESS.

The authors of [10] demonstrated the benefits of conducting P2P energy trading by matching prosumers and consumers in a centralized model and evaluated the platform to perform energy exchange with the goal of expanding to other types of models. The work supported the matching interaction between energy traders in a hybrid market and evaluated the platform to show the extent to which P2P energy trading can benefit prosumers in the network. This was achieved by varying their proportional bids in order to determine the optimal combination for maximum benefit.

The authors of [11] proposed a combined hierarchical P2P energy trading model with an efficient energy management scheme, which improves the utilization of local renewable energy rather than increasing dependence on the central main grid. In this study, three multi-grid cases were considered to measure the economic impact of the proposed model through the simulation. The scenarios were as follows Peer-to-Grid trading model (P2G), Peer-to-Peer single level trading model between microgrids (P2PS1), and Hierarchical Peer-to-Peer trading model between the nanogrids (HP2P). According to the simulation results, it was evident that the application of the energy management scheme reduces the operating cost of all microgrids together in the community area by 28.38% in scenario 1, 38.86% in scenario 2, and 39.21% in scenario 3, respectively.

The authors of [12] examined two types of P2P mechanisms, namely auction-based and bilateral contract-based P2P electricity trading mechanisms, analyzing their effectiveness in properly managing electricity trading among prosumers in future distribution systems. The authors in [13] explored the advantages of blockchain-based P2P energy trading with the integration of DERs and compared the profitability of the systems with traditional net metering (NEM) and feed-in tariff (FiT) models through the use of key performance indicators (KPIs) such as unpaid surplus energy and financial revenue from traded energy in a rural microgrid.

Several studies have investigated P2P markets, covering small to large numbers of customers. The largest concentration of studies focused on the regularization of the price of the market. For example, the authors in [14] [15], presented a comparative analysis of methods to decide prices, simulate the impacts of supply strategies that investigated the economic benefits, and analyze the auction mechanism. The authors in [16] proposed and defined three paradigms for the P2P energy trading market: bill sharing, mid-market price, and auction based pricing strategy. An example of each methodology was applied to a residential microgrid with PV system to validate the effectiveness of P2P energy trading. Also, the work mentions that more than one auction method can be used.

2.2.2 Major Challenges

In [4], the authors discussed the major control challenges in a microgrid, classifying possible control architectures as centralized and decentralized. The work studied the possible P2P energy trading architecture and also discussed the challenges presented by DERs in the microgrids. To identify the challenges of P2P energy trading, the authors of [17] presented energy exchange mechanisms focused on IoT development. The work presented the necessary characteristics, challenges in the physical network deployment, problems, and solutions for communication between devices. In particular, three types of distribution network challenges were identified: voltage limit violation, power loss, and congestion complexity. Other identified challenges include the hardware implementation needed to evaluate the performance of P2P trading frameworks in real-time distribution networks.

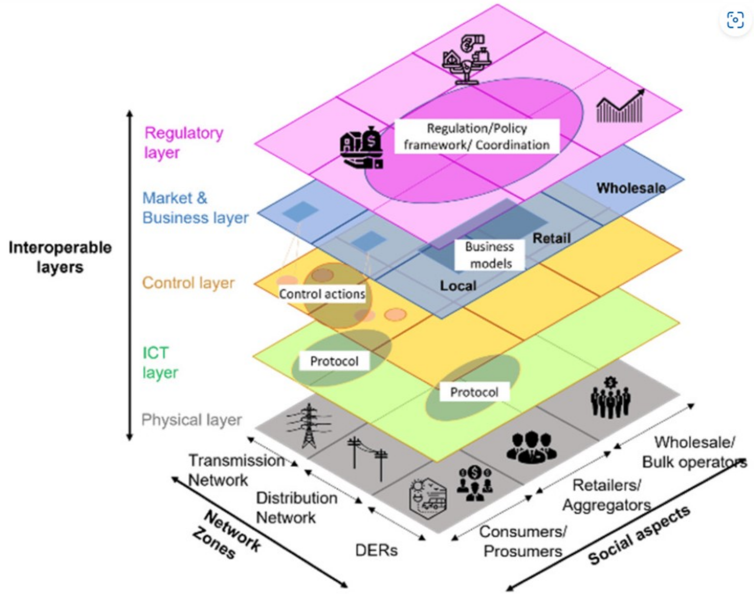


Figure 2.2: Five-layer architecture according to literature review.

2.2.3 P2P Architectures

In [18], the authors presented a four-layer architecture to implement P2P energy trading and designed a platform to facilitate energy transactions. The proposed architecture is as follows: the first dimension consists of physical components of the power system, such as feeders, transformers, and smart meters, among others. The ICT layer involves communication devices, protocols, and information flow. The third layer focuses on the control layer which deals with the control functions of the electricity distribution system. This layer defines the preservation of the quality and reliability of the power supply, including power control aspects such as voltage and current control. Finally, the business layer determines the electricity traded among peers.

The architecture of a P2P system, presented in Ref. [19], considered smart energy solutions for communities that show the advantages and challenges. The architecture consists of five layers: physical layer, ICT layer, control layer, market and business, and regulatory layers, as shown in Figure 2.2. In the case of Ref. [20], a proof of concept was made considering electric vehicles. The work presented a five-layer architecture that considered all components to generate an efficient energy model with the focus of reducing the carbon footprint in buildings. In [21], the study presented a detailed analysis of various P2P energy trading implementations to understand the implementation methodologies where a five-layer architecture was presented. In [22], the authors proposed an IoT–blockchain architecture for P2P energy trading in a microgrid. The system is composed of multiple entities that were divided into two layers: the physical layer and the virtual layer. The microgrid system consists of prosumers, consumers, BESS, and PV. This work developed and implemented a peer-to-peer energy trading platform that allows local energy trading between a consumer and a consumer, within a microgrid, that combines IoT and blockchain technologies.

2.2.4 Physical Connections and Infrastructure

The authors of [23] evaluated the impact of P2P energy trading between smart homes in a microgrid. The work focused on analyzing the impact of storage systems, renewable energy sources, and the combination of both on energy costs. The results obtained showed that the cost benefits showed a strong correlation, where the maximum cost savings are obtained at a saturation point that depends on the household loads, storage capacity, and renewable energy generation capacity of a specific area of the microgrid. Thus, the developed model could be useful for designing programs and incentives for households to accelerate the adoption of storage and renewable energy in the microgrid.

In [24], three case studies were considered by varying the number of participants. The work considered a connection system between the microgrid and the grid to realize the energy exchange. The main goal was to leverage the P2P transactional energy framework for optimal rooftop or neighborhood solar control with BESS. The work also considered that multiple neighboring customers are interconnected to form a community DC grid while the remaining customers are connected to the main power grid. Three case studies were defined: (i) a single home with solar system, (ii) a single home with solar system and BESS, and (iii) two or more homes with solar system and community energy storage to facilitate policy makers in making recommendations.

2.2.5 Blockchain Technology

In [25], the authors discussed the conceptual architecture of blockchain for electricity exchange. The work explained how to develop a Smart Contract and provided configuration details for a conceptual architecture of the P2P platform. In [26], the work discussed a conceptual architecture of blockchain in a negawatt trading. The work explored the use of blockchain to safeguard the security of transactions. The platform was implemented with Hyperledger where two scenarios were discussed. The first involves negawatt trade of response and demand between aggregator and buildings. The second scenario discusses negawatt trading between buildings to cover the contractual deficiency of the previous case. Unlike the previous study, the authors of [27] focused on selling excess energy with a blockchain network using the Hyperledger Fabric framework, where participants, assets, transactions, and the smart contract were defined. The implementation of the proposed platform was analyzed in a laboratory testbed using open-source Hyperledger. In [28], the authors evaluated the impact on the blockchain network with respect to throughput, latency, and scalability. The work concluded that an increase in concurrent transactions significantly affects the performance of the blockchain network, in particular latency, and that the type of transaction significantly influences the performance of the blockchain network.

The authors in [29] explored blockchain technology to support a P2P power trading system, which would qualify a consumer to participate in energy production while earning profits. The work developed a P2P energy trading platform based on the SIMBA blockchain, as it has an API that allows access to smart contracts. In addition, the work preseneted a trading process that can be seen in Figure 2.3. In [30], the authors presented privacy and security recommendations for P2P energy trading platforms. Several pilot projects in India have successfully implemented P2P energy trading. The study brings the elements necessary to achieve a cumulative impact in favor of the promotion of this technology. The work also highlighted that the Government of India has introduced several policies to promote the use of clean energy, which favors the trading of solar P2P energy. Finally, the work concluded that more work is needed to improve India's infrastructure capabilities to

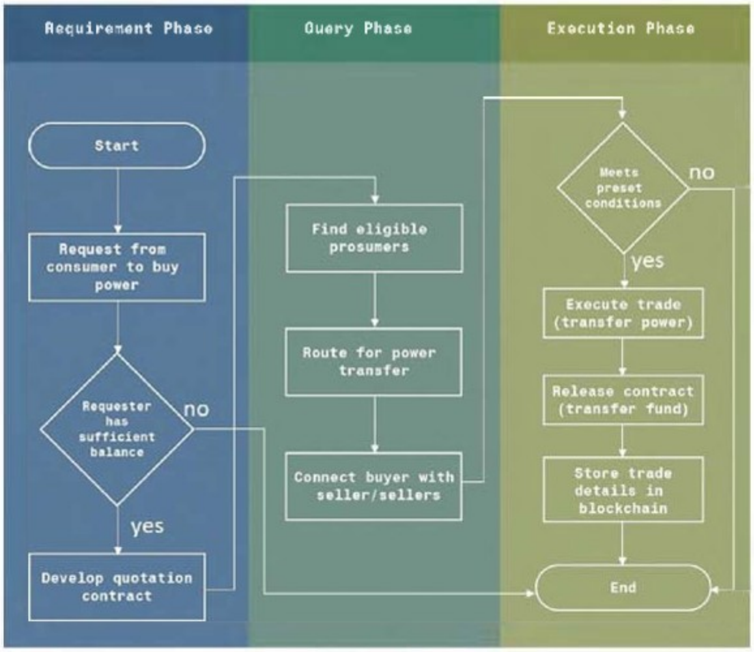


Figure 2.3: Trading process flow

implement blockchain-enabled P2P energy trading.

2.2.6 Communication System

The authors in [31] developed a system architecture for local P2P energy trading that consists of five layers: power grid, communication network, cloud management, blockchain, and application. The work evaluated the performance of HAN for a smart prosumer and NAN for a centralized community-based P2P architecture using the OPNET modeler. Different wireless and wired communication technologies were considered for a community P2P from one to ten peers. In [32], the authors investigated a standalone solar PV system concerning rural electrification in least developed countries to underline the potentiality of P2P energy sharing. An IoT-enabled automated solar energy sharing system has been developed to enable rural communities to install low-cost energy sharing systems and exchange surplus energy for sustainable energy solutions.

2.3 Energy Trading Projects

In [33], eight P2P energy trading platforms were analyzed to understand what makes P2P energy trading platforms more functional. Specifically, five items were compared, which are ”Grid Set-Up”, ”Market Mechanism”, ”Price Mechanism”, ”Information System”, and ”Regulations”. The work considered electrifying rural or remote areas by incorporating the use of renewable energy and energy storage systems and highlighted that the implementation of public policies should be developed to promote the use of the P2P energy trading system. This section summarizes the main P2P energy trading projects given in Table 2.3 .

Table 2.3: Main P2P energy trading projects.

Project	**Country**	**Year**
Vandebron	Netherlands	2014
Piclo	UK	2015
sonnenCommunity	Germany	2016
Power Ledger	Australia	2016
Vattenfall Powerpeers	Netherlands	2016
Brooklyn Microgrid	USA	2017
SunContract	Slovenia	2018
Brazilian Energy Communities	Brazil	2021

2.3.1 Vandebron

Vandebron is an energy company, founded in the Netherlands in 2014, that sources renewable electricity from local solar farms and large wind parks [34]. In 2017, Vandebron partnered with a smart electric vehicle charging station provider for homes and businesses, aiming to enhance grid stability using blockchain technology. The platform allows customers to support carbon offset projects in developing countries through their gas consumption. By leveraging a P2P model, Vandebron ensures that producers receive higher energy rates while consumers contribute directly to the growth of local renewable energy production.

Figure 2.4: Operation model of Vandebron

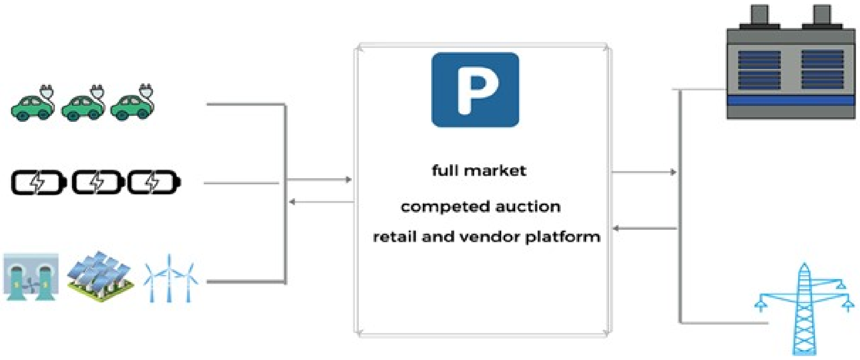


Figure 2.5: Operation model of Piclo

2.3.2 Piclo

Piclo is the first P2P market platform in the UK for renewable energy [35]. It utilizes advanced algorithms to match user demand with power generators based on preferences and location, and providing consumers with hourly data visualization and analysis. The energy supply company Good Energy manages contracts, metering data, pricing, and market insights, facilitating user interaction. Producers have the ability to impose producer taxes, while the costs of installing and maintaining local distribution networks are recovered through Distribution Use of System (DUoS) charges. These tariffs vary based on the electricity passing through the distribution network, as well as location and time of use. Piclo's DUoS model applies discounted rates for demand-supply matches, offering a weaker price signal than the Network Replicating Private Wires model, which aims to encourage more localized energy matching. However, this model is not well-suited for a large number of UK users, and its implementation may face challenges due to regulatory constraints.

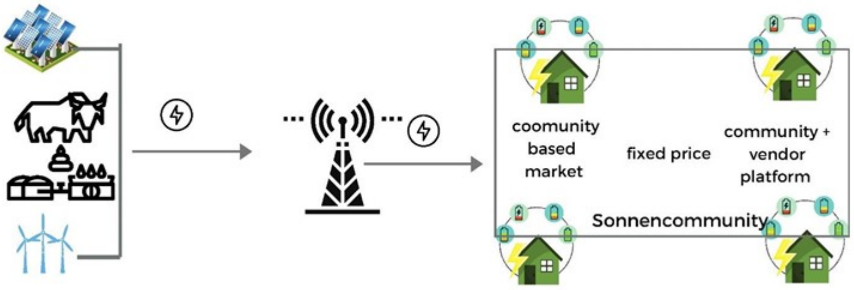


Figure 2.6: Operation model of SonnenCommunity

2.3.3 SonnenCommunity

SonnenCommunity is a platform for renewable energy trading founded in Germany in 2016. The SonnenCommunity is oriented to use a central software that connects and tracks all community members to achieve a balance between energy supply and consumption [36]. This project integrated various types of energy, such as solar, wind, and biomass energy, as shown in Figure 2.6.

For stabilization of power grids, distributed grid operators ensure constant supply and distribution of energy. Thousands of users of SonnenBatterie (the intelligent control center of the Sonnen Community) are connected to each other via Razonen-Flat-Box with huge battery reserves, creating the integration of a large number of independent home storage units. The massive volumes of energy accumulated through such ”virtual storage” contribute to the stabilization of the public power grid. As an intelligent control center, sonnenBatterie makes it easy to optimize solar energy consumption. For example, in the morning, when energy consumption is high but production is low, the sonnenBatterie allows the energy stored in the previous day to be used, while in the evening, when energy production is at its highest, the sonnenBatterie stores the largest proportion of energy produced.

2.3.4 Power Ledger

Power Ledger is a P2P energy trading platform that leverages blockchain technology to streamline market transactions and clearing processes. Power Ledger was founded in Aus-

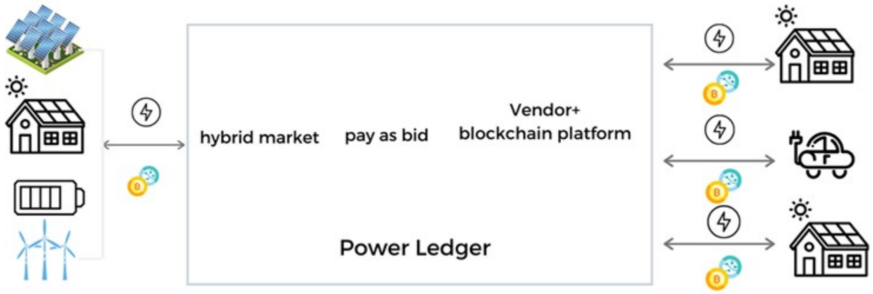


Figure 2.7: Operation model of Power Ledger.

tralia in 2016 [37]. This system enables both residential and commercial users to trade excess energy within the grid or operate as independent microgrids. However, energy trading through the distribution network requires that a portion of the profits be allocated to grid operators.

Power Ledger facilitates battery sales, storage, and utilization, with a strong emphasis on expanding renewable energy access for residential consumers. It has also developed an asset ownership model designed to enhance the activation and utilization of renewable energy resources. This platform was built based on Ethereum network contracts and introduced a dual token model for exchanging energy between self-generating residential units and neighbors. Figure 2.7 shows the power ledger operation model.

2.3.5 Vattenfall Powerpeers

Powerpeers is a social media-based energy platform and Europe's first digital and interactive marketplace designed to integrate local supply and demand for self-generated energy [38]. Powerpeers was founded in the Netherlands in 2016. Its goal is to make energy sharing as seamless as booking a stay on Airbnb, offering users the flexibility to choose their energy sources and consumers.

The Powerpeers platform enables energy trading by allowing customers to create a personalized supply mix from up to ten fully transparent sources. Users can also invite friends to participate in energy sharing. Producers can be selected according to location, energy type, or description, with no restrictions as long as supply is available. In addition, customers

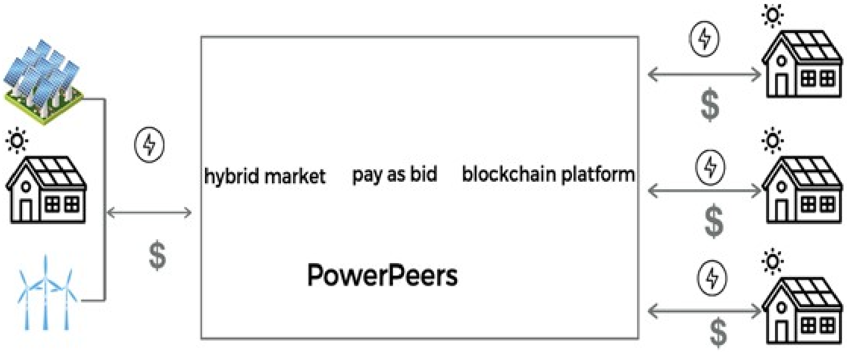


Figure 2.8: Operation model of Powerpeers

can change their preferred producers daily.

As a user-centric platform, Powerpeers operates on a many-to-many model, where consumers can have multiple energy suppliers, and suppliers can serve multiple consumers. This approach contrasts with traditional one-to-many energy supply models, which introduces real-time digital interaction into the energy market. The platform digitizes each kilowatt hour (kWh), ensuring near-instantaneous matching of supply and demand while providing full traceability of energy sources and quantities.

2.3.6 Brooklyn Microgrid

Brooklyn microgrid is a demonstration project in Brooklyn, New York, in 2017, based on the Ethereum photovoltaic energy trading platform. The project involved 50 residents who installed solar panels. The platform allows prosumers to decide whether to trade their self-generated solar energy, store the surplus in an online or offline storage device, or use the energy for domestic purposes. Energy transactions between neighbors are controlled by a blockchain network, where household meters indicate energy production and consumption activities. Figure 2.9 shows the operation model of Brooklyn microgrid.

The network uses the TransActiveGrid platform to ensure the security of customer transactions, which can be automatically produced from smart meters and smart contracts. Thus, the Brooklyn microgrid achieves the integration of the online energy market community

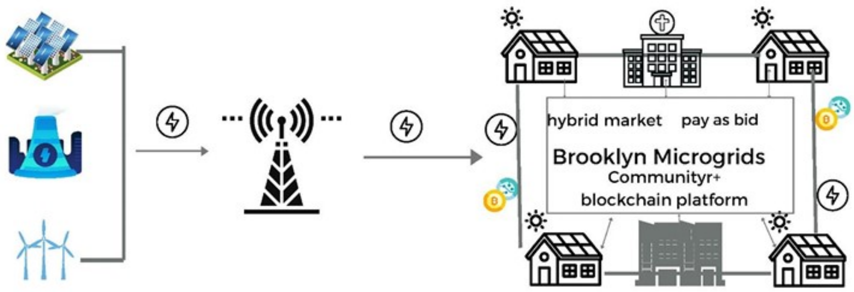


Figure 2.9: Operation model of Brooklyn Microgrid

and the energy distribution network. In addition, to avoid power interruptions, physical microgrids were established alongside the existing grid. In addition, the Brooklyn microgrid adopts a dual auction mechanism so that essential infrastructure (e.g., hospitals) can obtain power at a reasonable price, while residential and commercial units must bid for the remaining available energy.

2.3.7 SunContract

SunContract is a blockchain-powered peer-to-peer (P2P) platform that operates nationwide, enabling individuals to freely buy, sell or trade electricity. SunContract was established in Slovenia in 2018. Its primary objective is to enhance energy autonomy and sustainability by fostering a self-sufficient of renewable energy community with minimal environmental impact [39]. The company has developed an energy pool that connects electricity producers and consumers, facilitating energy trade. This pool allows participants to choose their preferred buyers and sellers, while giving producers the ability to set their own sale prices through double auction bids on the marketplace.

2.3.8 Brazilian Energy Communities

The energy communities in Brazil have historically emerged in three different contexts [40]. First, in rural areas without access to public utility services, where consumers often organized through rural cooperatives to develop their own distribution networks or

Figure 2.10: Operation model of SunContract

power generation facilities. Second, isolated communities, geographically distant from public utilities, which establish self-sufficient microgrids and energy resources to meet their needs. Third, prosumers connected to public utilities engaged in electricity trading through net metering programs. The first two types of community have been essential in expanding electricity access to populations underserved by traditional power providers. The Brazilian Energy Communities represent a novel approach to renewable energy trading within the framework of microgrids. With a focus on P2P energy exchange, these communities could be designed to harness and distribute renewable energy sources, primarily solar energy throughout Brazil.

This system not only ensures a continuous supply of renewable energy, but also plays a crucial role in stabilizing Brazil's power grid. A key feature of the Brazilian model is its energy pools, where the surplus energy generated by individual members — particularly during peak production periods — is stored for collective use within the community. Brazilian communities adopt a model that encourages participation and fair compensation to address the circular economy based on the local level. Prosumers are incentivized through a pricing structure that rewards them for their contributions to the energy pool via a blockchain account. This strategy ensures an equitable distribution of benefits among community members and promotes a more widespread adoption of renewable energy practices. The operation model can be seen in Figure 2.11.

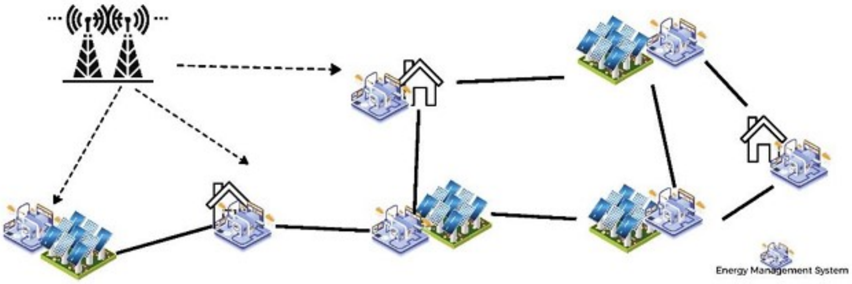


Figure 2.11: Operation model of Brazilian energy communities.

2.4 Testbed Implementation and Laboratory Experiments

In [41], the authors presented technical details for the use of IoT and blockchain to develop P2P energy trading. The work provided an open-source platform for a decentralized architecture as a proof-of-concept with two peers without a third party. Figure 2.12 shows the hardware setup used which consists of an Arduino UNO microcontroller and a current sensor.

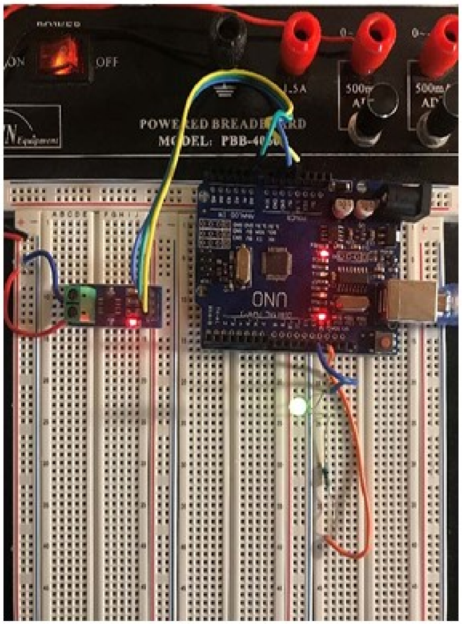
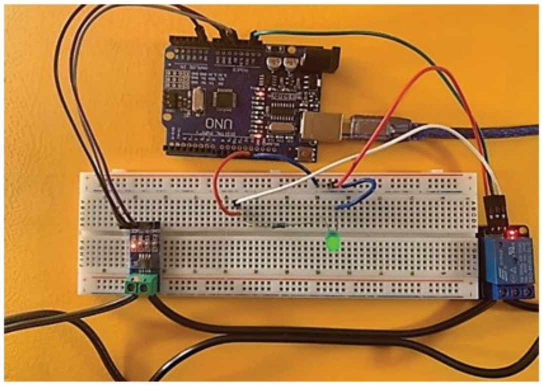
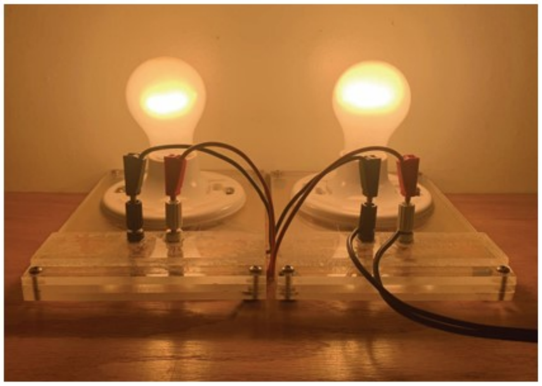


Figure 2.12: Hardware setup proposed.

In [42], the authors used open technologies to enable P2P energy trading for microgrids using IoT to transfer energy through peers, incorporating the use of Ethereum and Ganache to conduct energy exchange through a web platform. The hardware was implemented using an Arduino UNO, a relay, and current sensors that send the data to the server, and e-mail notification for transactions is incorporated, as shown in Figure 2.13.



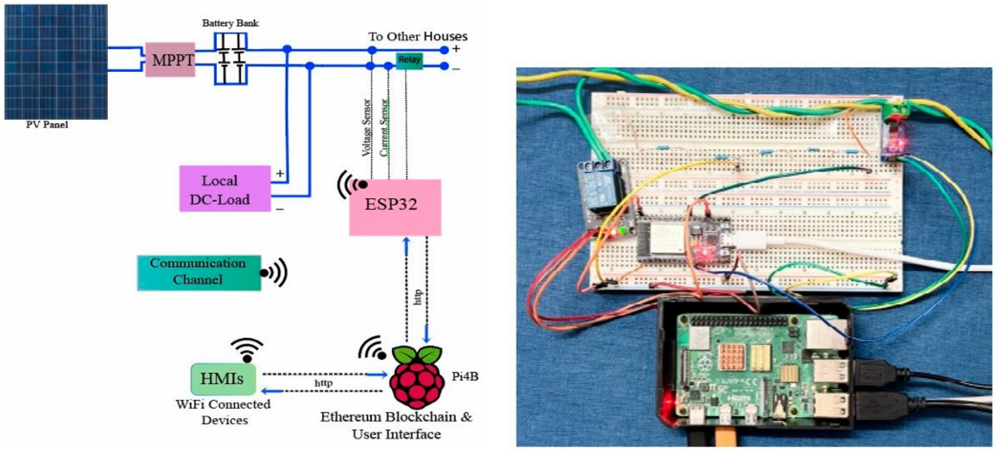
(a) Hardware prototype using Arduino UNO.



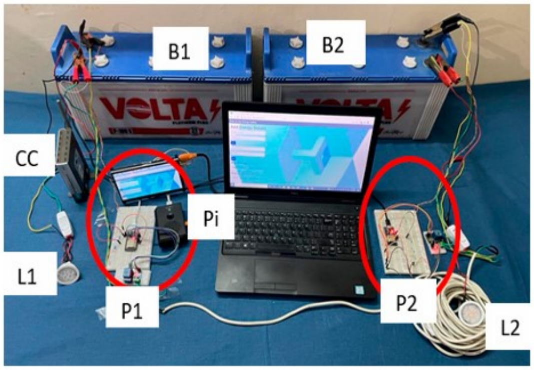
(b) Load example.

Figure 2.13: Experiment setup implemented (a) Arduino UNO, relay, and current sensor (b) Load.

In [43], a low-cost open source P2P energy trading was developed for a remote community. The system was developed for a rural area in Pakistan where a Raspberry Pi 4B will work as an IoT server and the ESP32 as a microcontroller. The system considered a user interface and an Ethereum blockchain server. A WiFi network and the Hyper Transfer Protocol were utilized to communicate between the server and the client. The developed system allowed users to sell and buy energy through the created interface. Figure 2.14 shows a general diagram of the system and the hardware experiment.



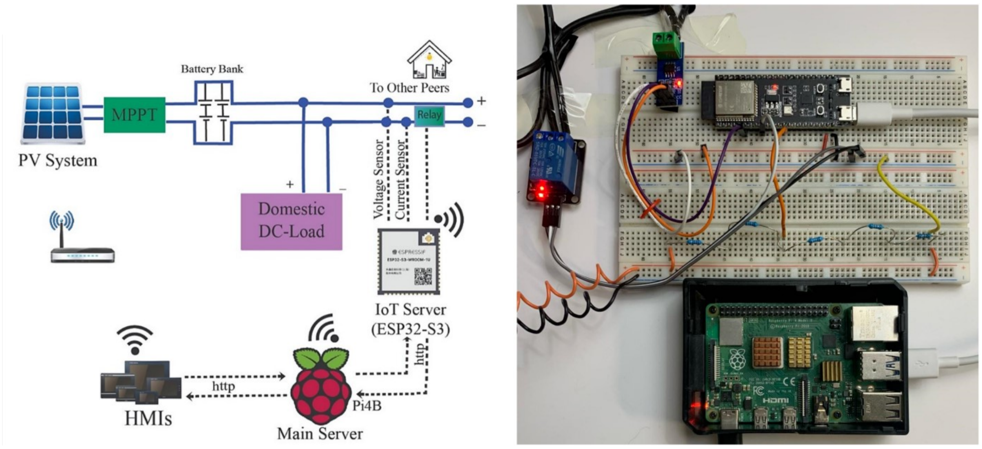
(a) General diagram of the prosumer system. (b) Hardware prototype using RaspberryPi.



(c) Laboratory experiment testbed.

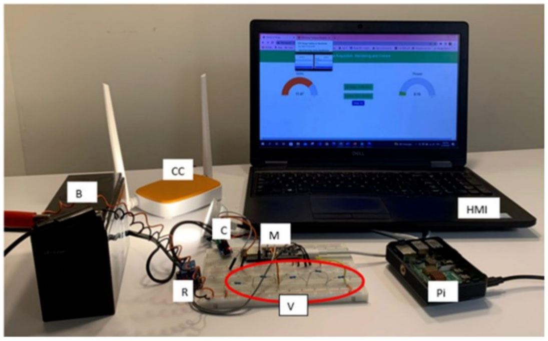
Figure 2.14: Experiment setup for P2P system (a) General diagram (b) Hardware prototype (c) Testbed

In [44], the authors presented a blockchain-based P2P energy trading system using IoT. The UI server of this work was built using a Raspberry Pi 4, which was connected to the interface through an ESP32-S3 microcontroller, as shown in Figure 2.15. Furthermore, the work selected the Ethereum blockchain to provide security for energy and money transfer, and Angular was used to develop a web platform.



(a) General diagram of prosumer system.

(b) Hardware prototype.



(c) Laboratory experiment testbed.

Figure 2.15: Experiment setup for P2P system (a) General diagram (b) Hardware prototype (c) Testbed.

The authors in [45] described a user-centered cooperative mechanism that enhances user participation in P2P energy trading. The work carried out an experiment with 19 houses and 9 electric vehicles (EV) to evaluate the P2P energy trading system in view of feasibility and economics aspects. The work also designed a trading agent that allows energy trading to be performed on behalf of the user in such a way that the user does not take any action. Decisions can be made through the essential requirements that are measurement, prediction, and ordering. The main component is called the home agent, whose process can be seen in Figure 2.16. An example of a tested hardware configuration can be seen in Figure 2.17. Finally, the study confirmed that prosumers were able to sell their surplus electricity and that consumers preferentially purchased renewable energy when it was available.

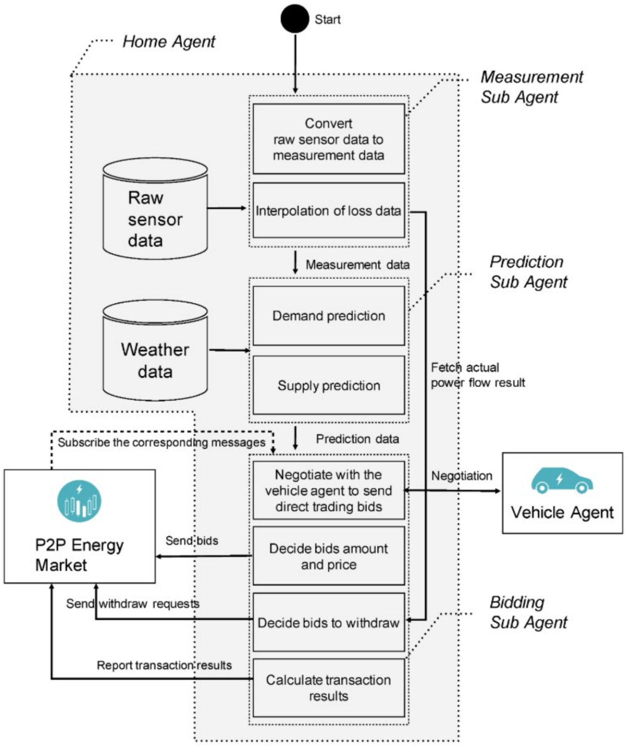


Figure 2.16: Home Agent mechanism flow chart

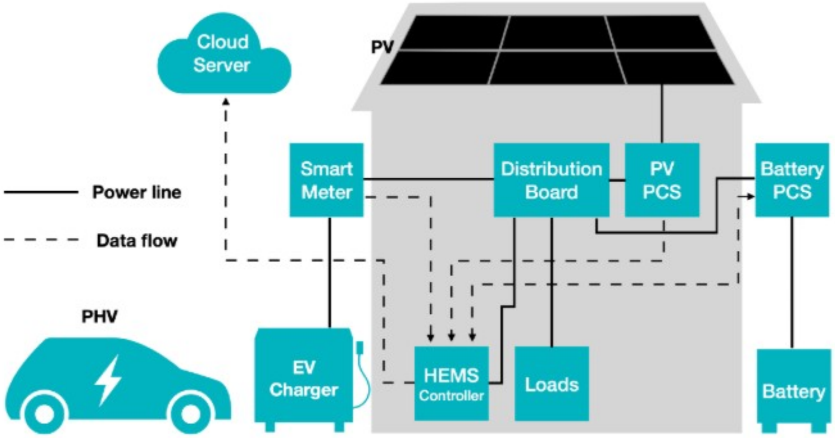


Figure 2.17: Hardware diagram testbed in Higashi-Fuji Demonstration

The authors in [46] explored the design of local energy markets and how they are relevant for smart grid and microgrid applications and their contribution to sustainability in smart cities. The work introduced the concept of local energy market for P2P energy trading with six case studies that present a platform for blockchain-enhanced energy exchange. In [47], the authors presented an open-source energy trading platform that provides real-time data acquisition. The developed system uses an interface that utilizes a private Ethereum blockchain, an IoT server to monitor the trading between peers, and an ESP32-S2 microcontroller for the system. The work uses the message queuing telemetry transport (MQTT) protocol for data transfer over a local network.

Unlike the other works, the authors in [48] analyzed the use of aggregated battery control in a residential microgrid. The main contribution of the work was to explore the advantages of battery control and to formulate the problems associated with the implementation of P2P energy trading when the sensing and communication capabilities are limited. In [49], the explanation of the use of blockchain technology for a decentralized architecture for energy exchange was reviewed. Ethereum was used and the system was tested at the laboratory level, as shown in Figure 2.18. The work introduced a multilayer framework for P2P energy trading and presented what types of sensors and components should be used. The authors in [50] developed a working model for the purchase and sale of energy units, thus reducing the waste of energy produced. This can be achieved by establishing a user-oriented software platform. The platform was built using React JS and Node JS. An analysis of the time required to send values between MQTT and the HTTP protocol in tabular format was given. The developed architecture in shown in Figure 2.19.

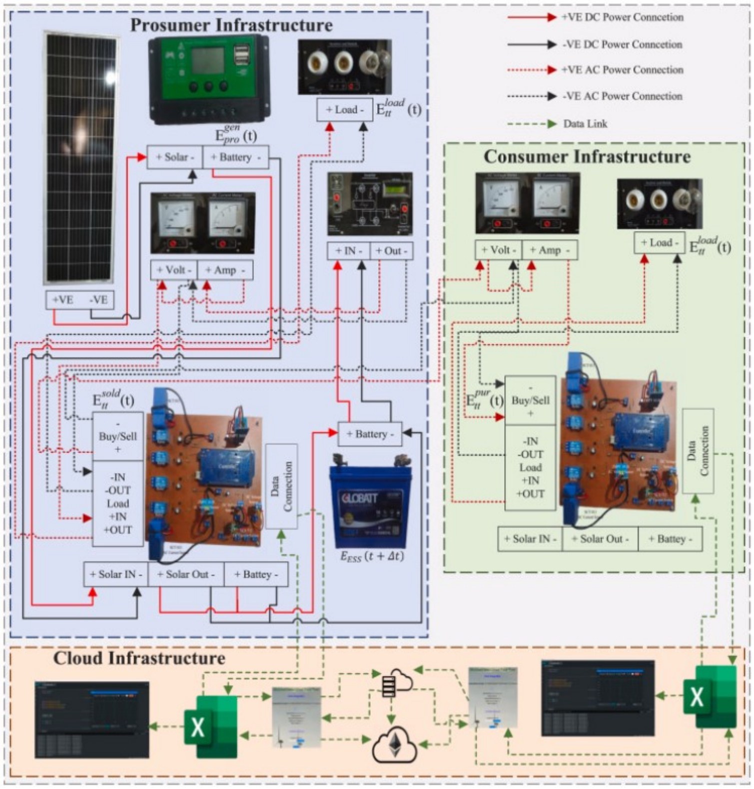


Figure 2.18: General microgrid connection in a laboratory experiment.

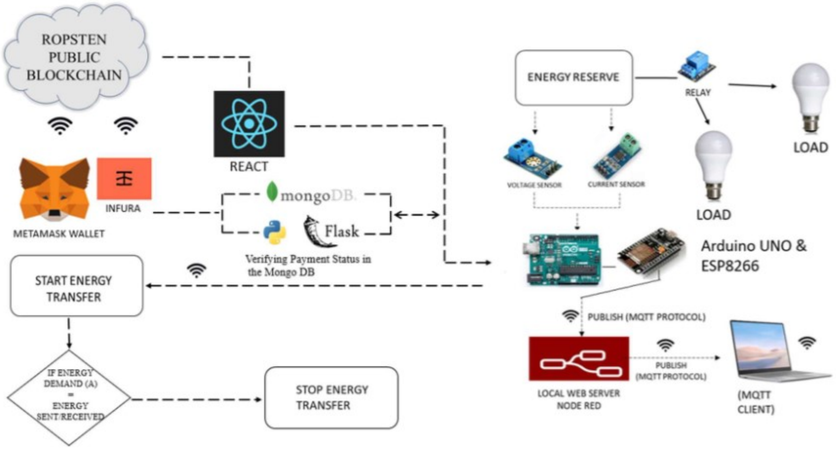


Figure 2.19: Architecture diagram of the laboratory experiment.

Table 2.4 summarizes the main implementation and laboratory setup of P2P energy trading, while Tables 2.5 and 2.6 summarize the main studies of P2P energy trading.

Table 2.4: Literature review for laboratory experiment of P2P energy trading system. "✓" represents "included", a cross mark "×" represents "not included" in the reviewed articles.

Reference	**Year**	**Sensor Meter**	**Communication Network**	**Cloud Service**	**Blockchain**	**User Interface**
[23]	2019	×	×	×	×	×
[25]	2019	×	×	×	✓	✓
[41]	2020	✓	✓	×	✓	✓
[42]	2021	✓	✓	×	✓	✓
[43]	2022	✓	✓	×	✓	✓
[44]	2023	✓	✓	×	✓	✓
[45]	2021	✓	✓	✓	✓	No specify
[47]	2021	✓	✓	×	✓	✓
[49]	2024	✓	×	×	✓	✓
[50]	2022	✓	✓	×	✓	✓
This work	2025	✓	✓	✓	✓	✓

Table 2.5: Summarize of literature review for main P2P energy trading.

Reference	Year	Type	Contribution
[5]	2024	Simulation	Sensitive analysis of local P2P PV energy trading in a community microgrid.
[12]	2019	Review	Examine two types of P2P mechanisms.
[13]	2024	Review	Explore the advantages of blockchain-based P2P energy in the DERs integration and compared the profitability of systems.
[16]	2017	Review	Propose and define three P2P energy trading market paradigms.
[17]	2022	Survey	Identify the challenges of P2P energy trading.
[18]	2018	Review	Present a four-layer architecture to implement P2P energy trading.
[19]	2022	Review	Present the advantages and challenges of P2P energy trading and proposed architecture with five layers.
[23]	2019	Review	Evaluate the impact of P2P energy trading between smart homes of a microgrid, algorithms with heuristics are proposed to solve the problem of less computation.
[24]	2023	Review	Propose a connection system between the microgrid and the grid to realize the energy exchange.
[25]	2019	Review	Developed a smart contract and compared different Blockchains.

Table 2.6: Cont. Summarize of literature review for main P2P energy trading.

Reference	**Year**	**Type**	**Contribution**
[26]	2019	Review	Discuss a conceptual architecture of blockchain in a negawatt trading system.
[27]	2018	Review	Use the Hyperledger Fabric framework and define actors in P2P energy trading.
[28]	2019	Review	the authors evaluate the impact on the blockchain network with throughput, latency, and scalability.
[31]	2023	Communication Simulation	Develope architecture for local P2P energy trading and evaluated the performance of HAN/-NAN wireless and wired communication for a community P2P.
[41]	2020	Laboratory experiment	Present a basic hardware setup.
[43]	2022	Implementation	Real P2P energy trading implementation in remote area.
[45]	2021	Implementation	Experiment P2P energy trading with houses and EV, and design a smart agent.
[47]	2021	Laboratory experiment	Develop a system with MQTT protocol
[49]	2024	Laboratory experiment	Specify connections and sensors used in the proof of concept
[50]	2022	Laboratory experiment	Build a web platform using frameworks, MQTT and HTTP protocol.

Chapter 3

Local P2P Energy Trading Architecture

The IoT will play an important role in supporting the future Smart Grid (SG) systems by enabling various network functions across energy generation, transmission, distribution, and consumption. This will be achieved through the integration of IoT devices, together with connectivity, automation, and monitoring capabilities for these devices [51]. In the literature, most of the works have covered IoT and SGs separately, while others have summarized IoT-assisted SG systems. This thesis seeks to develop and implement an IoT-aided SG architecture for local P2P energy trading. This chapter explains the proposed P2P energy trading architectures and the market design. First, the types of IoT and smart grid architectures are defined in a general way and later define our proposed architecture. In addition, this section provides an overview of the main technologies that are needed for the implementation of the P2P energy trading platform. The three-dimensional SG architecture added with the IoT architecture is defined. Finally, this chapter presents the market design to be developed in this thesis.

3.1 IoT-based Architectures

IoT is a framework in which all things have a representation and presence on the Internet [52]. The ”Things” are various, such as sensors, people, actuators, vehicles, among others.

Considering perspectives of IoT systems, there are important characteristics that need to be considered:

- *Sensor Data Acquisition, Storage, Filtering, and Analysis:* observation of physical environment/entity and direct data to Cloud for storage and analysis.
- *Connectivity:* interconnection between Physical and Virtual things with the help of the Internet and global communication infrastructure.
- *Device Heterogeneity and Intelligence:* the interoperability of devices (based on different network hardware platforms) with the provision of ambient intelligence at the hardware and software level enables intelligent interactions.
- *Scalability:* the connectivity of IoT devices shifts from human interactions to device-to-device interactions.
- *Security:* the security paradigm is required to be implemented on the network to ensure data security.

IoT architectures can be represented in different ways, with the most common models being Three-layer, Five-layer, and Six-layer. Although IoT architectures share the same fundamental objective, their distinction lies in how they divide system functionalities between layers. The most common layers are:

- **Things Layer:** includes smart devices with sensors and controllers that send and receive data.
- **Connectivity Layer:** manages real-time data transmission using various communication protocols.
- **Data Storage Layer:** ensures data consistency and efficient storage for application use.
- **Application Layer:** categorizes and processes data for specific applications.

The three-layer model is the simplest model, as shown in Figure 3.1.(a). It is made up of:

- **Perception Layer:** collects data from physical sensors and transmits it to the network.
- **Network Layer:** transfers data through IoT gateways and integrates multiple networks.
- **Application Layer:** provides user services and processes data for analysis.

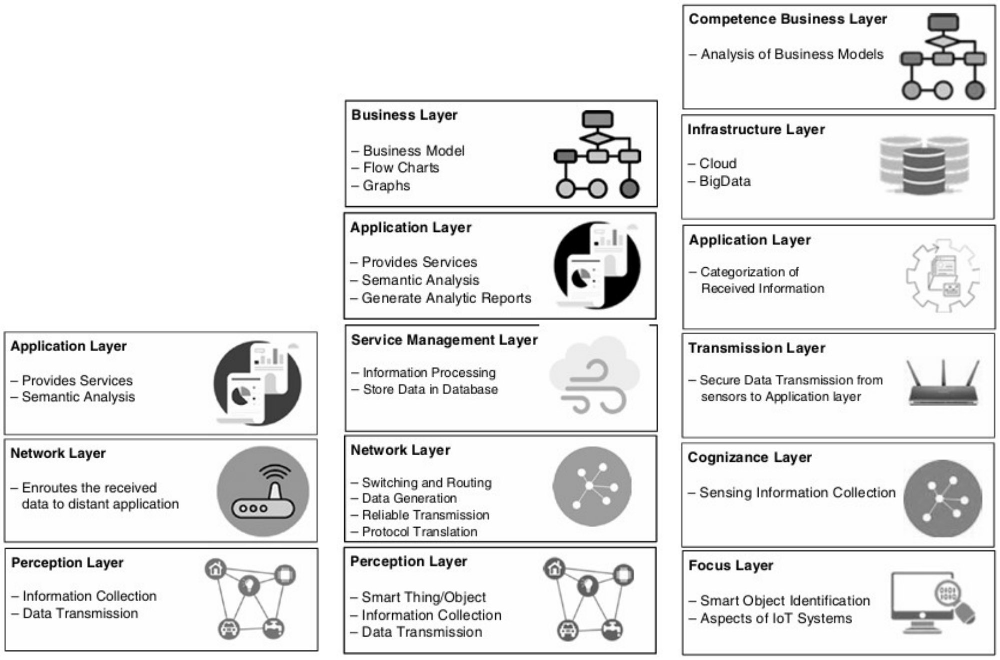
The five-layer model extends the three-layer architecture by adding middleware for data processing and a business layer for strategic decision-making, as shown in Figure 3.1.(b). This architecture is composed of:

- **Object (Perception) Layer:** identifies and collects data through physical sensors.
- **Object Abstraction (Network) Layer:** secures and transmits data for processing.
- **Service Management (Middleware) Layer:** matches services with requests and processes heterogeneous data.
- **Application Layer:** delivers user services and enables semantic data analysis.
- **Business Layer:** oversees IoT operations, automates decision-making, and supports business strategies using Big Data.

The six-layer architecture comprises of the Focus Layer, Cognizance Layer, Transmission Layer, Application Layer, Infrastructure Layer, and Competence Business Layer, as shown in Figure 3.1.(c). This model is designed for integrating multiple IoT systems across different domains and analyzing their business impact. It consists of:

- **Focus Layer:** identifies smart objects and key aspects of IoT systems.
- **Cognizance Layer:** collects data through sensors, actuators, and monitoring modules.

- **Transmission Layer:** transfers collected data to the application layer.
- **Application Layer:** organizes data based on different application needs.
- **Infrastructure Layer:** manages service-oriented technologies such as cloud computing, Big Data, and data mining.
- **Competence Business Layer:** analyzes the IoT business models and the implications for value.



(a) Three-layer architecture (b) Five-layer architecture (c) Six-layer architecture

Figure 3.1: Different IoT-based architectures.

3.2 SG-based Architectures

Previous research works have presented different architectures for smart power grids and smart community-based microgrids. In [18], the authors identified and classified the key elements and technologies involved in P2P energy trading based on their roles. The system architecture was structured into three dimensions. The first dimension encompasses the fundamental components and technologies required for P2P energy trading, organized into a four-layer architecture.

- **The Power Grid Layer** includes all physical elements of the power system, such as smart meters, loads, and distributed energy resources (DERs). These components form the physical electricity distribution network.
- **The ICT Layer** comprises communication devices, protocols, applications, and information flow. Communication devices include sensors, network connections, and protocols such as TCP / UDP. Information flow refers to data exchanges between senders and receivers.
- **The Control Layer** focuses primarily on the control functions of the electricity distribution system, including voltage control, frequency regulation, and active power management.
- **The Business Layer** defines how electricity is traded among peers and third parties. It involves participants such as prosumers, suppliers, distribution system operators (DSOs), and energy market regulators.

The second dimension of the system is classified based on the scale of the peers participating in P2P energy trading, including premises, microgrids, cells, and regions.

- An **Individual Premise/Home** refers to a single household connected to the electricity distribution system.
- A **Microgrid** consists of multiple premises/homes that can operate in either grid-connected or islanded mode.
- A **Cell** contains several microgrids and may also function in grid-connected or islanded mode.
- A **region** can be as large as a city, where multiple cells act as peers and trade energy with each other.

The third dimension represents the time sequence of the P2P energy trading process:

1. **Bidding**- The initial stage where participants negotiate and establish agreements.
2. **Energy Exchange**- The phase in which energy is generated, transmitted, and consumed.
3. **Settlement**- The final stage where transactions are processed and payments are made according to settlement arrangements.

In [19], the authors presented a comparison among different layer architectures for community microgrids. Some of the architectures followed the Smart energy Grid Architecture Model (SGAM) which consists of layers (components, communication, information, function, and business), domains (generation, transmission, distribution, DER, and customer premises), and zones (process, field, station, operation, enterprise, and market), as shown in Figure 3.2. The main aim of peer-to-peer energy trading is to support direct energy trading among prosumers and consumers based on the concept of a sharing economy or P2P economic. This P2P energy trading is enabled and supported by information and communication technologies [53].

In [22], the authors proposed an IoT–blockchain architecture for P2P energy trading in a microgrid. The system is composed of multiple entities that are divided into two layers: the physical layer and the virtual layer. The physical layer is the IoT layer and the virtual layer is composed by Off-Chain and Blockchain layer. In [31], the authors represented a five-layer architecture which consists of the power grid, communication network, cloud management, blockchain, and application. Table 3.1 shows different architectures for P2P energy trading system.

Table 3.1: Different Architectures for P2P energy trading system

[18]	[19]	[22]	[31]
Power Grid Layer ICT Layer Control Layer Business Layer	Physical Layer ICT Layer Control Layer Market & Business Layer Regulatory Layer	IoT Layer Off-Chain Layer Blockchain Layer	Power Grid Layer Communication Network Layer Cloud Management Layer Blockchain Layer Application Layer

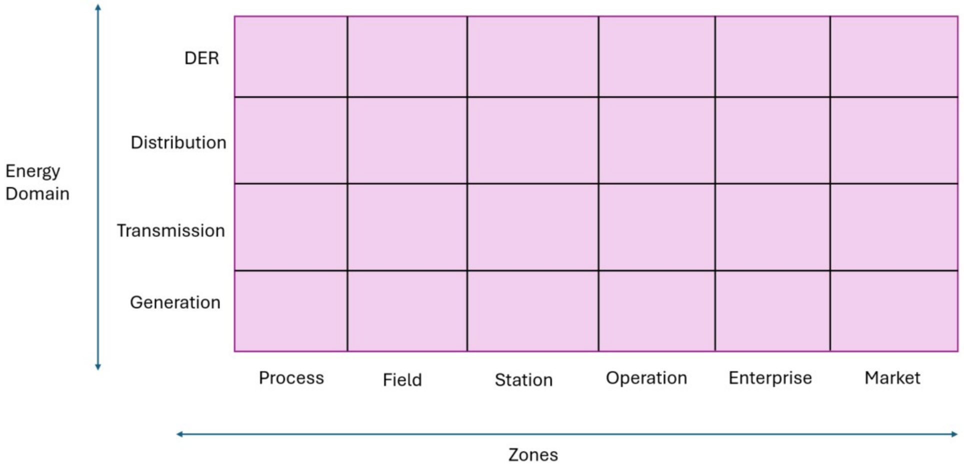


Figure 3.2: General SGAM architecture for P2P energy trading.

Based on the Smart Energy Grid Architecture Model (SGAM), to efficiently manage the electrical system, different zones of control are defined:

- **Process Zone:** handles real-time control of generation, transmission, and distribution processes.
- **Field Zone:** includes sensors, smart meters, and local controllers that monitor and automate electrical equipment.
- **Station Zone:** manages the substations that regulate voltage, frequency, and power flow.
- **Operation Zone:** controls and optimizes grid functions at a regional level.

- **Enterprise Zone:** focuses on business-level decision making, including energy trading and corporate strategies.
- **Market Zone:** manages energy markets, trading platforms, and regulatory frameworks for electricity pricing and transactions.

3.3 Proposed SG-IoT Architecture

3.3.1 SG-based Architecture

In smart grid, the energy management system (EMS) is a crucial element that supports monitoring, protection, and control at different levels. Such EMSs manage both the electrical process (the actual flow and conversion of electricity) and the information flow (how data about the system are processed and used for control and decision making).

The smart grid can be structured as follows.

- Physical Domains of Electrical Energy Conversion Chains – These represent the different stages where electricity is generated, transmitted, distributed, and consumed.
- Hierarchical Zones of Electrical Process Management – These define how information is managed across different levels of control and decision-making.

The smart grid plane provides a framework that illustrates how the different domains interact with each other and what hierarchical levels are used for information management. This helps to understand the structure of the smart grid.

- *Domains (or chains) of energy conversion*, which include:
    - **Generation:** power plants and renewable sources producing electricity.
    - **Transmission:** high-voltage power lines that transport electricity over long distances.

  - **Distribution:** medium-voltage and low-voltage networks that deliver electricity to consumers.
  - **Distributed Energy Resources (DERs):** small-scale generation units such as solar panels and battery storage that integrate with the grid.

There are different types of end-user premises such as residential, commercial, and industrial consumers, where power producers generate and supply energies. On the other hand, P2P energy trading includes major players for the exchange of energy. Following the focus of this thesis, the following actors can be defined:

- **Consumer/Prosumer:** consumers (only consumes energy without generation) and prosumers (consumes and produces energy from renewable resources) actively participate in local energy markets, fostering community-driven sustainability and reducing dependence on traditional energy suppliers.
- **Coordinator:** a central entity or platform that facilitates and optimizes P2P energy trading. The coordinator fosters trust among participants, ensuring fair trade, transparency, and reliability of the network.
- **Microgrid:** independent local power grid that operates autonomously or in connection with the main grid. If scalability of the microgrid is desired, it can exchange energy with each other or interact with external grids.
- **Bulk Operator:** to complement the overall power grid, they can incorporate a connection to the large-scale grid operator or energy supplier who are responsible for balancing supply and demand at the national or regional level. Operators usually manage the integration of P2P energy trading with the main grid, ensuring that supply fluctuations do not disrupt grid stability.

The previously defined details of SG architecture can be visualized in a two-dimensional plane: on one side there are Energy Domains and on the other side there are the energy zones, as shown in Figure 3.3.

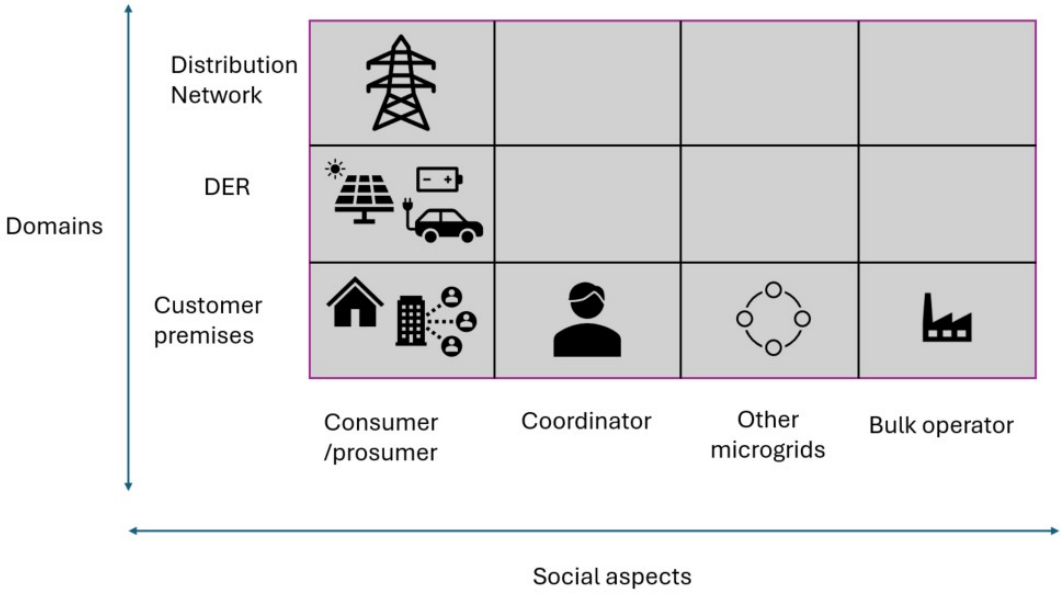


Figure 3.3: Proposed SG-based architecture for P2P energy trading.

3.3.2 SG-IoT-based Architecture

Taking into account the previous definitions, this thesis proposes a six-layer SG-IoT architecture for P2P energy trading. The complete SG-IoT architecture for P2P energy trading is shown in Figure 3.4.

- **Physical Layer:** This layer consists of physical objects that can be part of the home, such as solar panels, batteries, and electric vehicles, among others. The energy generated by the solar panels is part of this layer.
- **Data Acquisition Layer:** This layer consists of sensors and microcontrollers that can be used to measure data from different subsystems such as PV, BESS, and other devices.
- **Communication Layer:** This layer supports different technologies (wired/wireless communication) that can be used to communicate, such as WiFi and LoRa, which can be used in this work.

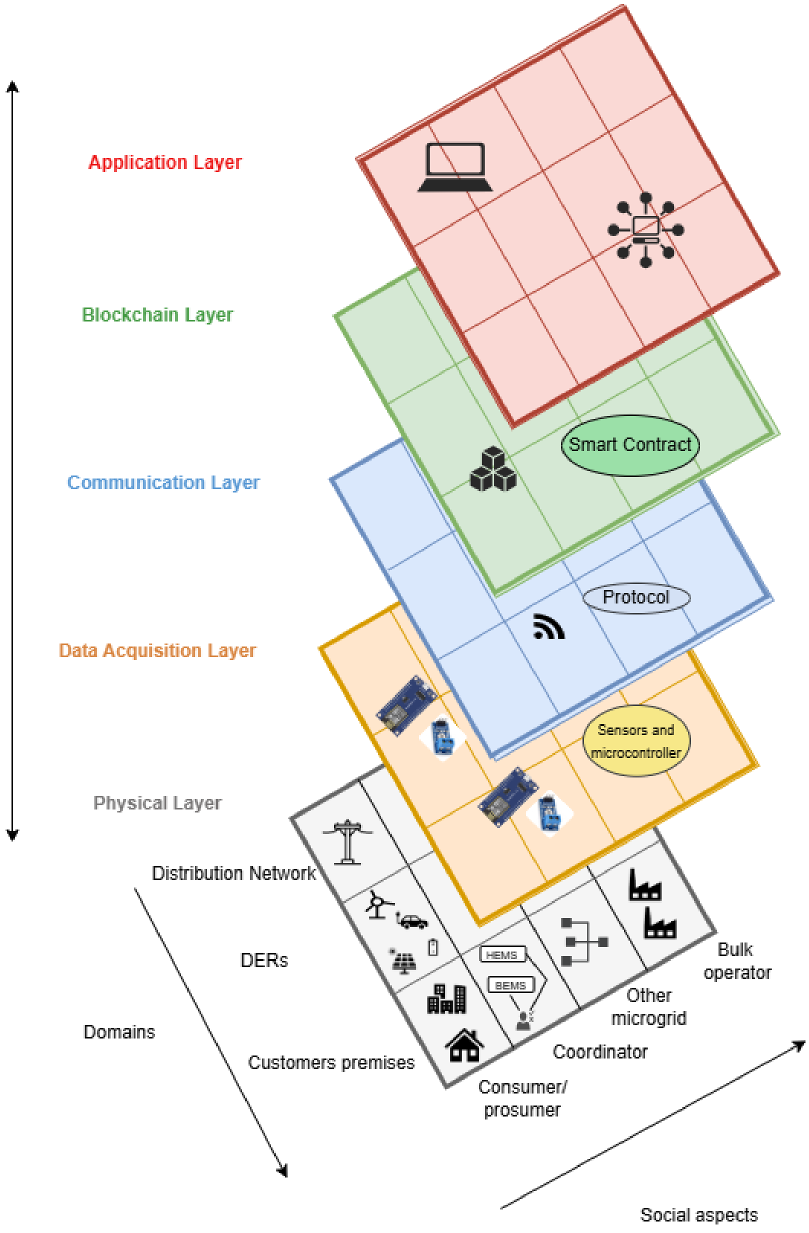


Figure 3.4: Proposed SG-IoT architecture for P2P energy trading.

- **Cloud:** This layer aims to store the data obtained by the sensors. ThingSpeak paltform is an example that can be used in this work, which is easy to configure and friendly to use IoT. In addition, saved data can be viewed through the cloud platform.
- **Blockchain Layer:** This layer considers the business behind energy trading, providing system security, transparency, and independence from external parties. This provides a decentralized system that can allow peers to make such a P2P trading process.
- **Application Layer:** This layer consists of the software developed to carry out the energy trading. It includes a user interface that allows the visualization of the energy exchange and allows to publish the prosumer's needs.

As the focus of this work is on a local community microgrid, Figure 3.5 shows the proposed IoT-based architecture. In each layer, the left part mentions the focus of the layer, while the right part names the function or the elements used. The layers can be briefly defined, and the technologies used in each layer can be summarized as follows.

3.3.2.1 Physical Layer

The physical layer consists of the physical things presented in the P2P energy trading system. Among the physical devices considered are the PV system, BEES, and electrical consumption in houses. These "things" will be connected to smart sensors / meters to measure energy production, energy storage, energy consumption, and home appliances, among others.

3.3.2.2 Data Acquisition Layer

The data acquisition layer is composed of sensors, microcontrollers, and smart meters responsible for measuring different parameters and depend on the "things" to be sensed. In this thesis, voltage and current sensors will be used for PV and BESS monitoring. In

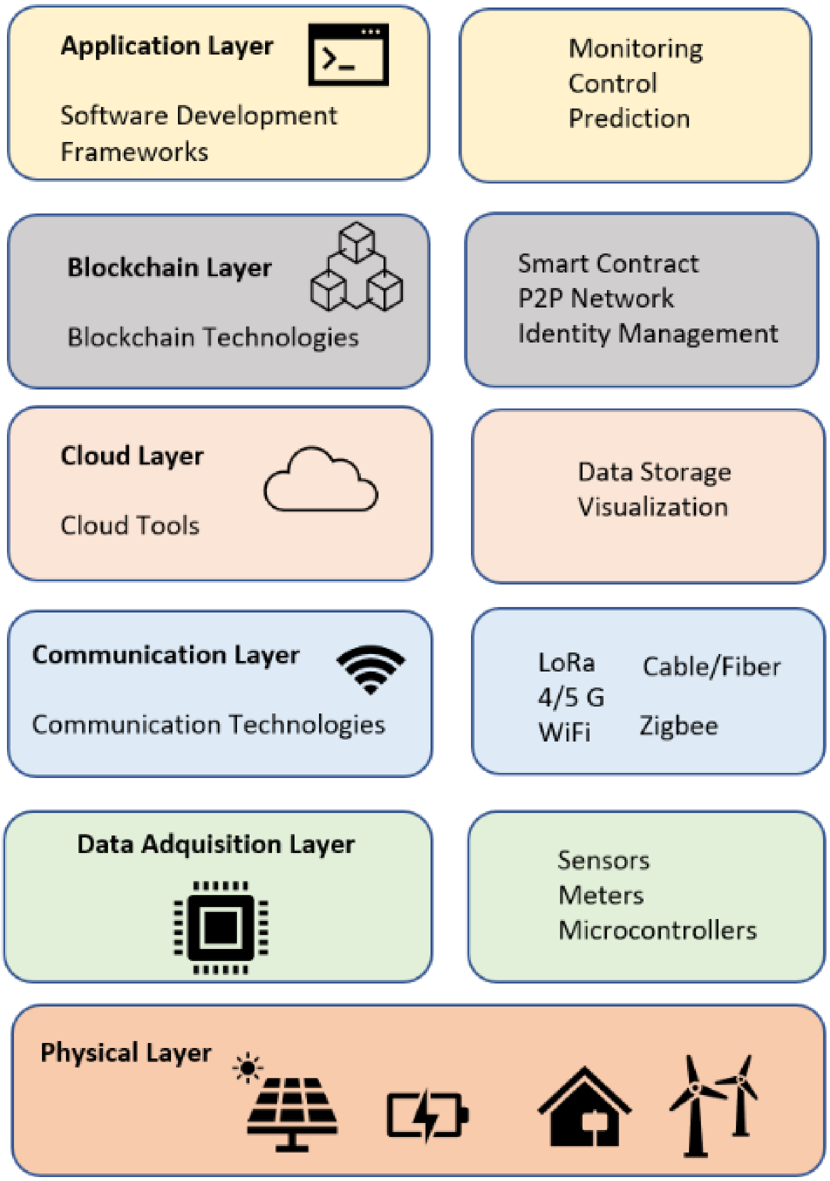


Figure 3.5: Proposed IoT architecture for P2P energy trading.

specific, the voltage sensor used is the model FZ0430 which is composed of a voltage divider of 30K and 7.5K resistors, so the maximum voltage that can be measured will be 25 V for a 5 V power supply and 16.5 V for a 3.3 V power supply. However, the current sensor used is the model SCT-013-010 which consists of a clip-on sensor for ease of installation and safety that allows an input current of 0-10A AC/1V. To monitor the energy consumption of the home, smart plugs are used [54], which consist of a sensor module that allows the measurement of voltage, current, power, and accumulated power. In addition, a time stamp was added to each measurement.

3.3.2.3 Communication Layer

The communication layer enables integration and communication between different devices and entities. In this work, two types of technologies (wired and wireless) will be implemented and analyzed. In addition, this layer incorporates IoT communication protocols such as MQTT, which will be used during the implementation of the testbed. In the context of smart homes, the communication layer can be divided according to the coverage range into Home Area Network (HAN) and Neighborhood Area Network (NAN). In the first case, HAN communication is of a short range, so the most common wireless technologies are WiFi, Zigbee, and Bluetooth. However, for the NAN, the communication range may vary according to the scenario. In the rural scenario, the range can be greater than in the urban case where the most common LPWAN wireless technologies are LoRa, NB-IoT, and Sigfox.

3.3.2.4 Cloud Layer

This layer is used for data storage through the use of cloud services. Some cloud services allow data visualization, such as ThingSpeak [55], which allows the integration of IoT projects and offers a non-commercial free service for small projects (<3 million messages/year or 8200 messages/day). It also allows integration with Matlab for data analysis. ThingSpeak allows to aggregate, visualize, and analyze live data streams in the cloud.

3.3.2.5 Blockchain Layer

This layer plays a critical role in enabling secure and transparent energy trading in the microgrid by providing a decentralized and trusted platform for energy transactions. This layer considers smart contracts to carry out the exchange of energy. The use of blockchain technology further enhances the security and efficiency of the energy trading platform by automating the execution and compliance of the platform rules. There are different types of public and private blockchains. The most common are Ehtereum, Hyperledger Fabric, Bitcoin, among others.

3.3.2.6 Application Layer

This layer helps to simplify the visualization of the collected data and to perform energy exchange between the end user and the coordinator. It is necessary to have a web application that facilitates these actions. Such a web application will enable users to monitor and control smart home with the use of HEMS and opens the door to the use of prediction and analysis of the data obtained by the data acquisition layer. Among the common technologies and frameworks to use are React JS and Angular.

3.4 Market Design for Peer-to-Peer Energy Trading

The implementation and operation of P2P energy trading requires an appropriate market design to effectively enable participants to share their resources with other peers in the same network. In general, there are three types of P2P marketplaces: centralized, decentralized, and hybrid. This work will focus on decentralized architecture.

3.4.1 Centralized Market

In a centralized market, the peers communicate their needs or will to a central entity, called the Coordinator, which decides the amount of energy, the purchase and sale prices, and

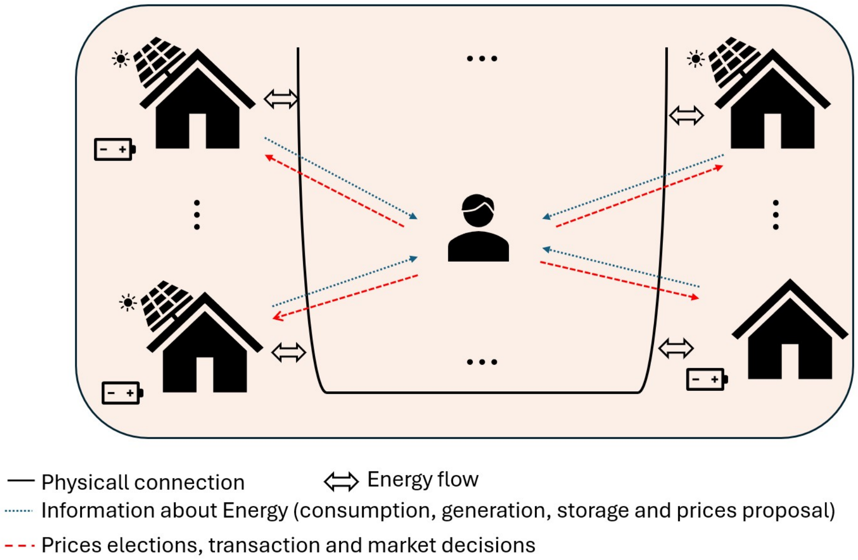


Figure 3.6: Schematic diagram of a centralized market model.

distributes the revenues among the peers. The complete availability of information at the central point results in the maximum overall social welfare of the P2P community compared to distributed and decentralized approaches, i.e., the coordinator handles all the information of the microgrid, overloading the communication infrastructure as everything goes through the coordinator, plus the peers share their data with the system operator.

During the operation of the centralized market, peers notify the central controller or coordinating entity of their intention to perform a transaction. The coordinating entity facilitates the transaction by connecting the peer with another party interested in buying energy. This adds a level of organization to the peer-to-peer market, where transaction confirmations are handled by the coordinator. The central entity determines aspects such as the amount of energy and the price and then distributes the energy among the peers. In this case, all peers share their data with the central entity or coordinator, generating a risk to their privacy, as can be seen in Figure 3.6.

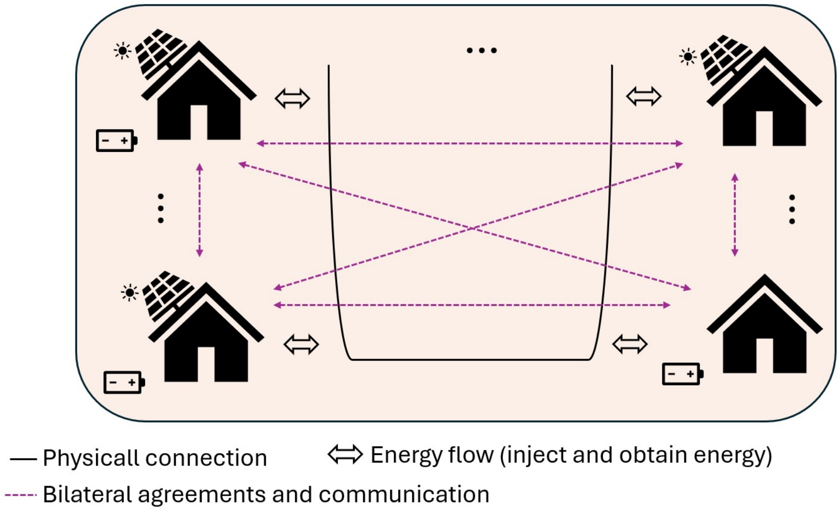


Figure 3.7: Schematic diagram of a decentralized market model.

3.4.2 Decentralized Market

In a decentralized market, there is no central entity coordinating transactions, as the trading is done individually. Each peer is completely independent in managing their devices and in making decisions about energy consumption and sales. Unlike centralized systems, the Coordinator is not involved in the trading process, which makes it difficult for the distribution utility to schedule resources, which may reduce the operational efficiency of the system. In addition, by prioritizing individual interests over collective welfare, this methodology tends to decrease the social welfare of the P2P community.

During the operation of the decentralized market, each peer is free to set the price at which it wishes to buy or sell its household energy. Furthermore, the distribution operator does not intervene in the transactions, allowing a completely decentralized market, as can be seen in Figure 3.7. The authors in [46] analyzed different energy trading markets. Following such analysis, Table 3.2 shows the comparison between the centralized and decentralized design.

market.

Table 3.2: Comparison between centralized and decentralized market design.

Market	**Advantages**	**Disadvantages**
Centralized	• Provides greater market coordination and overall efficiency • Reduces uncertainty of supply and demand • Ensures the viability of the daily dispatch • Provides clear and well-defined market prices • Provides high quality grid services and energy supply	• Diminishes participant autonomy and privacy • Suffers from vulnerability of single-point failure • Increases computational and communication burden • Offers slow response to network events in daily markets. • Offers little daily dispatch flexibility • Reduces market transparency and network scalability
Decentralized	• Provides high autonomy and privacy • Offers high reliability without occasional failures • Offers scalability • Facilitates and simplifies market clearing • Increases market transparency	• Low market coordination and overall efficiency • Complex network management • Reliance on block orders and complex bidding • Intraday continuous trading problems • Unable to ensure high quality grid services and power supply

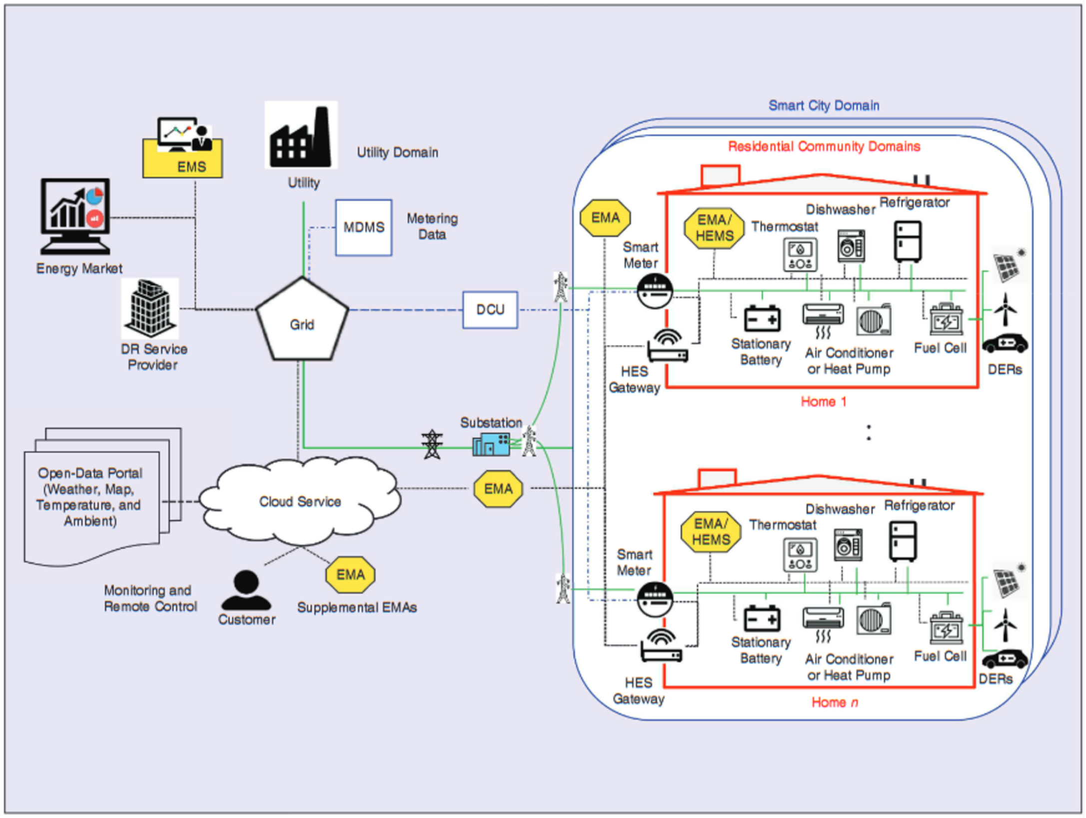
Chapter 4

System Modeling of a Smart Home

The Home Energy Management System (HEMS) concept has been developed to efficiently manage energy within the home. In the P2P market, the HEMS will allow end users to participate in the energy market, which is supported by sensors and relays to manage home consumption and a user platform suitable for efficient management, where the focus is on limiting load consumption with available energy [56]. The HEMS consists of five main modules including monitoring, logging, control, management, and alarm. To ensure correct operation of the HEMS, it is necessary to establish a communication network to connect sensors, smart meters, and network devices for real-time monitoring and control. This communication network can be wired or wireless.

This section focuses on modeling the actions and information that HEMS devices will perform. Both HEMS and electronic devices communicate through information and control signals to optimize energy consumption and production within a Home Area Network (HAN). Specifically, it is important to know the status of the devices and the energy to perform different HEMS actions. Among the applications of HEMS is the performance analysis of various devices, using different algorithms, to promote better energy usage and expenditure at home by having greater control over the energy of the home. Finally, it allows integration with other programs.

On the other hand, the ISO/IEC 15067-3-31 standard specifies an energy management



MDMS: meter data management system; DCU: data concentrator unit; HES: home electronic system.

Figure 4.1: EMA example in ISO/IEC 15067-3-31 standard.

agent (EMA) protocol to facilitate communication among these agents for the demand response (DR) energy management application. This EMA specifies a communication protocol that includes a logical connection between EMAs in different scenarios, including houses. This protocol is key in the integration of smart devices within homes and residential communities, enabling optimization of energy consumption through communication and coordination between energy management agents. The standard focuses on the architecture of these agents, the service procedures, and the message formats used for demand management and energy response [57] [58]. In addition, EMAs can reduce electricity consumption by flattening or shifting demand to help integrate various renewable energy sources, and can use energy storage units to store energy during off-peak hours or to discharge stored energy during peak hours on the customer side. Figure 4.1 shows an example of an EMA in the ISO / IEC 15067-3-31 standard.

The EMA protocol (EMAP) supports interaction between EMAS and the OSI layer including application and data messages. Thus, the interactions provide the ability of a system with a single EMA to allocate energy between homes efficiently in a community and between applications within homes, and to accommodate a selection of external and/or local energy resources linked to the EMA. EMAP enables energy management applications to cooperate and coordinate between EMAs and specifies an application layer protocol that includes protocol procedures such as protocol syntax, semantics, messages formats, messages sequences.

The incorporation arises with Artificial Intelligence (AI) to enable autonomous operation of the EMA. The EMA will be able to acquire, process, and apply knowledge and skills for the seamless energy management of local generation, energy allocation, transactional energy, energy storage, and consumption. This is defined in ISO/IEC 15067-3-51 as a software module called Narrow AI Engine that collects data from both local renewable energy management systems and public power suppliers. In addition, all information transmitted in or out of the home must pass through the Home Electronic System (HES) Gateway, which also provides Internet access. In this form, the machine learning capability in AI Engine will help the EMA to control, predict, and make decisions about maximizing efficiency in energy consumption, make decision in pricing, and device control.

For home appliances, we considered the appliances available in the laboratory, taking into account that the power, current, and voltage information of each appliance is important and must be known. Table 4.1 summarizes the data size of the home appliances, and Table 4.2 summarizes the data size of information sent from EMA/HEMS, as shown in Figure 4.2.

Table 4.1: Home appliances data size

Data	**Data size in Bytes**
Home appliances power	48
Home appliances current	48
Home appliances voltage	48
Home appliances timestamp	94
Home appliances control	6
Total	**244**

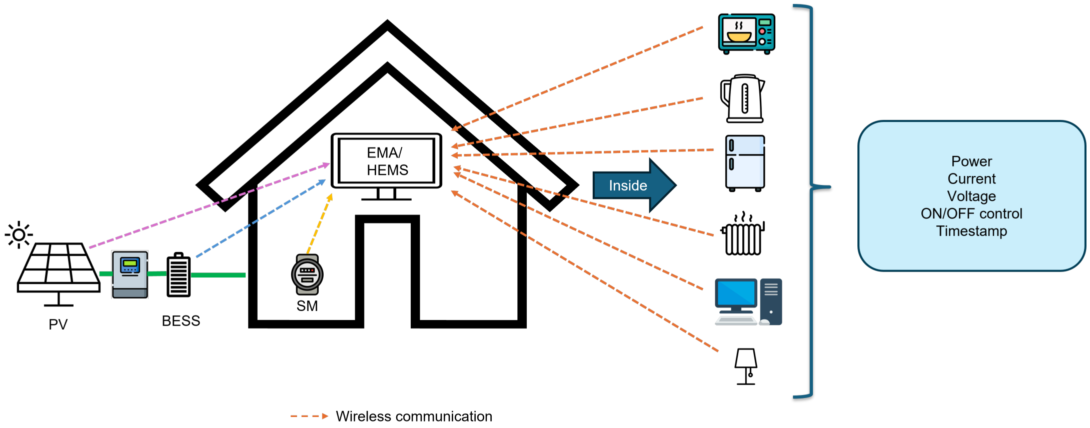


Figure 4.2: Information flow between EMA/HEMS and different home devices.

Table 4.2: EMA/HEMS information data size

Data	**Data size in Bytes**
Home appliances information	244
Smart Meter information	24
PV and BESS information	56
Total	**324**

For performance evaluation of the communication network, this scenario is simulated using NetSim with a data rate of 162 bytes/s. The details of this modeling are explained in this chapter.

4.1 Modeling Smart Home Domain

In this section, the main components inside the smart home are defined, including a Smart Meter, a PV system, and a BESS. In the next section, each component will be defined in detail. A smart meter is used to measure total energy consumption. The consumption data are sent to the EMA/HEMS. In the same way, data from the power generation from the PV system and data from the energy storage system are sent to the EMA/HEMS in the corresponding houses. Figure 4.3 shows the main components inside a smart home where the data is sent to EMA/HEMS.

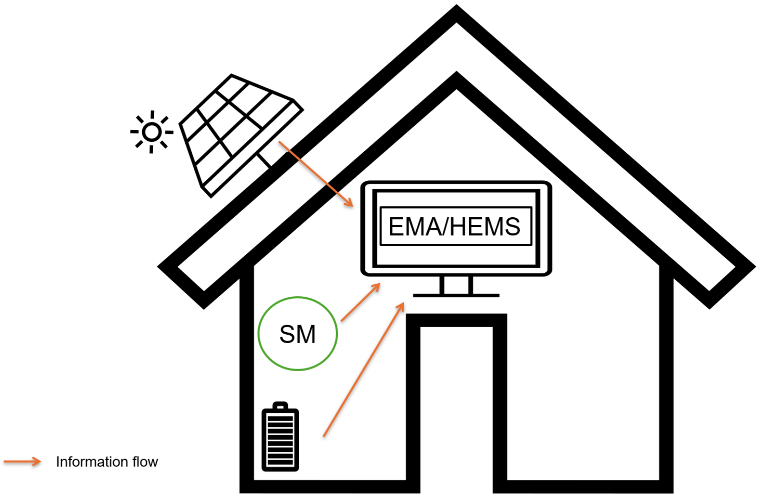
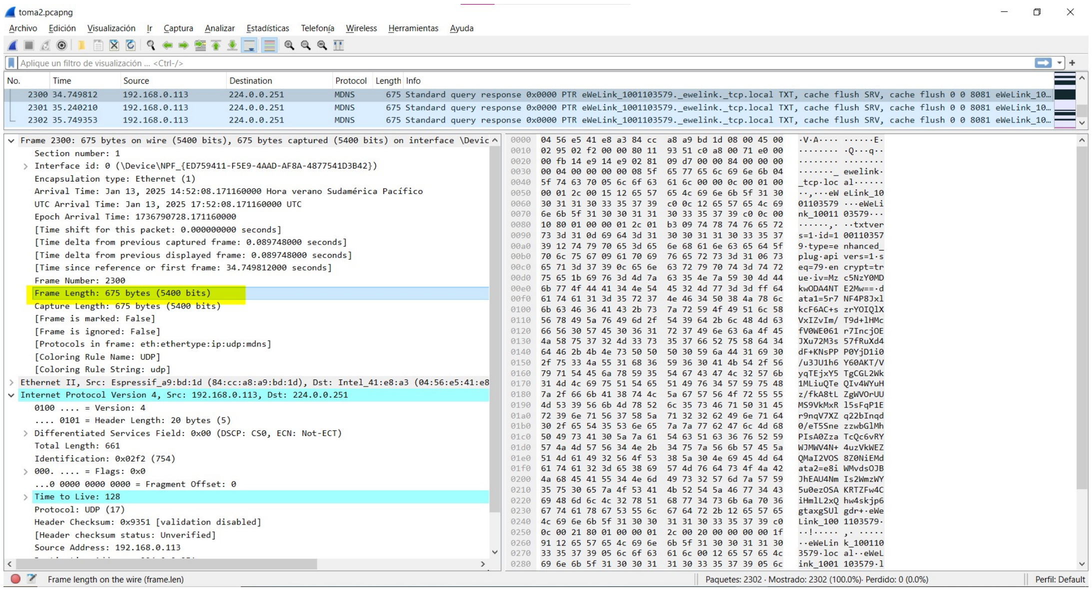


Figure 4.3: Main components and information flow in a smart Home.

4.1.1 Modeling Smart Meter

To measure energy consumption, a smart meter is designed and used. In the first instance, a SONOFF device is used, which allows monitoring of current, voltage, and power. This device allows to connect to a wireless local private LAN network using WiFi to obtain the measured data where the eWeLink API is used. The data from the SONOFF device is stored in a JSON format. In order to obtain the size of the packets, Wireshark is used to capture and analyze the data size. As can be seen in Figure 4.4, the size of the packet sent by the API is 675 bytes. In addition to sending the parameters necessary for the analysis of this work, the SONOFF device sends other device-specific information such as IP address, MAC, device name, and model.

In this work, we define the variables necessary for the monitoring of the smart meter, as given in Table 4.3. The main parameters of the Smart meter are the voltage, current, power, and time stamp. To evaluate network capacity and scalability, the scenario is simulated using NetSim with a data rate of 40 bytes/s.



```
No.   Time       Source         Destination  Protocol Length Info
2300 34.749812  192.168.0.113  224.0.0.251  MDNS     675 Standard query response 0x0000 PTR eWeLink_1001103579._ewelink._tcp.local TXT, cache flush SRV, cache flush 0 0 8081 eWeLink_10…
2301 35.240210  192.168.0.113  224.0.0.251  MDNS     675 Standard query response 0x0000 PTR eWeLink_1001103579._ewelink._tcp.local TXT, cache flush SRV, cache flush 0 0 8081 eWeLink_10…
2302 35.749353  192.168.0.113  224.0.0.251  MDNS     675 Standard query response 0x0000 PTR eWeLink_1001103579._ewelink._tcp.local TXT, cache flush SRV, cache flush 0 0 8081 eWeLink_10…
```

```
v Frame 2300: 675 bytes on wire (5400 bits), 675 bytes captured (5400 bits) on interface \Devic
    Section number: 1
  > Interface id: 0 (\Device\NPF_{ED759411-F5E9-4AAD-AF8A-4877541D3B42})
    Encapsulation type: Ethernet (1)
    Arrival Time: Jan 13, 2025 14:52:08.171160000 Hora verano Sudamérica Pacífico
    UTC Arrival Time: Jan 13, 2025 17:52:08.171160000 UTC
    Epoch Arrival Time: 1736790728.171160000
    [Time shift for this packet: 0.000000000 seconds]
    [Time delta from previous captured frame: 0.089748000 seconds]
    [Time delta from previous displayed frame: 0.089748000 seconds]
    [Time since reference or first frame: 34.749812000 seconds]
    Frame Number: 2300
    Frame Length: 675 bytes (5400 bits)
    Capture Length: 675 bytes (5400 bits)
    [Frame is marked: False]
    [Frame is ignored: False]
    [Protocols in frame: eth:ethertype:ip:udp:mdns]
    [Coloring Rule Name: UDP]
    [Coloring Rule String: udp]
> Ethernet II, Src: Espressif_a9:bd:1d (84:cc:a8:a9:bd:1d), Dst: Intel_41:e8:a3 (04:56:e5:41:e8
v Internet Protocol Version 4, Src: 192.168.0.113, Dst: 224.0.0.251
    0100 .... = Version: 4
    .... 0101 = Header Length: 20 bytes (5)
  > Differentiated Services Field: 0x00 (DSCP: CS0, ECN: Not-ECT)
    Total Length: 661
    Identification: 0x02f2 (754)
  > 000. .... = Flags: 0x0
    ...0 0000 0000 0000 = Fragment Offset: 0
  > Time to Live: 128
    Protocol: UDP (17)
    Header Checksum: 0x9351 [validation disabled]
    [Header checksum status: Unverified]
    Source Address: 192.168.0.113
```

```
0000  04 56 e5 41 e8 a3 84 cc  a8 a9 bd 1d 08 00 45 00   ·V·A···· ······E·
0010  02 95 02 f2 00 00 80 11  93 51 c0 a8 00 71 e0 00   ········ ·Q···q··
0020  00 fb 14 e9 14 e9 02 81  09 d7 00 00 84 00 00 00   ········ ········
0030  00 04 00 00 00 00 08 5f  65 77 65 6c 69 6e 6b 04   ·······_ ewelink·
0040  5f 74 63 70 05 6c 6f 63  61 6c 00 00 0c 00 01 00   _tcp·loc al······
0050  00 01 2c 00 15 12 65 57  65 4c 69 6e 6b 5f 31 30   ··,···eW eLink_10
0060  30 31 31 30 33 35 37 39  c0 0c 12 65 57 65 4c 69   01103579 ···eWeLi
0070  6e 6b 5f 31 30 30 31 31  30 33 35 37 39 c0 0c 00   nk_10011 03579···
0080  10 80 01 00 00 01 2c 01  b3 09 74 78 74 76 65 72   ······,· ··txtver
0090  73 3d 31 0d 69 64 3d 31  30 30 31 31 30 33 35 37   s=1·id=1 00110357
00a0  39 12 74 79 70 65 3d 65  6e 68 61 6e 63 65 64 5f   9·type=e nhanced_
00b0  70 6c 75 67 09 61 70 69  76 65 72 73 3d 31 06 73   plug·api vers=1·s
00c0  65 71 3d 37 39 0c 65 6e  63 72 79 70 74 3d 74 72   eq=79·en crypt=tr
00d0  75 65 1b 69 76 3d 4d 7a  63 35 4e 7a 59 30 4d 44   ue·iv=Mz c5NzY0MD
00e0  6b 77 4f 44 41 34 4e 54  45 32 4d 77 3d 3d ff 64   kwODA4NT E2Mw==·d
00f0  61 74 61 31 3d 35 72 37  4e 46 34 50 38 4a 78 6c   ata1=5r7 NF4P8Jxl
0100  6b 63 46 36 41 43 2b 73  7a 72 59 4f 49 51 6c 58   kcF6AC+s zrYOIQlX
0110  56 78 49 5a 76 49 6d 2f  54 39 64 2b 6c 48 4d 63   VxIZvIm/ T9d+lHMc
0120  66 56 30 57 45 30 36 31  72 37 49 6e 63 6a 4f 45   fV0WE061 r7IncjOE
0130  4a 58 75 37 32 4d 33 73  35 37 66 52 75 58 64 34   JXu72M3s 57fRuXd4
0140  64 46 2b 4b 4e 73 50 50  50 30 59 6a 44 31 69 30   dF+KNsPP P0YjD1i0
0150  2f 75 33 4a 55 31 68 36  59 36 30 41 4b 54 2f 56   /u3JU1h6 Y60AKT/V
0160  79 71 54 45 6a 78 59 35  54 67 43 47 4c 32 57 6b   yqTEjxY5 TgCGL2Wk
0170  31 4d 4c 69 75 51 54 65  51 49 76 34 57 59 75 48   1MLiuQTe QIv4WYuH
0180  7a 2f 66 6b 41 38 74 4c  5a 67 57 56 4f 72 55 55   z/fkA8tL ZgWVOrUU
0190  4d 53 39 56 6b 4d 78 52  6c 35 73 46 71 50 31 45   MS9VkMxR l5sFqP1E
01a0  72 39 6e 71 56 37 58 5a  71 32 32 62 49 6e 71 64   r9nqV7XZ q22bInqd
01b0  30 2f 65 54 35 53 6e 65  7a 7a 77 62 47 6c 4d 68   0/eT5Sne zzwbGlMh
01c0  50 49 73 41 30 5a 7a 61  54 63 51 63 36 76 52 59   PIsA0Zza TcQc6vRY
01d0  57 4a 4d 57 56 34 4e 2b  34 75 7a 56 6b 57 45 5a   WJMWV4N+ 4uzVkWEZ
01e0  51 4d 61 49 32 56 4f 53  38 5a 30 4e 69 45 4d 64   QMaI2VOS 8Z0NiEMd
01f0  61 74 61 32 3d 65 38 69  57 4d 76 64 73 4f 4a 42   ata2=e8i WMvdsOJB
0200  4a 68 45 41 55 34 4e 6d  49 73 32 57 6d 7a 57 59   JhEAU4Nm Is2WmzWY
0210  35 75 30 65 7a 4f 53 41  4b 52 54 5a 46 77 34 43   5u0ezOSA KRTZFw4C
0220  69 48 6d 6c 4c 32 78 51  68 77 34 73 6b 6a 70 36   iHmlL2xQ hw4skjp6
0230  67 74 61 78 67 53 55 6c  67 64 72 2b 12 65 57 65   gtaxgSUl gdr+·eWe
0240  4c 69 6e 6b 5f 31 30 30  31 31 30 33 35 37 39 c0   Link_100 1103579·
0250  0c 00 21 80 01 00 00 01  2c 00 20 00 00 00 00 1f   ··!····· ,· ·····
0260  91 12 65 57 65 4c 69 6e  6b 5f 31 30 30 31 31 30   ··eWeLin k_100110
0270  33 35 37 39 05 6c 6f 63  61 6c 00 12 65 57 65 4c   3579·loc al··eWeL
0280  69 6e 6b 5f 31 30 30 31  31 30 33 35 37 39 05 6c   ink_1001 103579·l
```

Frame length on the wire (frame.len)

Paquetes: 2302 · Mostrado: 2302 (100.0%)· Perdido: 0 (0.0%)

Perfil: Default

Figure 4.4: Wireshark capture of dataframe sended by eWeLink API.

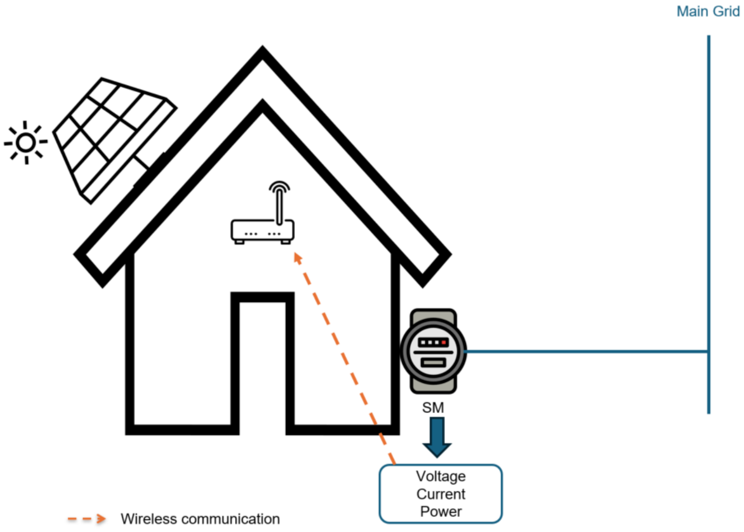


Figure 4.5: Main parameters for monitoring the Smart meter.

Table 4.3: Smart meter data size

Data	**Data size in Bytes**
Voltage	8
Current	8
Power	8
Timestamp	16
Total data	**40**

4.1.2 Modeling PV System

To measure the energy production of photovoltaic panels, it is necessary to monitor three important parameters, which are current, voltage, and power. These parameters are independent of the electrical system being used in the home. Figure 4.6 shows PV system with (a) Battery Energy Storage System (BESS) and (b) without Battery Energy Storage System (BESS).

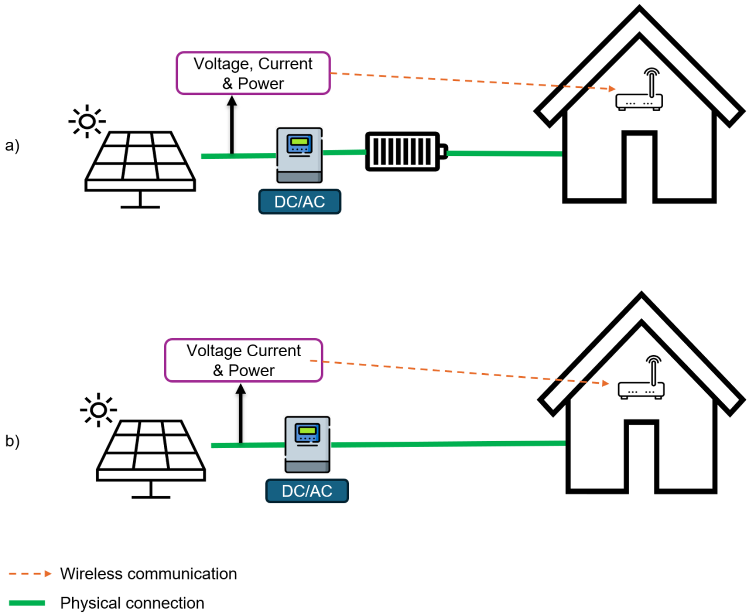


Figure 4.6: PV modeling for Energy Trading (a) With BESS (b) Without BESS.

Table 4.4 shows the size of the data for different measuring parameters and a time stamp that needs to be added to control the data. Finally, to evaluate the network capacity and scalability, this scenario is simulated with a data rate of 40 bytes/s.

Table 4.4: PV data size

Data	**Data size in Bytes**
Voltage	8
Current	8
Power	8
Timestamp	16
Total data	**40**

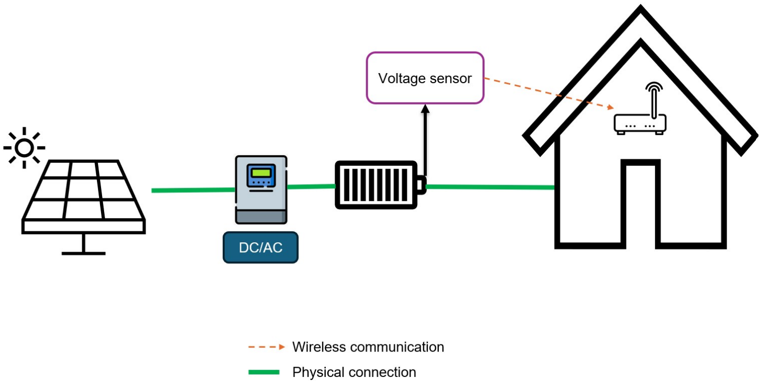


Figure 4.7: BESS for Energy Trading.

4.1.3 Modeling BESS

This work considers the use of BESS in some homes, so it is necessary to monitor the use and state of charge of batteries, as shown in Figure. 4.7. In this case, it is important to know the charge level of the battery at a certain time instant. Table 4.5 shows the size of the data for BESS.

Table 4.5: BESS data size

Data	**Data size in Bytes**
Voltage	8
Current	8
Timestamp	16
Total data	**32**

4.1.4 Home Appliances

The power consumption of home appliances is measured in ”W” or ”kW”. The list of the main appliances considered is as follows:

- Microwave
- Dishwasher
- Furnace
- Home office
- Wine cellar
- Garage door
- Kitchen
- Barn
- Living room

For the modeling of the household, we considered the main appliances available in the laboratory, which are common in a household and which are also present in the dataset that will be used. For the lab-scale experiment, it is considerate the following rooms: Kitchen, home office, and living room. The following appliances are considered microwave, kettle, fridge, heater, computer, and lamp.

4.2 Peer-to-Peer Modeling

This section defines the requirements of the ICT infrastructure for P2P energy trading, in particular, the data transmitted to carry out the energy exchange. Based on [59], Table 4.6 shows detailed information on data packets and data size, in bytes, for the P2P market, which are transmitted in centralized and decentralized architectures.

Table 4.6: Data published for P2P energy trading.

Data	**Data size in Bytes**
Peer ID	6
Role	6
Energy Amount	8
Price	8
Timestamp	16
Offer ID	8
Total	**52**

Considering different market architecture, in a centralized market, information on energy generation, energy storage, energy consumption, and the market proposal made by each peer should be sent. In this way, taking into account the data from section 4.1, the type of data and its size can be seen in the following Table 4.7. In the decentralized market, only the information from Table 4.6 is sent.

Table 4.7: Data published for P2P energy trading centralized case

Data	**Data size in Bytes**
P2P Market	52
Smart Meter	24
Energy Generation	32
BESS	8
Total	**116**

To evaluate scalability and network capacity, both architectures can be configured, modeled, and simulated, with a data rate of 928 bytes/s for the centralized architecture and a data rate of 416 bytes/s for decentralized architecture.

Chapter 5

Communication Network Results and Discussion

In this work, a network simulation tool (NetSim) is used to evaluate the performance of the communication network for Solar P2P energy trading. The smart home is integrated with a PV system and a BESS. A rural neighborhood is considered for the design and evaluation of solar P2P energy trading system. Figure 5.1 shows the actual locations of the rural neighborhood located in Valparaiso City, Chile, and the distribution of the houses using Google Maps. In this scenario, it is considered that each house has an EMA/HEMS and a PV system. However, not all houses are equipped with BESS. A total of 7 houses are considered in the rural neighborhood, as shown in Figure 5.2. In order to evaluate the performance of the communication network, different wired and wireless communication technologies are simulated using NetSim Simulator. The simulated scenarios are shown in Figure 5.3.

With respect to the communication network, we consider the most commonly available technologies, including Ethernet and WiFi. Both technologies are simulated to assess the feasibility of implementing this system in a real local community microgrid. The scenarios described are for HAN and NAN. The communication range of Ethernet and WiFi is suitable for EMA/HEMS to communicate with sensor nodes and measurement devices in

Figure 5.1: Google maps for the rural neighborhood in Valparaiso City, Chile.

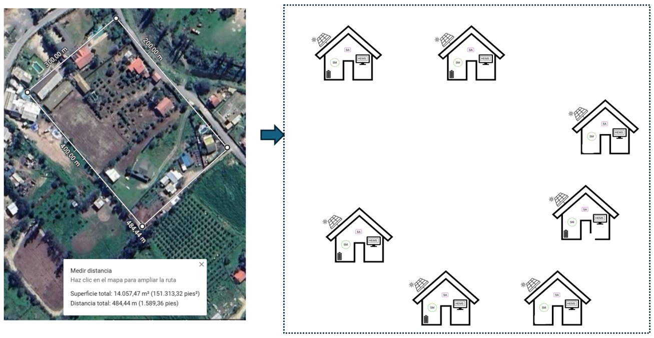


Figure 5.2: Schematic diagram for the selected homes of the rural neighborhood.

the community microgrid. The simulated wireless technologies are the following: IEEE 802.11b: 2.4 GHz, IEEE 802.11g: 2.4 GHz, IEEE 802.11n: 2.4 GHz, IEEE 802.11n: 5 GHz, and IEEE 802.11ac: 5 GHz. Table 5.1 shows some important aspects of different wireless technologies [60]. For the case of wired architecture, the simulation models considered Ethernet with channel capacities of 100 Mbps and 1 Gbps [61].

Table 5.1: Wireless standard information.

IEEE Standard	**802.11b**	**802.11g**	**802.11n 2.4 GHz**	**802.11n 5 GHz**	**802.11ac 5 GHz**
Year Realased	1999	2003	2009	2009	2014
Frequency	2.4GHz	2.4GHz	2.4GHz	5GHz	5GHz
Maximum Data Rate	11Mbps	54Mbps	600Mbps	600Mbps	1.3Gbps
Theoretical maximum range (m)	30	100	300	300	50

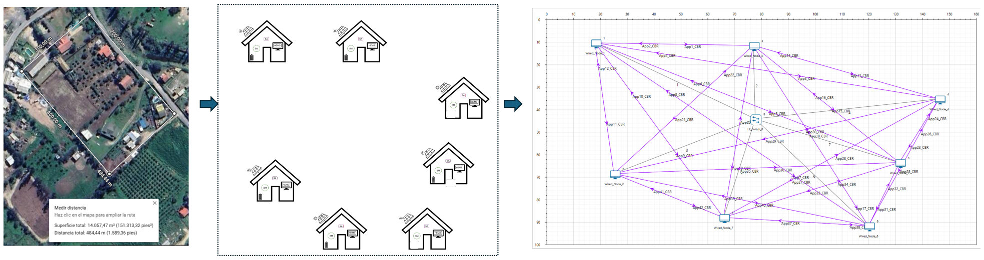


Figure 5.3: Simulation model of the rural neighborhood using NetSim simualtor.

5.1 Communication Network Results

5.1.1 Smart Home - HAN Results

The simulation results for HAN including Smart Meter, PV system, BESS, and HEMS can be seen in Table 5.2. With respect to wireless communication, the results show that IEEE 802.11g has the best performance, while IEEE 801.11b has a higher delay. In the case of wired architecture, the results show that IEEE 802.3ab (1 Gbps) has better performance compared to IEEE 802.3u (100 Mbps) . However, the implementation of wireless technology is better than that of wired technology considering different factors, such as high costs and flexibility of implementation. Note that the data size used for the simulation model is given in Chapter 4.

5.1.2 Smart Community - NAN Monitoring Results

The simulation results of NAN considering different numbers of prosumers can be seen in Figure 5.4 for wireless communication, and in Figure 5.5 for wired communication. Table 5.3 shows the results of the average wireless delay in the decentralized market with a different number of participants.

Table 5.2: Simulation results for HAN

Communication type	**IEEE Standard**	**Smart Meter**		**PV Monitoring**		**BESS Monitoring**		**HEMS/EMA**	
		Delay [ms]	**Jitter [ms]**	**Delay [ms]**	**Jitter [ms]**	**Delay [ms]**	**Jitter [ms]**	**Delay [ms]**	**Jitter [ms]**
Wireless	802.11b	1.575	0.287	1.575	0.287	1.551	0.287	1.987	0.287
	802.11g	0.326	0.061	0.326	0.061	0.322	0.061	0.410	0.061
	802.11n	0.575	0.136	0.575	0.136	0.572	0.136	0.638	0.136
	802.11n 5G	0.488	0.106	0.575	0.136	0.484	0.106	0.550	0.106
	802.11ac 5G	0.535	0.061	0.535	0.061	0.532	0.061	0.587	0.061
Wired	802.3u	0.142	0.232	0.142	0.231	0.117	0.185	0.373	0.601
	802.3ab	0.127	0.231	0.127	0.231	0.104	0.185	0.317	0.601

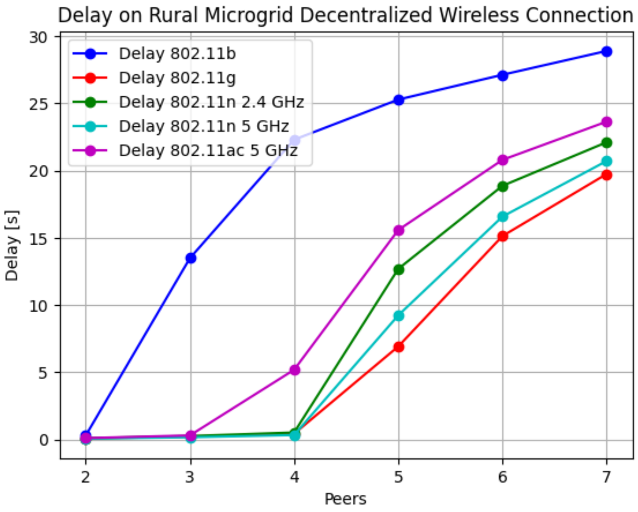


Figure 5.4: Wireless Communication delay for Rural Neighborhood

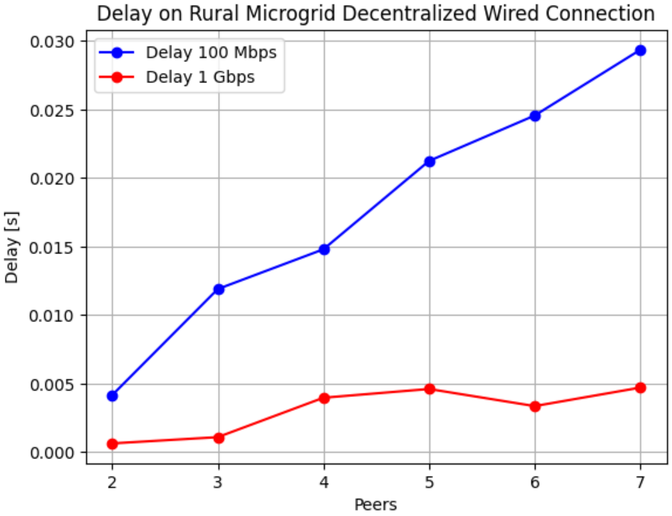


Figure 5.5: Wired Communication delay for Rural Neighborhood

In the case of the NAN scenario, the IEEE 802.11g and IEEE 802.11n 5 GHz have a lower delay and a packet delivery rate (close to 100%), so both technologies comply with the acceptable conditions to establish a network for the 7 houses. On the other hand, the lower performance for the communication protocol is IEEE 802.1b. This communication protocol has significantly lower performance, with higher delays and jitter. Therefore, it is not recommended for dense NAN systems or with real-time requirements.

Table 5.3: Delay on Decentralized Remote/Rural Neighborhood Wireless Communication for each scenario

Scenario	802.11b	802.11g	802.11n 2.4 GHz	802.11n 5 GHz	802.11ac 5 GHz
2 Prosumer	0.289	0.064	0.077	0.053	0.093
3 Prosumer	13.484	0.203	0.248	0.156	0.292
4 Prosumer	22.298	0.416	0.511	0.319	5.178
5 Prosumer	25.281	6.914	12.686	9.231	15.578
6 Prosumer	27.128	15.127	18.866	16.576	20.795
7 Prosumer	28.900	19.745	22.108	20.712	23.641

5.1.3 NAN - Energy Trading Results

Figure 5.6 shows the delay results with different numbers of peers using wireless communication, and Figure 5.7 shows the delay for wired communication. Table 5.4 shows the delay results for the decentralized market.

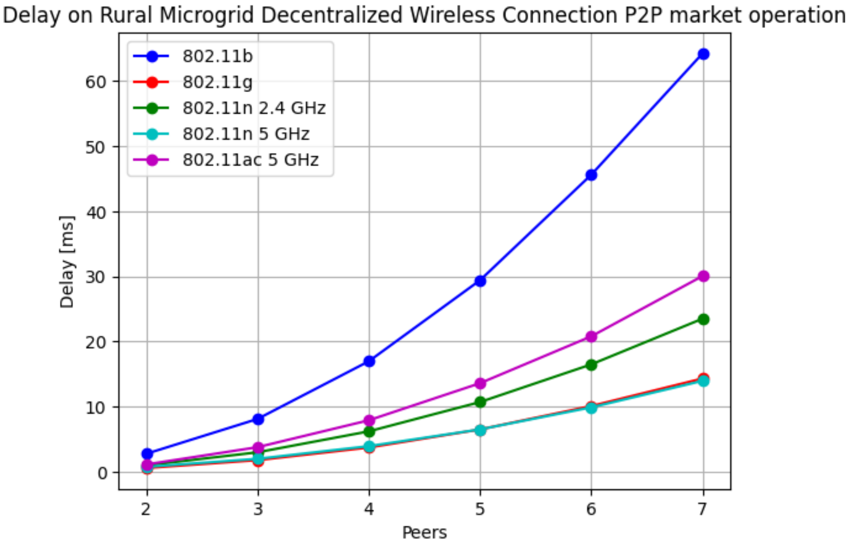


Figure 5.6: Wireless Communication delay for Rural Neighborhood scenario.

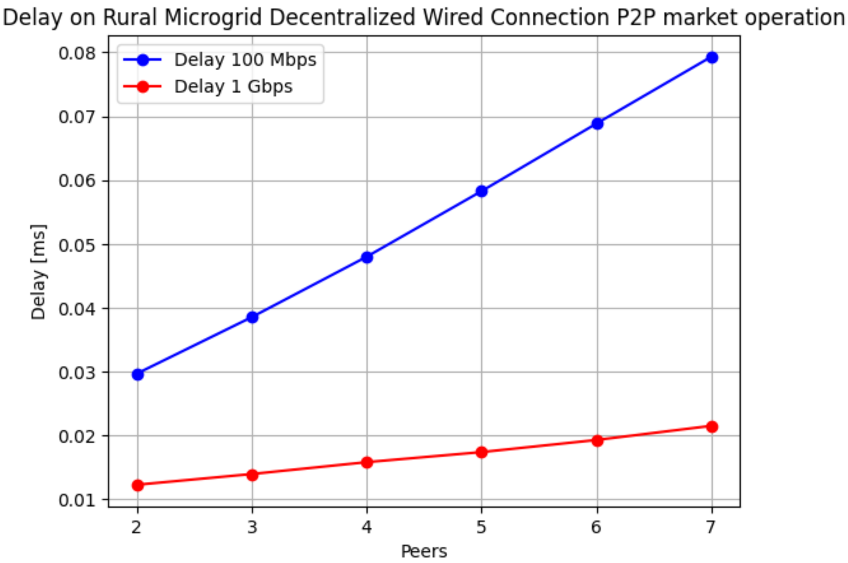


Figure 5.7: Wired communication delay for Rural Neighborhood scenario.

Table 5.4: Delay in millisecond on Decentralized market in Remote/Rural Neighborhood Wireless Communication for each scenario

Scenario	**802.11b**	**802.11g**	**802.11n 2.4 GHz**	**802.11n 5 GHz**	**802.11ac 5 GHz**	**802.3u**	**802.3ac**
2 Prosumer	2.788	0.602	1.012	0.777	1.152	0.029	0.012
3 Prosumer	8.132	1.814	3.015	2.017	3.800	0.039	0.014
4 Prosumer	16.986	3.752	6.228	3.958	7.928	0.048	0.016
5 Prosumer	29.421	6.524	10.728	6.529	13.622	0.058	0.017
6 Prosumer	45.614	10.113	16.508	9.914	20.812	0.069	0.019
7 Prosumer	64.221	14.336	23.515	13.981	30.064	0.079	0.021

The results of NAN show that, in a decentralized market, the best results are obtained by the IEEE 802.11n 5 GHz and IEEE 802.11g is the second option. However, as in the previous case, wired communication presents better results, specifically with a channel capacity of 1 Gbps. The implementation of wireless technology is better compared with wired technology considering different aspects such as cost and implementation.

The microgrid communication infrastructure plays an essential role in real-time monitoring and control for P2P energy trading. The results show that wired communication performs better than wireless communication. However, the implementation cost and flexibility of wireless communication should also be considered. For our testbed implementation, IEEE 802.11g will be used due to the results previously described for HAN and NAN.

Chapter 6

Testbed Implementation for Local Energy Trading

This chapter presents the design and implementation of a testbed for local energy trading. The testbed system consists of hardware and software (blockchain components and smart contracts). In addition, this chapter shows the necessary configurations to perform local energy trading and the detailed implementation of the testbed in the laboratory.

6.1 Prototype Implementation for a Smart Prosumer

6.1.1 Hardware

Figure 6.1 shows the developed testbed for a single prosumer in local P2P energy trading system. Following the proposed architecture in Section 3.3, the hardware layer is composed of data acquisition (sensors and microcontroller), which is necessary to monitor energy production and energy exchange. The sensors used are voltage and current sensors. The microcontroller considered is a Raspberry Pi Pico 2 W. This microcontroller incorporates a WiFi antenna compatible with the 802.11 b/g/n standard at 2.4 GHz. For the second layer, Communication layer, a WiFi module incorporated in the microcontroller is

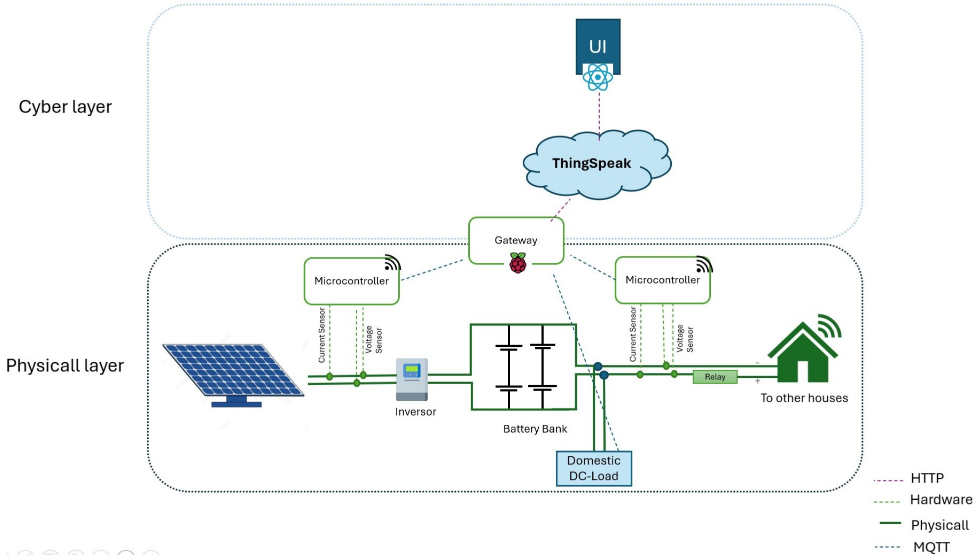


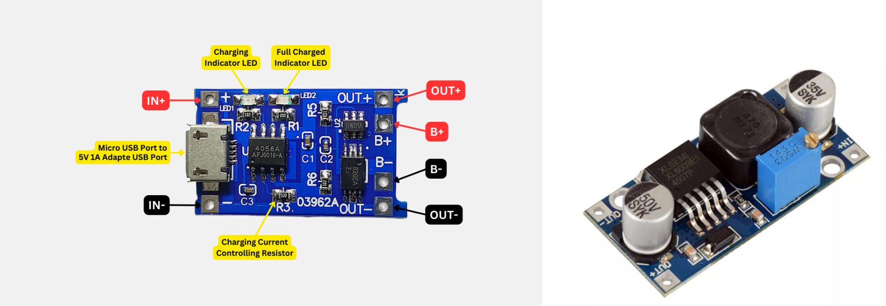
Figure 6.1: Developed tested for a single prosumer in local P2P energy trading

used which is connected to ThingSpeak Cloud. For sending data, ThingSpeak is chosen to send sensor readings to a cloud system through WiFi using internet protocols such as TCP/UDP/HTTP/FTP. Table 6.1 shows the list of the main hardware components used, while Appendix A.1 shows the hardware details.

Table 6.1: Hardware components used in this work.

Component	**Model**	**Usage**
Raspberry Pi	Pico 2 W	Processes and coordinates the sending of data from the sensors. Sends the sensed data to the cloud
Current Sensor and Voltage Sensor	SCT-013 & FZ0430	Data collection after a time interval
Relay	2ph63091a	Support the function of a switch allowing the energy trading to other houses
Protoboard, Cables M-M and M-F	-	Necessary to connect the sensors
LED, Socket, Wires, and Plug	-	Represent the energy trading to another house

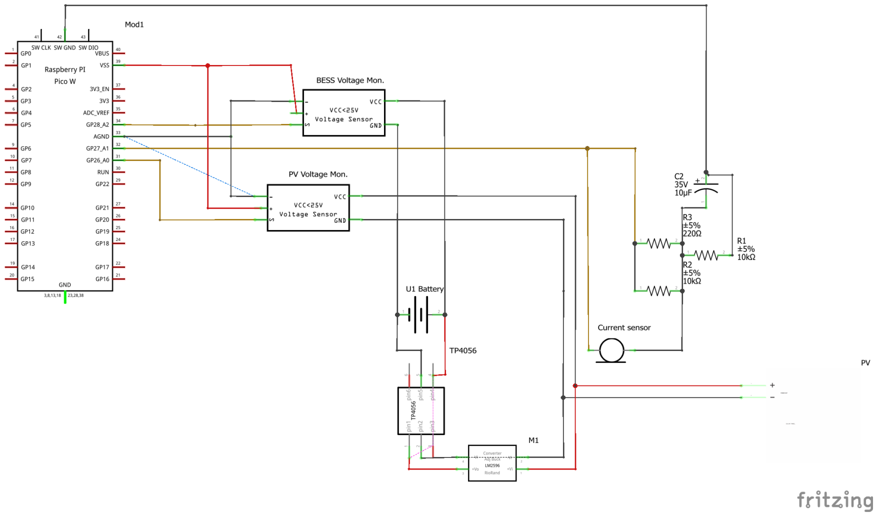
The voltage sensor and current sensor are used for the monitoring of PV energy production and BESS storage (lithium battery). For laboratory implementation, a battery charger module TP4056 which allows charging of lithium batteries with Micro USB connector and input from the solar panel is used. The battery charger module can be used for charging 3.6V - 3.7V batteries, while the nominal input voltage of the module is 5V. The details of the modules are shown in Figure 6.2(a). For the PV system, the solar panel used in the laboratory prototype generates a voltage higher than 20V in midday hours. The nominal values for the panel are 10 W, 23.4V, and 0.57A for power, voltage, and current, respectively. Therefore, the input voltage to the TP4056 must be decreased. In this case, a DC-DC Step Up Xl6009 converter is used to regulate the input voltage of the TP4056. This converter works with an input voltage between 3.3V and 32V, while its output voltage is adjustable between 5 and 35V. Once the output voltage of the module is adjusted, it remains constant, and it does not require further modification or regulation. This module can be seen in Figure 6.2 (b).



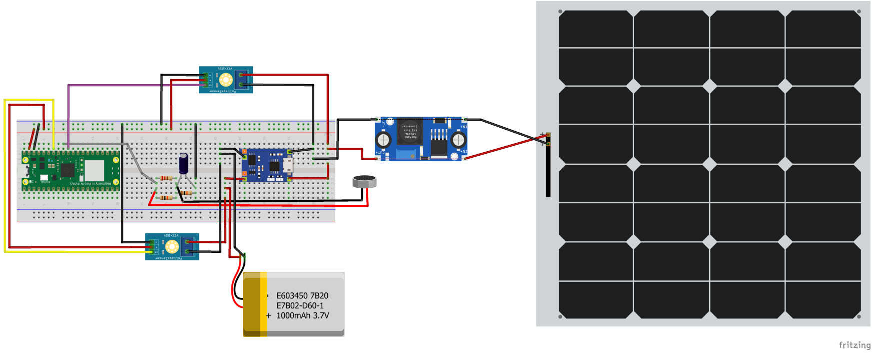
(a) TP4056 pinout details (b) DC-DC Step Up module

Figure 6.2: Charging regulation modules. (a) Battery charger module (b)DC-DC converter

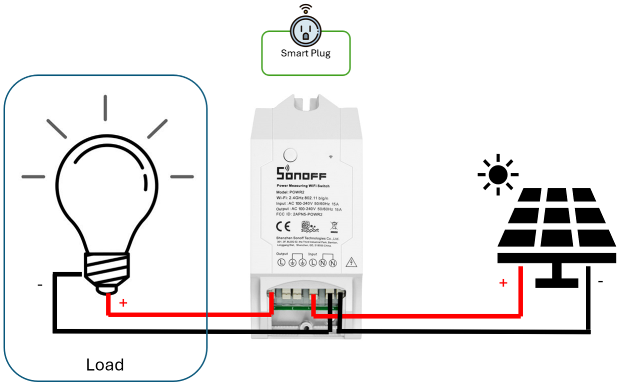
Figure 6.3 shows the prototype of a single prosumer that includes the schematic diagram of the PV and BESS monitoring system, the details of PV and BESS monitoring prototype, and the smart meter prototype.



(a) Schematic diagram of PV and BESS monitoring prototype in the Laboratory.



(b) Details of PV and BESS monitoring prototype in the Laboratory.



(c) Smart meter prototype in the Laboratory.

Figure 6.3: Laboratory prototype for a single prosumer. (a) Schematic diagram of PV and BESS monitoring system, (b) PV and BESS monitoring prototype, (c) Smart meter prototype.

To monitor the energy consumption of the house, a Sonoff device (Smart Plug) is installed as a Smart Meter, as shown in Figure 6.3(c). For the laboratory testbed, the Sonoff device (smart plug) is used as a smart meter, allowing to monitor the day's accumulated energy, voltage and instantaneous current through the use of an API called "ewelink". This configuration enabled us to support the same function of the smart meter in the home, which allows the monitoring of voltage, current, and power of the house load.

6.1.2 Middleware

For the testbed, a Raspberry Pi is used as an HEMS/EMA that receives the data from the sensor nodes and sends it to the ThingSpeak cloud. The Raspberry Pi runs an operating system (usually the Raspberry Pi OS, based on Linux) and has GPIO ports, WiFi, among others. The main functions of the HEMS/EMA developed on the Raspberry Pi are as follows:

1. **Data collection:** collects data from sensors and devices through MQTT and HTTP.
2. **Device control:** sends instructions to turn on or off devices or relays. In this case, to enable energy exchange among peers.
3. **Communication with the cloud and the web interface:** sending data to ThingSpeak and integration with the developed platform in React.

In order to send data to the cloud, two Python codes are developed to receive the information. In the case of monitoring power generation, the data is sent through MQTT where HEMS/EMA acts as a broker and subscribes to the necessary data topics. On the other hand, to receive the data from the smart meter (Sonoff device), a request is made to the 'ewelink' API to obtain the measured data from the smart plug.

MQTT is a lightweight messaging protocol that is ideal for communicating among devices in networks with low bandwidth or limited resources (such as sensors, microcontrollers, etc.). The MQTT protocol is based on the "publisher/subscriber" model and runs over

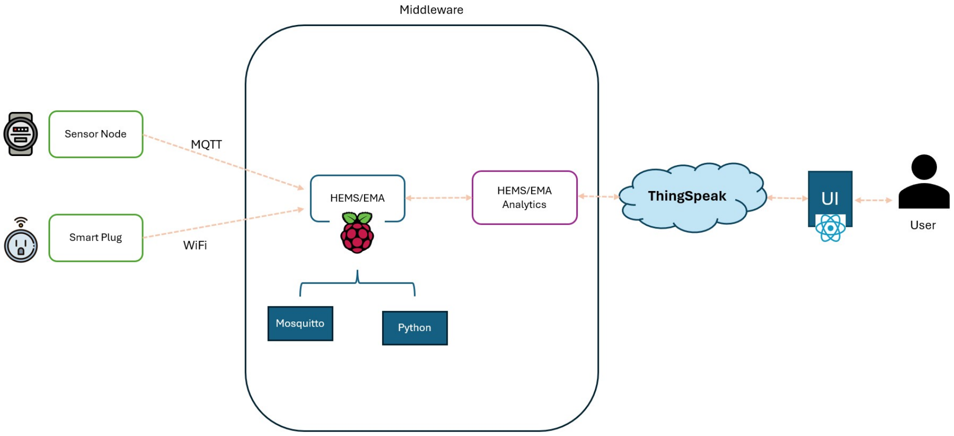


Figure 6.4: Schematic diagram for local HEMS/EMA implemented for a single prosumer.

TCP/IP. In this thesis, HEMS/EMA acts as a Broker, which is the communication intermediary, i.e., all messages go through it. The sensor nodes and the Sonoff are the clients that can publish or subscribe to a topic which is a "channel" with a label. The broker used in this case is Mosquitto which is an open-source MQTT broker. The MQTT broker was set up by default on port 1883. Figure 6.4 shows the configuration of the middleware part, and the developed code can be seen in Appendix A.2.

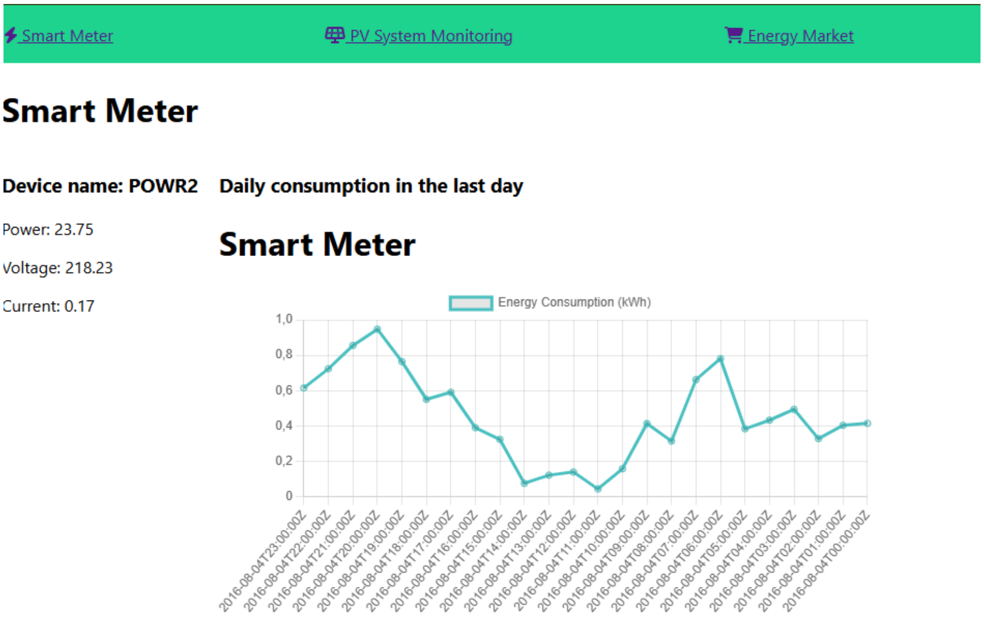
6.1.3 Framework for User Interface

To visualize and store the monitored information, React JS and ThingSpeak are used. The application seeks to enable the user to visualize the data in an intuitive way. The technologies used are described below:

- **ReactJS** is an open source JavaScript library, developed by Meta (formerly Facebook), oriented to the development of user interfaces (UI) for web applications. The main goal is to facilitate the construction of efficient and dynamic interfaces through an architecture based on reusable components. ReactJS is especially useful in the development of Single Page Applications (SPA), where the content of the page can change dynamically without the need to completely reload it from the server [62].

- **ThingSpeak** is a cloud platform developed by MathWorks that enables the collection, analysis, and visualization of data from Internet of Things (IoT) devices. The architecture is oriented to facilitate the connection of sensors and microcontrollers through protocols such as HTTP or MQTT, allowing users to build intelligent applications and remote monitoring systems in real time. ThingSpeak offers tools for graphing data in real time, allowing users to interpret behaviors, trends, or states of variables measured by connected sensors. Being integrated with MATLAB, it allows the execution of scripts directly from the cloud to process, analyze, or make automatic decisions based on the data received [55].

The UI is configured on a localhost created using ReactJS and can be accessed via http://localhost:3000/. There is a navigation bar that helps the end user visualize the information he needs. In the first instance, there is home monitoring that allows visualization of the energy consumption during the day and momentarily through a history-type graph and the information obtained by smart meter. Figure 6.5 shows the visualization of the information on the energy consumption of the prosumer (information obtained from the smart meter, in this case the Sonoff) and the information obtained is the current values and historical data accumulated during the last month.



Smart Meter

Device name: POWR2

Daily consumption in the last day

Power: 23.75

Voltage: 218.23

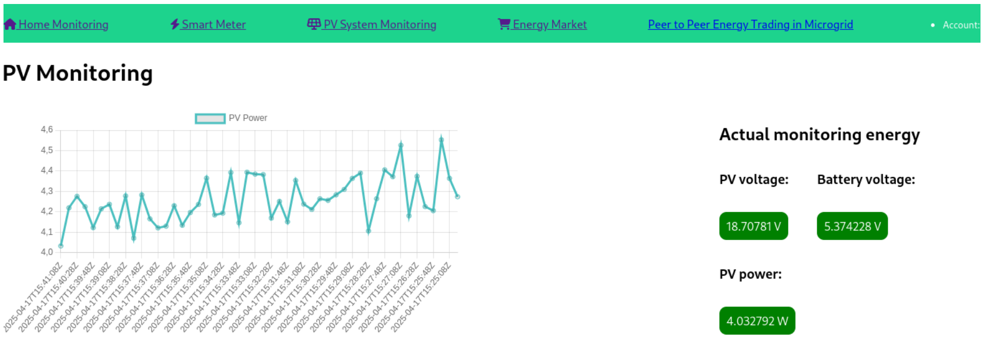
Current: 0.17

Smart Meter

Figure 6.5: Visualization of power consumption in a house.

To obtain the information from the Sonoff, the ’ewelink’ API is used. For this, initially a JavaScript script is used to obtain the ’access-token’ of the ’ewelink’ account that can be seen in Appendix A.3. This code enables the url ’http://127.0.0.1:8000/redirectUrl’ which allows ”logging in” with the ewelink credentials, where it then delivers the access token as an HTTP response. This access token is used in the main code to obtain the data measured by the Sonoff. The code is given in the Appendix A.4. In addition, the plotted data are obtained from the data set [63] and sent to ThingSpeak, which is processed through a Jupyter notebook, and the data accumulated on a specific day is obtained for energy generation and consumption.

On the other hand, there is the PV Monitoring section, where the end-user can find a graph with the information obtained from ThingSpeak and informative boxes painted according to the voltage and the power range. In this case, the data displayed in the boxes is the latest data saved in the cloud. Figure 6.6 shows the user interface developed for visualization of information on the monitoring of energy generation and energy storage.



PV Monitoring

Actual monitoring energy

PV voltage: 18.70781 V

Battery voltage: 5.374228 V

PV power: 4.032792 W

Figure 6.6: Visualization of photovoltaic power generation monitoring and battery charging voltage.

The developed codes for the user interface can be found in GitHub repository[1].

6.2 Prototype Implementation for a Smart Community

This section explains the details for the prototype implementation of energy trading in the local community microgrid.

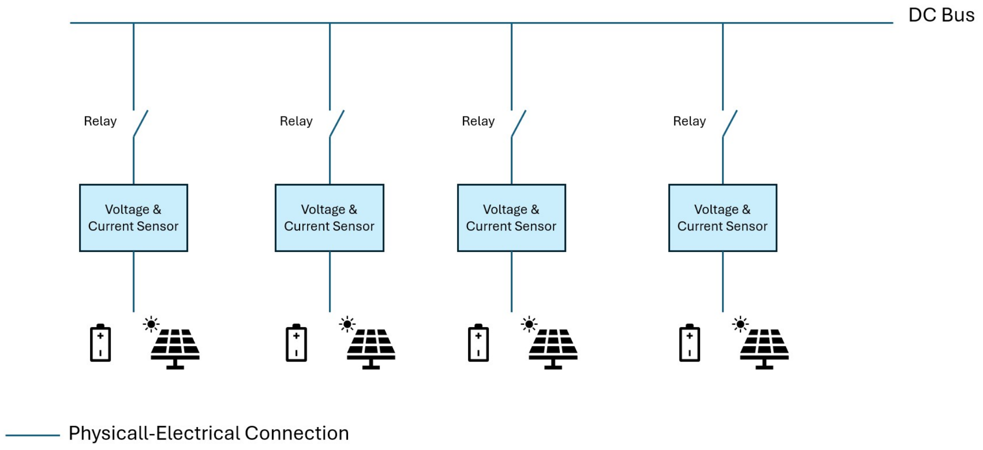
6.2.1 Hardware

To enable energy trading among prosumers, a relay node will be activated, allowing the transfer of energy between peers. The power transfer was represented by a light bulb which, when turned on/off, indicates that the energy exchange is taking place. To confirm the amount of energy exchanged, the sensor nodes composed of voltage and current sensors operate and measure on the pairs participating in the transaction. Figure 6.7 shows an example of the energy transaction between two houses. In this way, each house will be composed of a smart meter and a smart agent (HEMS/EMA). The data obtained by the sensor nodes are sent to the HEMS/EMA, represented by a Raspberry Pi, through the use

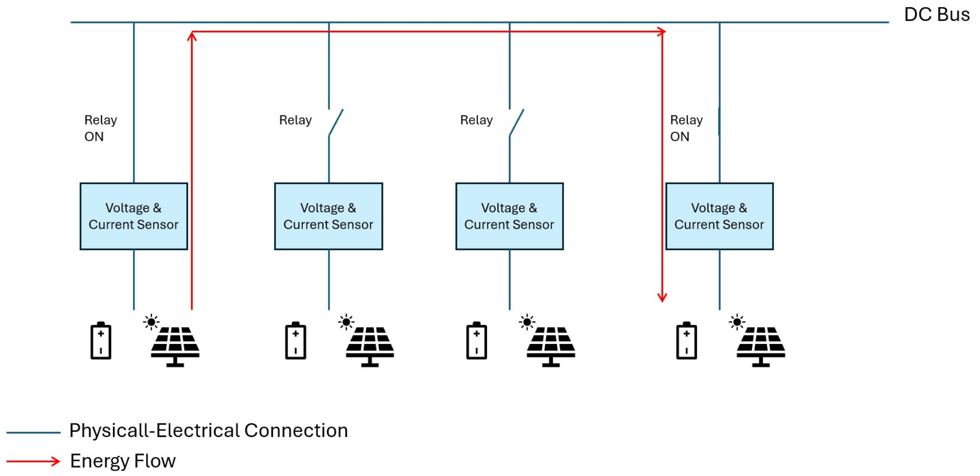
---

[1] https://github.com/fransa27/Blockchain-desarrollo

of MQTT using wireless communication via WiFi. The data is then sent to the cloud, as shown in Figure 6.8.



(a) Shared DC bus among peers.



(b) Example of local energy trading among two peers.

Figure 6.7: Local energy trading example. (a) Shared DC bus among peers (b) Example for energy flow between two peers

6.2.2 Energy Trading Market

The developed user interface aims to provide specific services to users involved in energy trading. In addition, the idea behind the user interface is to make it as intuitive as possible,

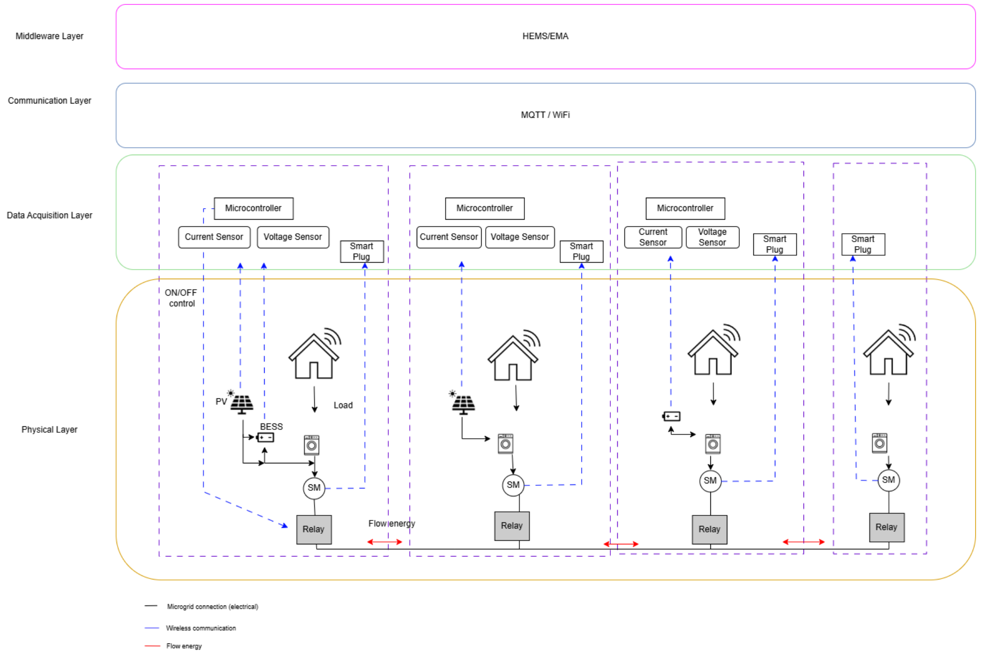


Figure 6.8: Developed tested for local P2P energy trading in a local community microgrid

ensuring that users can easily identify different elements and actions within it. The software system was built using the following frameworks: React, Ganache, and Metamask. These frameworks were integrated together to create a more enhanced user interface. The developed frameworks are explained below:

- **Ganache** is a development tool for Ethereum that allows to run a local personal blockchain to create, test, and debug smart contracts in a secure, controlled, and fast environment. It is part of the Truffle suite of tools, one of the most widely used frameworks in the development of decentralized applications.

- **Metamask** acts as a bridge between standard web browsers and the Ethereum blockchain. It supports authentication using either a mnemonic phrase or a single private key. MetaMask is available as a browser extension, particularly for Google Chrome, and can be configured to connect to a local Ethereum network such as Ganache. Within MetaMask, users can manage multiple Ethereum accounts, each with its own address and private key. Through this tool, users can send and receive Ether, as well as interact with Ethereum-compatible tokens, enabling seamless

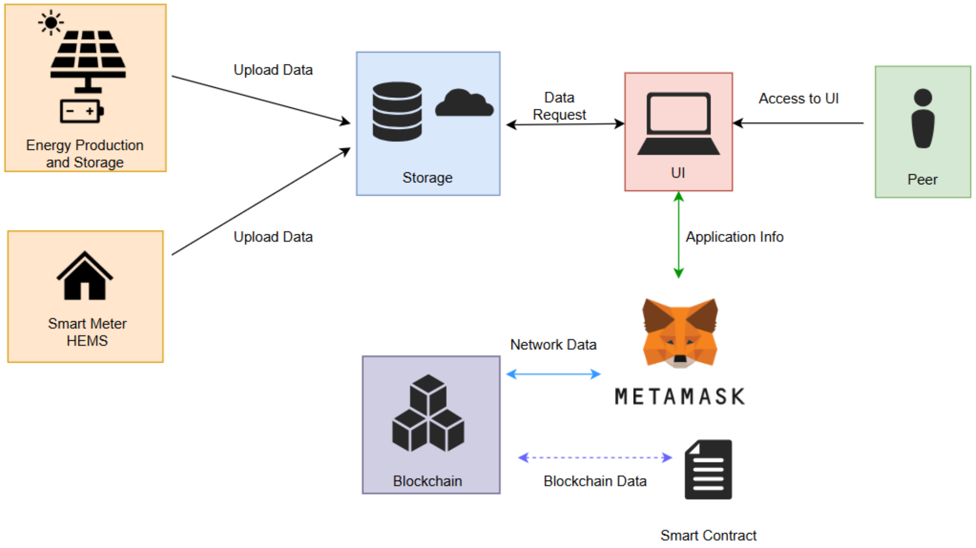


Figure 6.9: General architecture for the developed local energy trading platform

participation in decentralized applications.

Figure 6.9 shows the general architecture for the energy trading platform using the frameworks explained above. The Web platform is configured on a localhost, enabling the monitoring of production and energy consumption. The Web platform is created using ReactJS and can be accessed via http://localhost:3000/. The system was created to support different scenarios of systems presented in the energy trading market, which was explained in Section 2 ”Peer-to-Peer Energy Trading”. In general, the decentralized system allows all users to conduct direct energy transactions with other users. However, a centralized system, on the other hand, only allows a coordinator to facilitate transactions among peers, selecting the best options for the other peers.

For energy trading, it is necessary for the end user to start the metamask in the browser and link his virtual account to the blockchain. The platform checks the connection with the metamask and then enters the energy market window. In the case where the user wants to sell energy, the user publishes the offer. On the other hand, in the case of buying energy, the user can check the list of published offers and select an offer, or publish an offer if required. Then, the selected bid is blocked and reserved during the bidding time window. Finally, the energy exchange is started within the allowed window. Later, the settlement

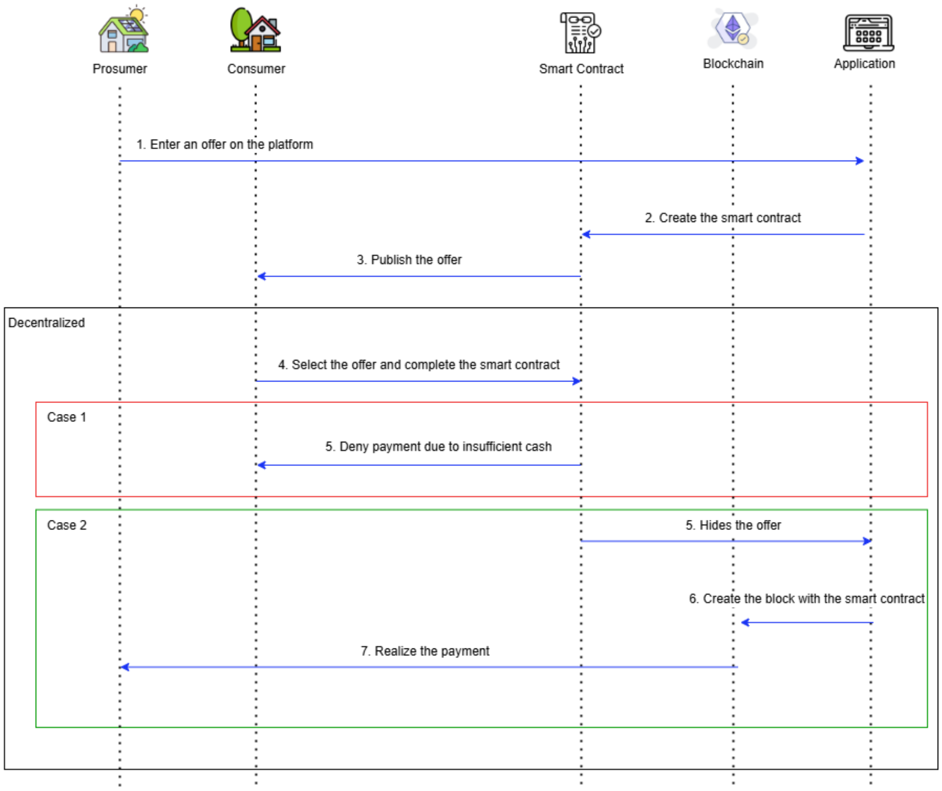


Figure 6.10: Sequence diagram for energy trading application

process takes place. The flow chart of the decentralized system can be seen in Figure 6.11.

In the decentralized market, the visualization of the UI is the same for all peers. In addition to including the display described in the previous section, the peer can publish the offer for sale in the 'marketplace' window using a simple process. On the same page, the peer can see the offers published for both sales offers and purchase offers. The offer list shows the availability for each offer; if the offer is available, the buy button is enabled; otherwise, the offer indicates that it is not available.

6.2.3 Smart Contract

A smart contract is a program stored on the blockchain that automatically executes actions when certain conditions are met, without needing a middleman. To establish the rules, it is necessary to write them using a tool. For this purpose, Solidity is used to write the rules and logic of the contracts. Solidity is a high-level programming language that is used to write smart contracts that run on blockchains; most commonly, they are Ethereum, Binance Smart Chain, and Polygon. Solidity is composed of the compiler definition, contract declaration, state variables, constructor, visibility and behavior modifiers, and functions.

In the case of P2P energy trading, the smart contract is composed of:

- **Compiler:** 0.8.0
- **Contract:** Marketplace
- **Struct:** Product and ProductBuyer
- **Event:** ProductCreated and ProductPurchased
- **Functions:** createProduct, createProduct_buyer and purchaseProduct

The details of the smart contract definitions can be found in Table 6.2 and can be checked in A.5.

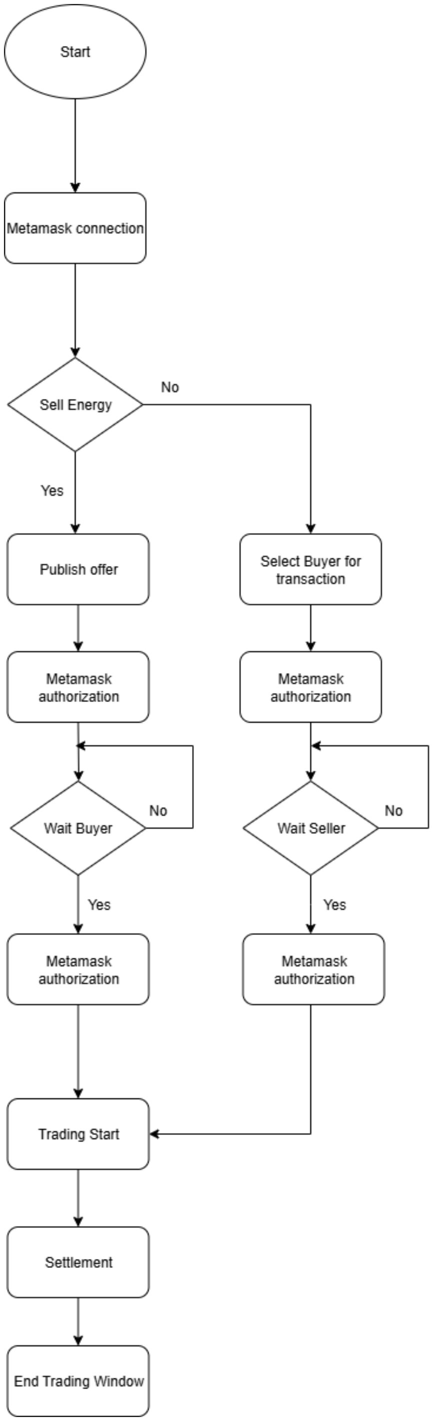


Figure 6.11: Flowchart of decentralized energy trading system .

Table 6.2: Smart contract details.

Operation	**Details**
Product	Represents an energy offer including its price, type, owner, and purchase status
ProductBuyer	Represents a demand for energy including its price, type, and buyer
ProductCreated	Broadcast for the creation of a product
ProductPurchased	Broadcast for the purchase of a product

6.2.4 Oracle

In order to connect the physical layer with the cyber layer, it is necessary to use the oracle network. An oracle is an external service that provides real-world data to smart contracts on a blockchain, allowing them to interact with the outside world. Oracles act as intermediaries that connect blockchains with external data sources, systems, or events, as shown in Figure 6.12. The primary job is to collect and provide real data for the smart contract [64]. The oracle code used is presented in the Appendix A.6.

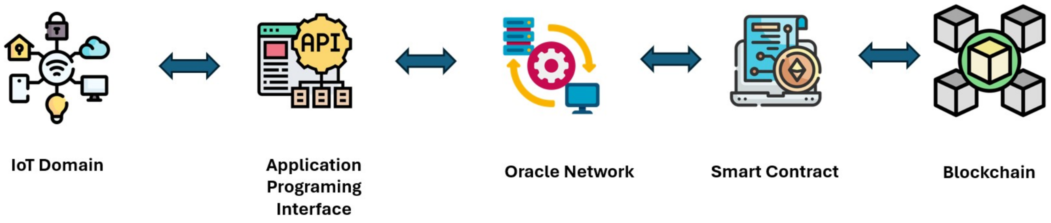


Figure 6.12: IoT and Blockchain interaction.

6.3 Market Setup

In this work, we considered real profiles for PV generation and house load demand. Based on [65] and [66], the energy consumption and energy generation profiles were selected for a day. After processing the dataset, it is plotted with a Python code, as shown in Figure 6.13. Then, the same data is loaded into ThingSpeak, as shown in Figure 6.14. To perform the energy exchange, a daily time interval is considered on the basis of the production behavior and the energy behavior.

We assumed a scenario where between 10:30 AM and 17:30 PM, the market will be open due to a higher energy demand for daily activities and photovoltaic generation. Throughout this window of time, users can use the platform to bid for prices and energy, accept offers, and pay to exchange energy. This open market window can be subdivided into two main windows; the first is the time when bids can be uploaded to the platform. This window is available in two periods, from 10:30 AM to 13:00 PM and from 14:00 PM to 16:30 PM. However, for the exchange of energy in the network, the time periods are between 13:00 PM to 14:00 PM and 16:30 PM to 17:30 Finally, between 17:30 PM to 23:59 PM the market is closed due to low energy production. Figure 6.15 presents the trading window described above. As energy demand and response in a P2P network are dynamic processes, the proposed time window can be modified.

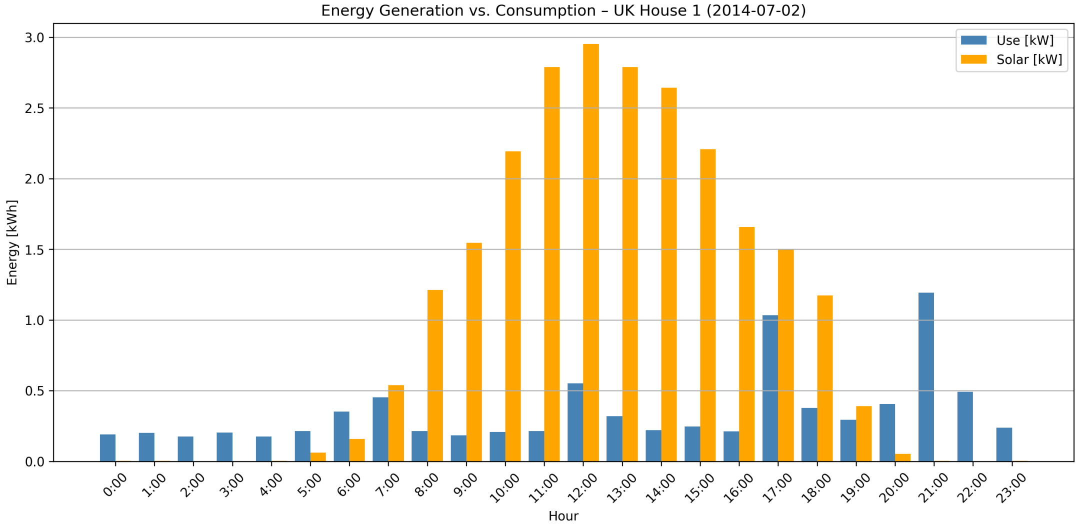
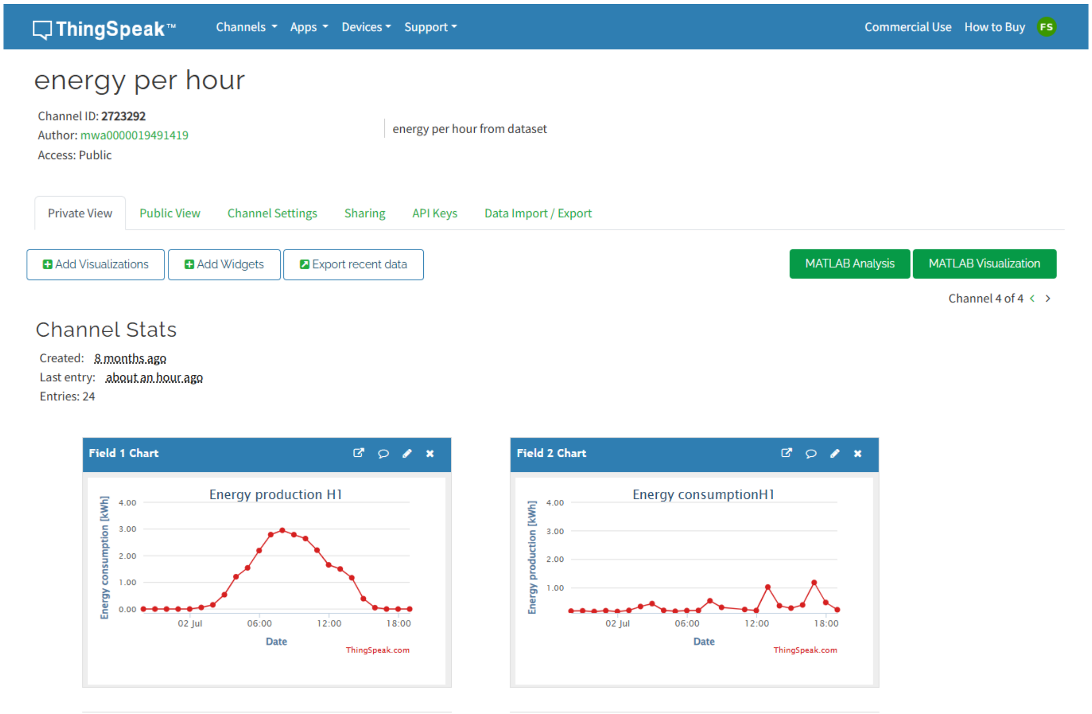


Figure 6.13: Data from house 1 .



energy per hour

Channel ID: 2723292
Author: mwa0000019491419
Access: Public

energy per hour from dataset

Channel Stats

Created: 8 months ago
Last entry: about an hour ago
Entries: 24

Figure 6.14: Data from house 1 in ThingSpeak.

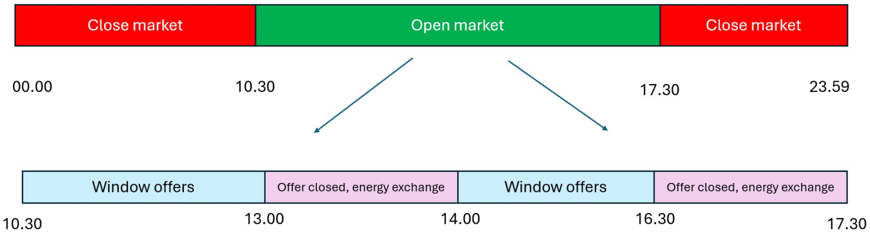


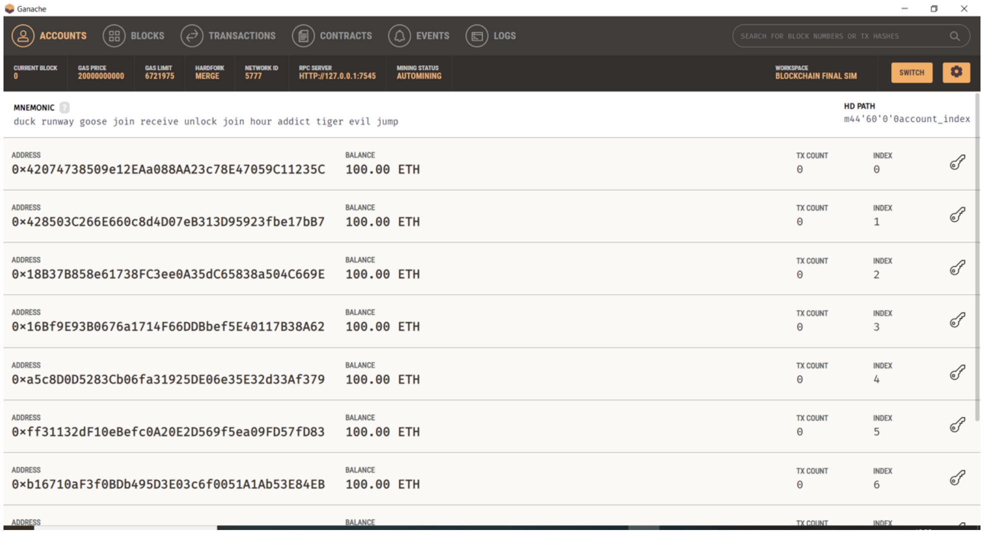
Figure 6.15: Trading window .

6.4 Blockchain Results

In this section, the results of the blockchain simulation are explained. This simulation consists of a blockchain installed on a local computer using a Windows operating system. To visualize the blockchain, the Ganache UI was used. This application allows viewing account data, stored blocks, transactions, smart contracts on the blockchain, and blockchain events. First, the blockchain is created in Ganache UI and linked to the *truffle-config.js* file that defines the parameters such as ports, solidity compiler, and directories of the smart contracts and ABI files. Initially, the blockchain only generates 10 accounts, as shown in Figure 6.16, with 100 ETH tokens each. Once this step is completed, the blockchain is generated by executing the commands in the files directory.

```
truffle compile
truffle migrate
truffle deploy
```

After executing the commands, the blockchain is displayed, as shown in Figure 6.17. Once the blockchain is created, the user must be created and linked to Metamask in order to perform the energy exchange on the marketplace platform. In the case of this simulation, the accounts with Indexes 1 and 2 are used. The information of each account is given by a hash that can be visualized in Figure 6.18. Figure 6.19 shows the initial web platform without uploaded bids. Upon completion, the user posts the bid and Metamask launches a pop-up window, as shown in Figure 6.20.



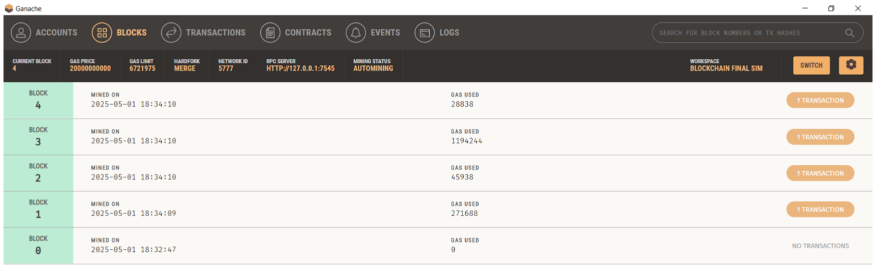
CURRENT BLOCK 0
GAS PRICE 20000000000
GAS LIMIT 6721975
HARDFORK MERGE
NETWORK ID 5777
RPC SERVER HTTP://127.0.0.1:7545
MINING STATUS AUTOMINING
WORKSPACE BLOCKCHAIN FINAL SIM

MNEMONIC
duck runway goose join receive unlock join hour addict tiger evil jump

HD PATH
m44'60'0'0account_index

ADDRESS	BALANCE	TX COUNT	INDEX
0×42074738509e12EAa088AA23c78E47059C11235C	100.00 ETH	0	0
0×428503C266E660c8d4D07eB313D95923fbe17bB7	100.00 ETH	0	1
0×18B37B858e61738FC3ee0A35dC65838a504C669E	100.00 ETH	0	2
0×16Bf9E93B0676a1714F66DDBbef5E40117B38A62	100.00 ETH	0	3
0×a5c8D0D5283Cb06fa31925DE06e35E32d33Af379	100.00 ETH	0	4
0×ff31132dF10eBefc0A20E2D569f5ea09FD57fD83	100.00 ETH	0	5
0×b16710aF3f0BDb495D3E03c6f0051A1Ab53E84EB	100.00 ETH	0	6

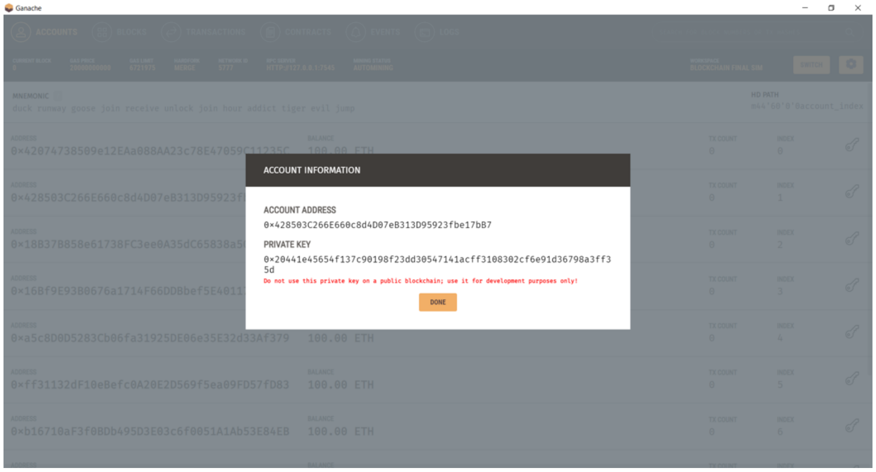
Figure 6.16: Initial blockchain created in Ganache UI.



CURRENT BLOCK 4
GAS PRICE 20000000000
GAS LIMIT 6721975
HARDFORK MERGE
NETWORK ID 5777
RPC SERVER HTTP://127.0.0.1:7545
MINING STATUS AUTOMINING
WORKSPACE BLOCKCHAIN FINAL SIM

BLOCK	MINED ON	GAS USED	
4	2025-05-01 18:34:10	28838	1 TRANSACTION
3	2025-05-01 18:34:10	1194244	1 TRANSACTION
2	2025-05-01 18:34:10	45938	1 TRANSACTION
1	2025-05-01 18:34:09	271688	1 TRANSACTION
0	2025-05-01 18:32:47	0	NO TRANSACTIONS

Figure 6.17: Blockchain after migrate and deploy smart contract.

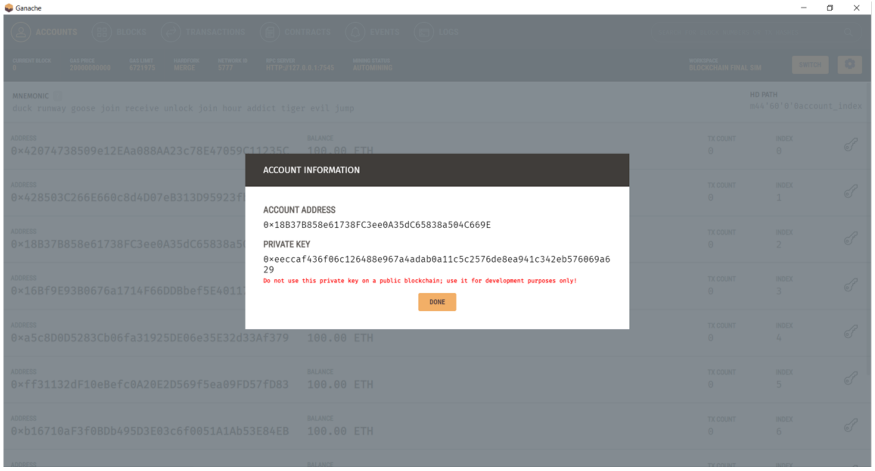


ACCOUNT ADDRESS
0×428503C266E660c8d4D07eB313D95923fbe17bB7

PRIVATE KEY
0×20441e45654f137c90198f23dd30547141acff3108302cf6e91d36798a3ff35d

Do not use this private key on a public blockchain; use it for development purposes only!

(a) Account 1.



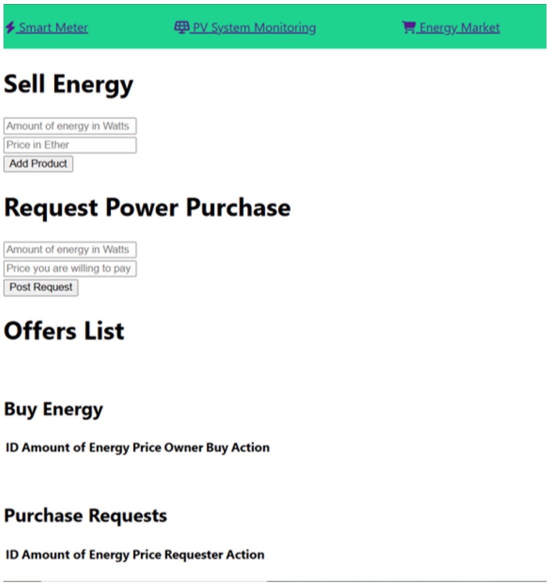
ACCOUNT ADDRESS
0×18B37B858e61738FC3ee0A35dC65838a504C669E

PRIVATE KEY
0×eeccaf436f06c126488e967a4adab0a11c5c2576de8ea941c342eb576069a629

Do not use this private key on a public blockchain; use it for development purposes only!

(b) Account 2.

Figure 6.18: Accounts used in the simulation.



Sell Energy

Request Power Purchase

Offers List

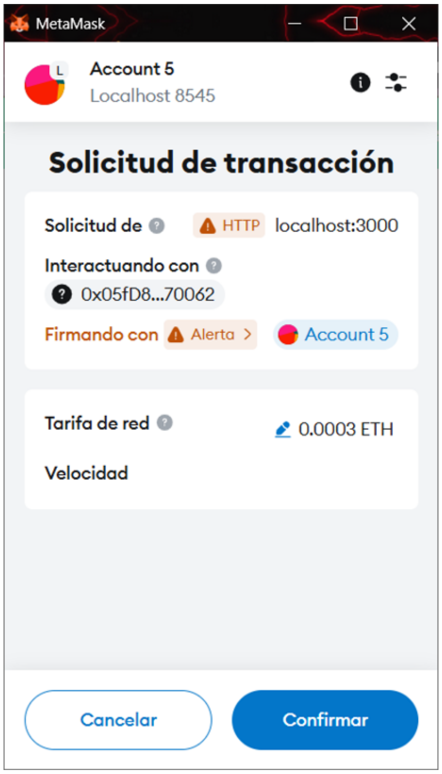
Buy Energy

ID Amount of Energy Price Owner Buy Action

Purchase Requests

ID Amount of Energy Price Requester Action

Figure 6.19: Initial marketplace in web platform.



Solicitud de transacción

Solicitud de HTTP localhost:3000

Interactuando con 0x05fD8...70062

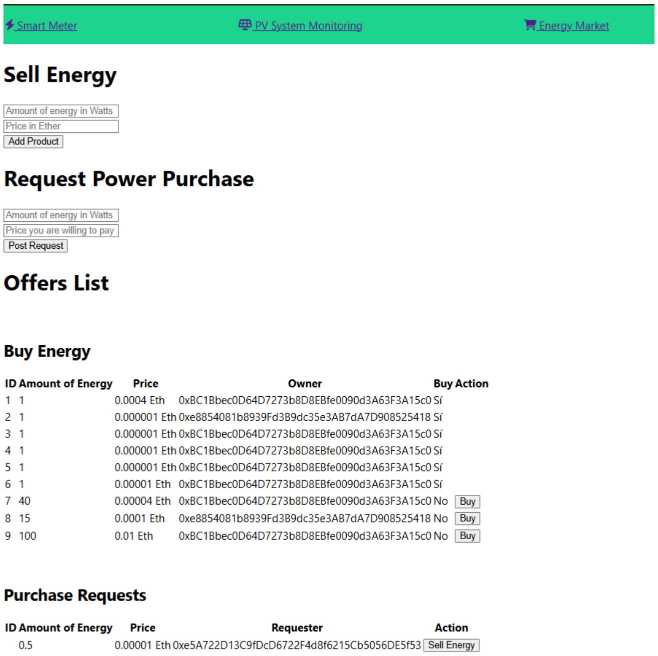
Firmando con Alerta Account 5

Tarifa de red 0.0003 ETH

Velocidad

Figure 6.20: Metamask pop-up window confirms transaction.

Once the offer is published, a block is created in the chain with the information and a notification from Metamask is sent to the user. In the case of this simulation, both users publish offers which are displayed on the marketplace page, as shown in Figure 6.21(a). In addition, it can be seen in Figure 6.21(b) that the blockchain is growing because when an offer is created, the corresponding block is created.



Sell Energy

Request Power Purchase

Offers List

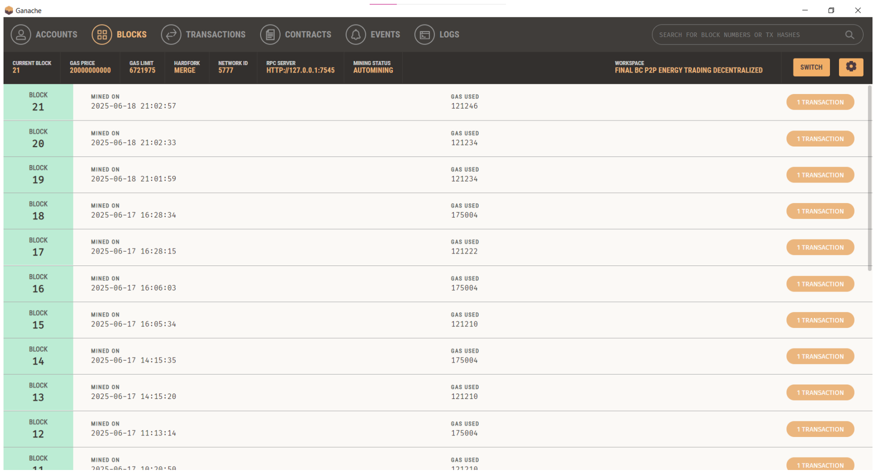
Buy Energy

ID	Amount of Energy	Price	Owner	Buy Action
1	1	0.0004 Eth	0xBC1Bbec0D64D7273b8D8EBfe0090d3A63F3A15c0	Sí
2	1	0.000001 Eth	0xe8854081b8939Fd3B9dc35e3AB7dA7D908525418	Sí
3	1	0.000001 Eth	0xBC1Bbec0D64D7273b8D8EBfe0090d3A63F3A15c0	Sí
4	1	0.000001 Eth	0xBC1Bbec0D64D7273b8D8EBfe0090d3A63F3A15c0	Sí
5	1	0.000001 Eth	0xBC1Bbec0D64D7273b8D8EBfe0090d3A63F3A15c0	Sí
6	1	0.00001 Eth	0xBC1Bbec0D64D7273b8D8EBfe0090d3A63F3A15c0	Sí
7	40	0.00004 Eth	0xBC1Bbec0D64D7273b8D8EBfe0090d3A63F3A15c0	No Buy
8	15	0.0001 Eth	0xe8854081b8939Fd3B9dc35e3AB7dA7D908525418	No Buy
9	100	0.01 Eth	0xBC1Bbec0D64D7273b8D8EBfe0090d3A63F3A15c0	No Buy

Purchase Requests

ID	Amount of Energy	Price	Requester	Action
	0.5	0.00001 Eth	0xe5A722D13C9fDcD6722F4d8f6215Cb5056DE5f53	Sell Energy

(a) Marketplace with offers.



CURRENT BLOCK 21
GAS PRICE 20000000000
GAS LIMIT 6721975
HARDFORK MERGE
NETWORK ID 5777
RPC SERVER HTTP://127.0.0.1:7545
MINING STATUS AUTOMINING
WORKSPACE FINAL BC P2P ENERGY TRADING DECENTRALIZED

BLOCK	MINED ON	GAS USED	
21	2025-06-18 21:02:57	121246	1 TRANSACTION
20	2025-06-18 21:02:33	121234	1 TRANSACTION
19	2025-06-18 21:01:59	121234	1 TRANSACTION
18	2025-06-17 16:28:34	175004	1 TRANSACTION
17	2025-06-17 16:28:15	121222	1 TRANSACTION
16	2025-06-17 16:06:03	175004	1 TRANSACTION
15	2025-06-17 16:05:34	121210	1 TRANSACTION
14	2025-06-17 14:15:35	175004	1 TRANSACTION
13	2025-06-17 14:15:20	121210	1 TRANSACTION
12	2025-06-17 11:13:14	175004	1 TRANSACTION
			1 TRANSACTION

(b) Blockchain with offers.

Figure 6.21: Available and initial offers in the simulation.

In the event that the user wants to buy an offer available in the marketplace, Metamask delivers a pop-up window with the transaction information and waits for the confirmation of the transaction, as shown in Figure 6.22. Subsequently, the product changes ownership. Once the blockchain is updated, the user's current amount of tokens can be seen in Metamask, as shown in Figure 6.23.

Account 13
Localhost 8545

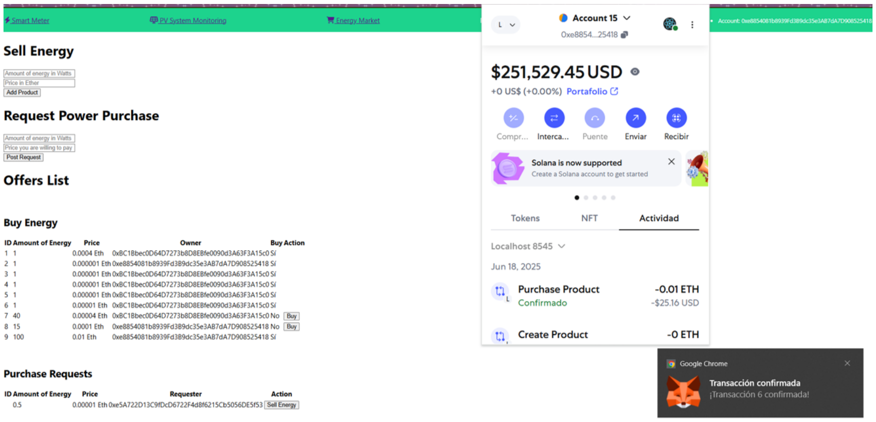
Solicitud de transacción

Solicitud de HTTP localhost:3000
Interactuando con 0x8d3D2...A6a90
Método Create Product

Tarifa de red 0.0003 ETH
0,92 US$
Velocidad
Tarifa máxima 0.0005

Nonce 0

Figure 6.22: Metamask window confirms purchase.



Account: 0xe8854081b8939Fd3B9dc35e3AB7dA7D908525418

Sell Energy

Amount of energy in Watts
Price in Ether

Request Power Purchase

Amount of energy in Watts
Price you are willing to pay

Offers List

Buy Energy

ID	Amount of Energy	Price	Owner	Buy Action
1	1	0.0004 Eth	0xBC1Bbec0D64D7273b8D8EBfe0090d3A63F3A15c0	Sí
2	1	0.000001 Eth	0xe8854081b8939Fd3B9dc35e3AB7dA7D908525418	Sí
3	1	0.000001 Eth	0xBC1Bbec0D64D7273b8D8EBfe0090d3A63F3A15c0	Sí
4	1	0.000001 Eth	0xBC1Bbec0D64D7273b8D8EBfe0090d3A63F3A15c0	Sí
5	1	0.000001 Eth	0xBC1Bbec0D64D7273b8D8EBfe0090d3A63F3A15c0	Sí
6	1	0.00001 Eth	0xBC1Bbec0D64D7273b8D8EBfe0090d3A63F3A15c0	Sí
7	40	0.00004 Eth	0xBC1Bbec0D64D7273b8D8EBfe0090d3A63F3A15c0	No Buy
8	15	0.0001 Eth	0xe8854081b8939Fd3B9dc35e3AB7dA7D908525418	No Buy
9	100	0.01 Eth	0xe8854081b8939Fd3B9dc35e3AB7dA7D908525418	Sí

Purchase Requests

ID	Amount of Energy	Price	Requester	Action
	0.5	0.00001 Eth	0xe5A722D13C9fDcD6722F4d8f6215Cb5056DE5f53	Sell Energy

Account 15
0xe8854...25418

$251,529.45 USD
+0 US$ (+0.00%) Portafolio

Solana is now supported
Create a Solana account to get started

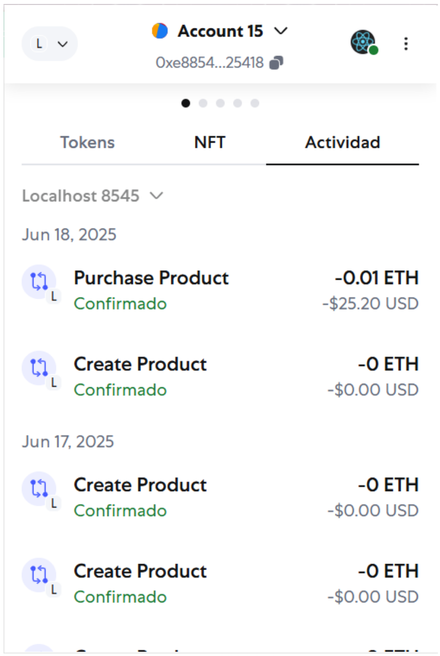
Localhost 8545
Jun 18, 2025

Purchase Product	Confirmado	-0.01 ETH -$25.16 USD
Create Product		-0 ETH

Google Chrome
Transacción confirmada
¡Transacción 6 confirmada!

Figure 6.23: Metamask and marketplace after transaction.

If another user would like to buy the remaining products, as explained above, the blockchain is updated, so the energy changes ownership and is no longer available for purchase. In addition, the available tokens of the purchasing user are updated on the Web platform. The Metamask allows the user to visualize the movements on the blockchain, including the creation and purchase of products, which can be seen in Figure 6.24.



L

Account 15

0xe8854...25418

Tokens NFT Actividad

Localhost 8545

Jun 18, 2025

Purchase Product -0.01 ETH
Confirmado -$25.20 USD

Create Product -0 ETH
Confirmado -$0.00 USD

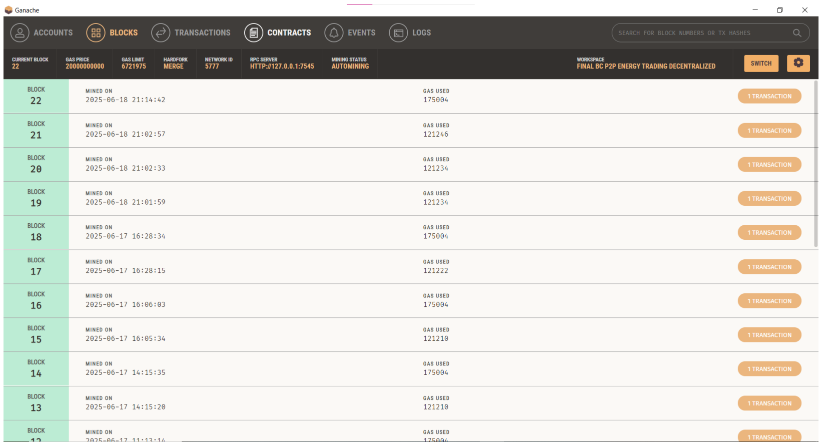
Jun 17, 2025

Create Product -0 ETH
Confirmado -$0.00 USD

Create Product -0 ETH
Confirmado -$0.00 USD

Figure 6.24: Metamask account summary after transactions.

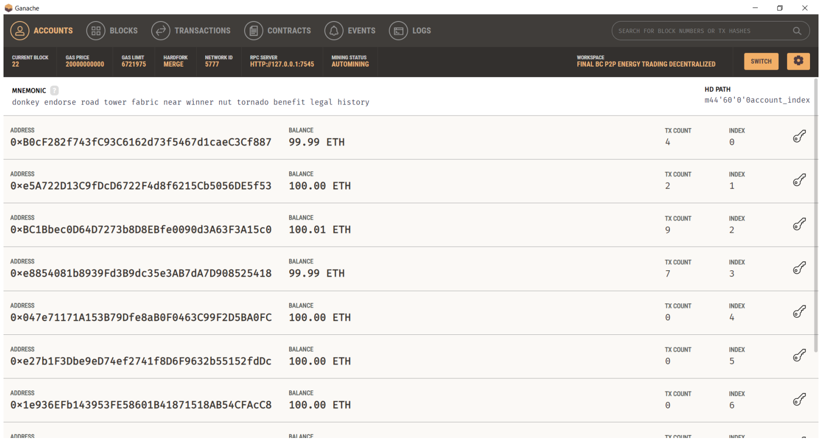
After the transactions, Ganache allows visualization of the created blocks, as shown in Figure 6.25. In addition, the current status of the tokens for each user is shown in Figure 6.26. In the events section, we can view the latest events that have occurred on the blockchain as shown in Figure 6.27, and the last transactions as shown in Figure 6.28.



CURRENT BLOCK 22
GAS PRICE 20000000000
GAS LIMIT 6721975
HARDFORK MERGE
NETWORK ID 5777
RPC SERVER HTTP://127.0.0.1:7545
MINING STATUS AUTOMINING
WORKSPACE FINAL BC P2P ENERGY TRADING DECENTRALIZED

BLOCK	MINED ON	GAS USED	
22	2025-06-18 21:14:42	175004	1 TRANSACTION
21	2025-06-18 21:02:57	121246	1 TRANSACTION
20	2025-06-18 21:02:33	121234	1 TRANSACTION
19	2025-06-18 21:01:59	121234	1 TRANSACTION
18	2025-06-17 16:28:34	175004	1 TRANSACTION
17	2025-06-17 16:28:15	121222	1 TRANSACTION
16	2025-06-17 16:06:03	175004	1 TRANSACTION
15	2025-06-17 16:05:34	121210	1 TRANSACTION
14	2025-06-17 14:15:35	175004	1 TRANSACTION
13	2025-06-17 14:15:20	121210	1 TRANSACTION

Figure 6.25: Final blockchain after transactions.



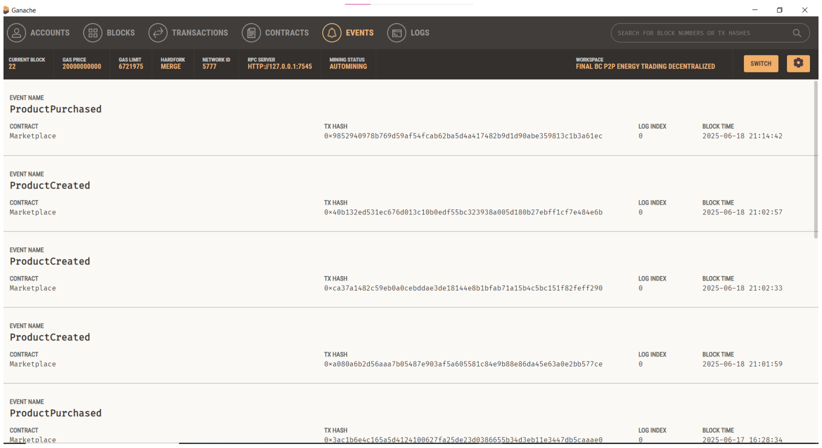
CURRENT BLOCK 22
GAS PRICE 20000000000
GAS LIMIT 6721975
HARDFORK MERGE
NETWORK ID 5777
RPC SERVER HTTP://127.0.0.1:7545
MINING STATUS AUTOMINING
WORKSPACE FINAL BC P2P ENERGY TRADING DECENTRALIZED

MNEMONIC
donkey endorse road tower fabric near winner nut tornado benefit legal history

HD PATH
m44'60'0'0account_index

ADDRESS	BALANCE	TX COUNT	INDEX
0×B0cF282f743fC93C6162d73f5467d1caeC3Cf887	99.99 ETH	4	0
0×e5A722D13C9fDcD6722F4d8f6215Cb5056DE5f53	100.00 ETH	2	1
0×BC1Bbec0D64D7273b8D8EBfe0090d3A63F3A15c0	100.01 ETH	9	2
0×e8854081b8939Fd3B9dc35e3AB7dA7D908525418	99.99 ETH	7	3
0×047e71171A153B79Dfe8aB0F0463C99F2D5BA0FC	100.00 ETH	0	4
0×e27b1F3Dbe9eD74ef2741f8D6F9632b55152fdDc	100.00 ETH	0	5
0×1e936EFb143953FE58601B41871518AB54CFAcC8	100.00 ETH	0	6

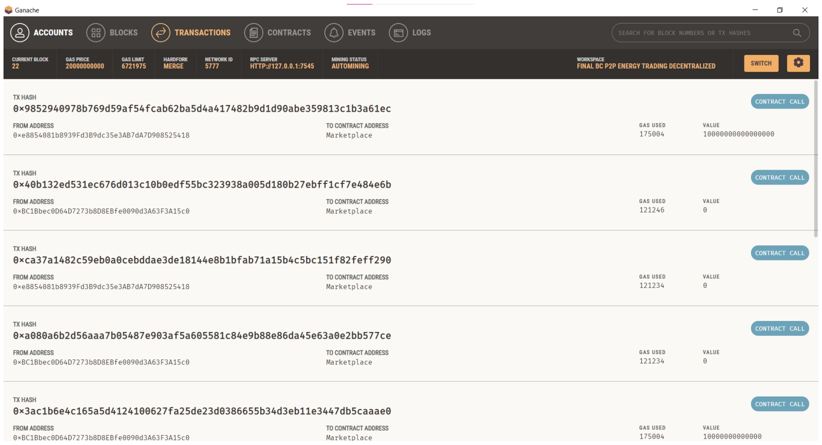
Figure 6.26: Final blockchain accounts after transactions.



CURRENT BLOCK 22
GAS PRICE 20000000000
GAS LIMIT 6721975
HARDFORK MERGE
NETWORK ID 5777
RPC SERVER HTTP://127.0.0.1:7545
MINING STATUS AUTOMINING
WORKSPACE FINAL BC P2P ENERGY TRADING DECENTRALIZED

EVENT NAME	CONTRACT	TX HASH	LOG INDEX	BLOCK TIME
ProductPurchased	Marketplace	0×9852940978b769d59af54fcab62ba5d4a417482b9d1d90abe359813c1b3a61ec	0	2025-06-18 21:14:42
ProductCreated	Marketplace	0×40b132ed531ec676d013c10b0edf55bc323938a005d180b27ebff1cf7e484e6b	0	2025-06-18 21:02:57
ProductCreated	Marketplace	0×ca37a1482c59eb0a0cebddae3de18144e8b1bfab71a15b4c5bc151f82feff290	0	2025-06-18 21:02:33
ProductCreated	Marketplace	0×a080a6b2d56aaa7b05487e903af5a605581c84e9b88e86da45e63a0e2bb577ce	0	2025-06-18 21:01:59
ProductPurchased	Marketplace	0×3ac1b6e4c165a5d4124100627fa25de23d0386655b34d3eb11e3447db5caaae0	0	2025-06-17 16:28:34

Figure 6.27: Last events in blockchain.



CURRENT BLOCK 22
GAS PRICE 20000000000
GAS LIMIT 6721975
HARDFORK MERGE
NETWORK ID 5777
RPC SERVER HTTP://127.0.0.1:7545
MINING STATUS AUTOMINING
WORKSPACE FINAL BC P2P ENERGY TRADING DECENTRALIZED

TX HASH 0×9852940978b769d59af54fcab62ba5d4a417482b9d1d90abe359813c1b3a61ec
FROM ADDRESS 0×e8854081b8939Fd3B9dc35e3AB7dA7D908525418
TO CONTRACT ADDRESS Marketplace
GAS USED 175004
VALUE 10000000000000000

TX HASH 0×40b132ed531ec676d013c10b0edf55bc323938a005d180b27ebff1cf7e484e6b
FROM ADDRESS 0×BC1Bbec0D64D7273b8D8EBfe0090d3A63F3A15c0
TO CONTRACT ADDRESS Marketplace
GAS USED 121246
VALUE 0

TX HASH 0×ca37a1482c59eb0a0cebddae3de18144e8b1bfab71a15b4c5bc151f82feff290
FROM ADDRESS 0×e8854081b8939Fd3B9dc35e3AB7dA7D908525418
TO CONTRACT ADDRESS Marketplace
GAS USED 121234
VALUE 0

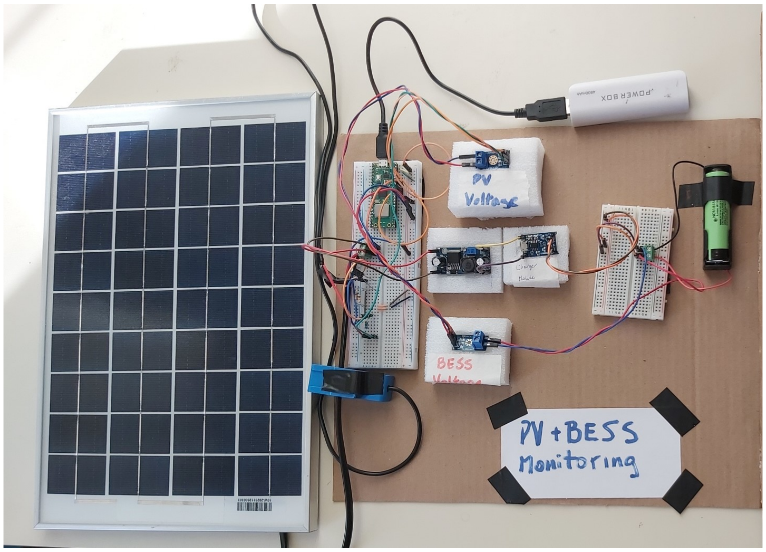
TX HASH 0×a080a6b2d56aaa7b05487e903af5a605581c84e9b88e86da45e63a0e2bb577ce
FROM ADDRESS 0×BC1Bbec0D64D7273b8D8EBfe0090d3A63F3A15c0
TO CONTRACT ADDRESS Marketplace
GAS USED 121234
VALUE 0

TX HASH 0×3ac1b6e4c165a5d4124100627fa25de23d0386655b34d3eb11e3447db5caaae0
FROM ADDRESS 0×BC1Bbec0D64D7273b8D8EBfe0090d3A63F3A15c0
TO CONTRACT ADDRESS Marketplace
GAS USED 175004
VALUE 10000000000000

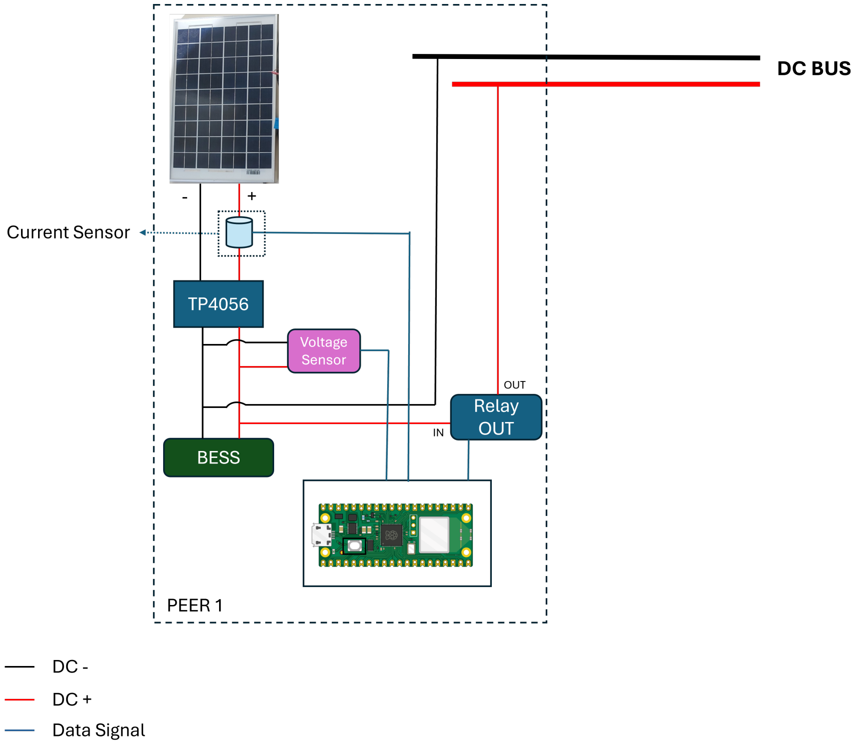
Figure 6.28: Last transactions in blockchain.

6.5 Testbed Results

In this section, the laboratory experiment of a decentralized P2P energy trading is explained. Two houses are implemented to carry out P2P energy trading. The first house consists of sensor nodes connected to the PV system and BESS. The monitoring data communicate via MQTT to HEMS/EMA in the house, as shown in Figure 6.29. The data is then sent to ThingSpeak. In addition, the information stored in the cloud is requested through the ThingSpeak API and is retrieved to display on the web interface. It is assumed that this implementation can be replicated for each market participant ”peer” with a PV system. Optionally, the peer can have PV and BESS.



(a) Laboratory experiment for smart prosumer.



(b) Schematic diagram of smart prosumer system.

Figure 6.29: PV and BESS monitoring in laboratory experiment.

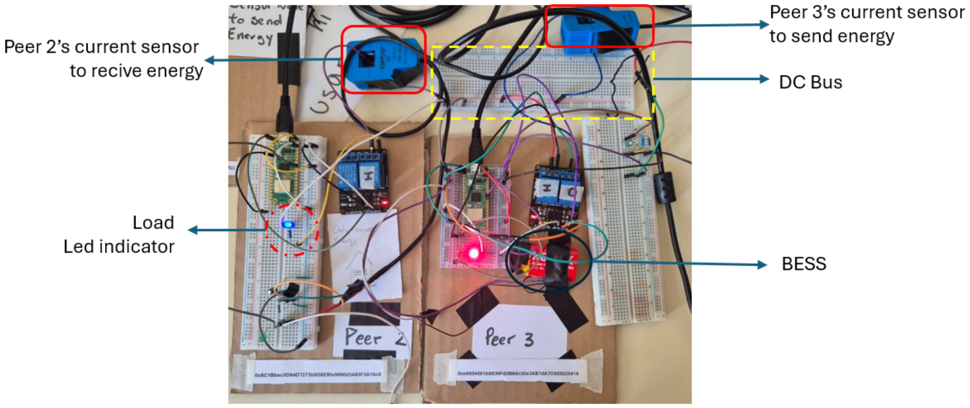
6.5.1 Case 1: Two Houses

To support P2P energy trading, a DC bus is implemented for energy transmission. For representing this DC bus, a protoboard is used. Then, each peer has a double relay to allow energy transmission to the DC bus. One relay represents ”IN Energy” (I) while the other represents ”OUT Energy” (O), in the case that the other pair has PV and/or BESS. The energy exchange is measured by the current sensor that is present on the positive wire corresponding to the energy exchange. Finally, each peer has a microcontroller, in each microcontroller the blockchain account is loaded. This is useful for the identification of each peer participating in each transaction, so that the participating peer can activate the corresponding energy input or output relay.

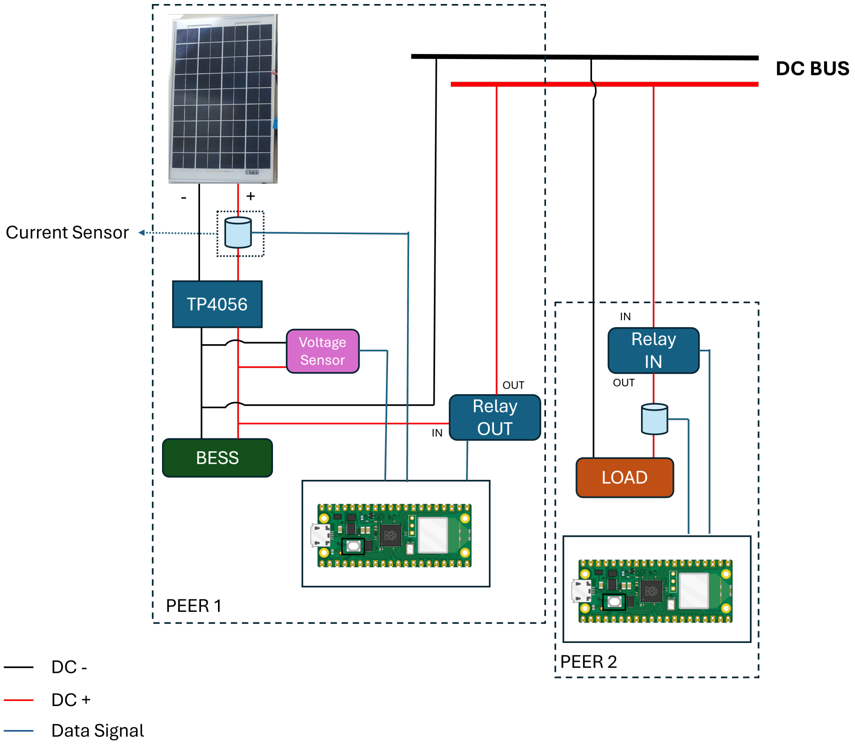
In this case, each microcontroller is connected to the MQTT Broker. This broker sends the data from/to Oracle connected to Blockchain. The format of the message sent from the broker is as follows:

```
New Transaction #{Number}: {energyToSend} from {SellerAccount}
    → {BuyerAccount}
```

Once the message is received and the transaction shift is activated, the microcontrollers activate the corresponding relay along with the measurement until the total transmitted energy is completed. To indicate that energy is being sent between the peers, an LED diode is connected. If the buyer’s LED is on, it indicates that it is receiving energy. For this experiment, 9 volt batteries are used. Figure 6.30 shows the laboratory implementation for energy exchange between two peers called Peer 2 and Peer 3. In this experiment, both peers are logged into the web platform using Metamask and transactions are registered on the blockchain.



(a) Laboratory experiment.



(b) Laboratory diagram.

Figure 6.30: Schematic diagram of P2P energy trading between two peers.

Figure 6.31 shows the blockchain loaded in the main server in a Raspberry Pi. Once the blockchain is loaded, the console returns the address of the user with his private key, which is used to bind the account in Metamask.

```
smart-grid@raspberrypi:~ $ ganache-cli --host 0.0.0.0 --accounts 7 --defau
ltBalanceEther 100 --gasLimit 30000000
Ganache CLI v6.12.2 (ganache-core: 2.13.2)

Available Accounts
==================
(0) 0x77E6bB9a364614FE6620A5211A02433C1583aA6e (100 ETH)
(1) 0xcD96885c6F0476Fb6e58bD93b2E2b0d7AC8C65af (100 ETH)
(2) 0x681783E6869DdBAfF5c04Bf1F9540FC4C9A4136D (100 ETH)
(3) 0x6b411728A21e1bA04e729677F7A011F8850F1263 (100 ETH)
(4) 0x5E4a9aB02c70b0258154939AB3829DF9A8aCFA02 (100 ETH)
(5) 0xA28EC3191Ac75D8E070c9573Ed51B1f501DFA7D3 (100 ETH)
(6) 0x1898f7677946888067BE99a593e944Af9E9bE7bc (100 ETH)

Private Keys
==================
(0) 0x759cb505883217b226baaabbb2c9cee589d8add1ff1ff5783a175a2e469cb7df
(1) 0xa41adfaa82a5bfd024c819b6ecce71e02d778eb0aa02069f5cc9f388523b9340
(2) 0x1ea032c30e1d30146d1bb058905981c58e5684239e9e3b1fb34bb5a9a84d9d1c
(3) 0x5428f5ddb3f773ae1a11acf54428955f656624201002c3ff2baf073e3ae193d0
(4) 0x7f2904bd35e280015bf736d8fc82f19ccf7c61a341984ce15fdc6cc1b98b3247
(5) 0x7789c606783797de7b23541817174d037855e861a1243457279aaa1da268743c
(6) 0x478d74ddb8dc84536557bfe96356fc34c307b15f1213b67ddc7bd124341f5a18

HD Wallet
==================
Mnemonic:      monster exhaust inherit property jacket talk ostrich claim
```

Figure 6.31: Capture of blockchain loaded in the main server

6.5.2 Case 2: Local Community with Five Houses

In the case of a local community with 5 houses, the energy exchange system is the same as in the previous case. However, in this case, to perform the energy exchange and because they are all connected to a bus, a special circuit is needed to enable the energy exchange among different peers at the same time.

Since each power delivery is connected by means of a relay, it is not necessary to implement voltage prevention techniques, and in this case all the batteries used were of the same voltage. Each peer has its blockchain account loaded, which serves as an indicator at the time of receiving the message for the transmission of energy. To perform the exchange in turns, the oracle stores locally a file with the transactions sent and performed, which is read at the time of sending the data to the broker, thus preventing the double exchange of energy. To link the account to the web platform, the private keys of the corresponding account are used through the use of a Metamask as in the case of two peers.

Figure 6.32 shows the laboratory implementation with five peers. At the time of execution, the microcontrollers are connected to a computer via USB and portable batteries.

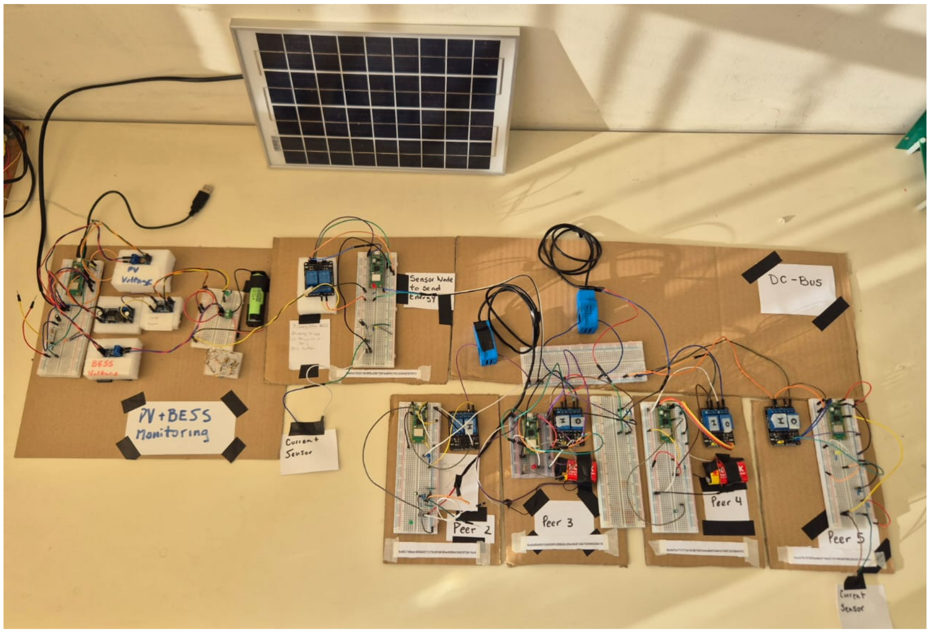


Figure 6.32: Complete testbed implementation with 5 peers

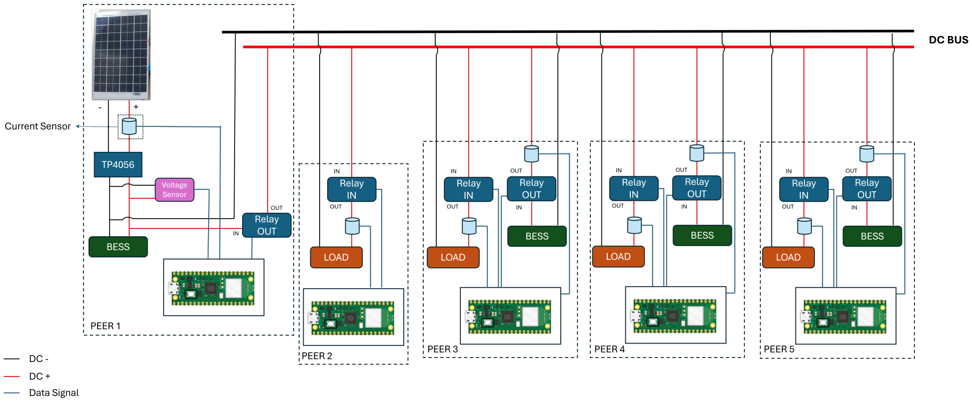


Figure 6.33: Schematic diagram for the configurations of the testbed

Chapter 7

Conclusion and Future Work

Peer-to-Peer energy trading represents an innovative solution for a decentralized energy market through the use of advanced technologies such as blockchain, smart contracts, and digital platforms compared with the traditional centralized power system. This approach allows prosumers to exchange surplus energy directly among themselves, promoting energy efficiency, local autonomy, and greater citizen participation in the energy market. This model not only reduces the dependence on large suppliers, but also opens up new opportunities to integrate renewable energy in a more flexible and distributed way. In addition, it is a possible solution to address the problem of electrification in remote and rural areas. Finally, this model allows for the incorporation of distributed renewable energy resources (DER), which will enhance the local balance of energy generation and consumption.

This thesis presented the design and implementation of an IoT-Blockchain platform for solar P2P energy trading among smart homes in a local community microgrid. The developed platform allows real-time monitoring for energy consumption and energy production using smart meters, and allows energy trading among smart houses. The platform uses a private blockchain and oracle network to facilitate energy trading between smart houses and incorporate different technologies. In addition, this work presented the performance evaluation of the communication network, including wired and wireless communication protocols, with different numbers of participants in the energy trading market.

The results showed that the developed platform is a promising solution for solar energy trading in a local community microgrid. The platform provides security, efficiency, and transparency using different technologies, such as Ethereum with Metamask, which allows for the elimination of intermediaries for the verification of processes and transactions. It also allows for real-time transactions and settlement. The developed platform allowed the use of smart contracts, which can be modified according to the specific requirements needed for the implementation of the P2P system through codes and rules. Furthermore, the developed platform allowed energy exchange among a group of users through hardware development.

The following are the main challenges and limitations of the developed energy trading platform. (1) For the use of the blockchain, Ganache offers 10 test accounts so that this system can be tested with ten peers, while the central server could run with more accounts. However, due to the limitations of the Raspberry Pi, it was not possible to run with a larger number of accounts, as it would cause crashes when raising the necessary services. (2) The developed hardware of the current testbed should be extend to the development of PCBs. Such a solution will enable simple wiring connections and make them easy to visualize and understand. In addition, the hardware should be complemented with the different types of sensors required to monitor the PV system and the BESS for each peer. (3) The developed system should be extended and tested with alternating current. In this regard, electrical knowledge is required to extend the current work, as well as to modify the current configuration of the testbed since the sensors and the measured values will be outside the allowed range according to the datasheet of the sensors used in the current testbed.

Another limitation of the current testbed is the dependence on the Internet. It is necessary to investigate a system that allows for offline power exchange and a backup system. An alternative can be with offline blockchain with subsequent synchronization or use real tokens. Also, investigating and including a price bidding system in a platform will allow a more fair, more equitable, and transparent pricing system. Other future work is to automate and optimize the process of selling/buying energy by including artificial intelligent algorithms.

With the adoption of electric vehicles (EV), recent works have begun to address the opportunities that electric vehicles could bring or support local energy trading in local communities. In addition, other energy resources can be included, such as wind and hydro generation. Finally, for a complete analysis, other energy trading markets and architectures, such as centralized and hybrid, should be studied, analyzed, and compared. Such architectures will require an adaptation of blockchain, smart contract, and user interface. This analysis will help make a complete comparison of the technical implementations and scalability of the local energy trading system.

A

Appendix

A.1 Hardware of Smart Prosumer

The components used for the sensor nodes are described in the following.

- **Raspberry Pi Pico W:** is an enhanced version of the original Raspberry Pi Pico, incorporating Wi-Fi and Bluetooth wireless connectivity. These boards are designed for IoT applications, automation, home automation, remote sensors and embedded projects. Its operating voltage is 3.3V and can be powered between 1.8V and 5.5V. As can be seen in Figure A.1, it contains 3 ADC inputs. Its programming way is compatible with MicroPyhton, C/C++ SDK and Arduino IDE. Finally this microcontroller is low power consumption so it is suitable for the proposed P2P energy trading system.

- **Current Sensor SCT-013:** is a Current Transformer (CT) type current sensor that allows measuring alternating current (AC) without interrupting the circuit. It is widely used in power consumption monitoring projects in IoT and power systems. It can measure up to 100A, for its use it is necessary to use 220Ω and 10kΩ resistors and 10μF capacitor, you can also use a LM358 chip. The sensor used as shown in Figure A.2.

- **Voltage Sensor:** The sensor used to monitor the energy production is the FZ0430 model that allows to monitor DC voltages between 0.02445 - 25V, it uses a voltage divider with 30K and 7K5 resistors. On the other hand, the ZMPT101B sensor allows single-phase mains voltage measurements (250VAC max.). The ZMPT101B Module solves the problem by reducing the input AC voltage value to a lower voltage, with positive values only, which can be read by any microcontroller with ADC inputs. It also contains a voltage divider and an operational amplifier circuit (OPAMP LM358) to add an offset to the analog output. It delivers a sine wave of amplitude adjustable by a potentiometer on board and thus we only have positive signal above zero. The offset depends on the supply voltage, in the case of this implementation the offset is 1.65V because the power supply of the module is 3.3V.

- **Relay:** is an electromagnetic device that functions as a switch controlled by an electrical circuit in which, by means of a coil and an electromagnet, a set of one or more contacts is actuated to open and close other independent electrical circuits. In the case of P2P energy trading, it is activated for the transfer of energy between peers.

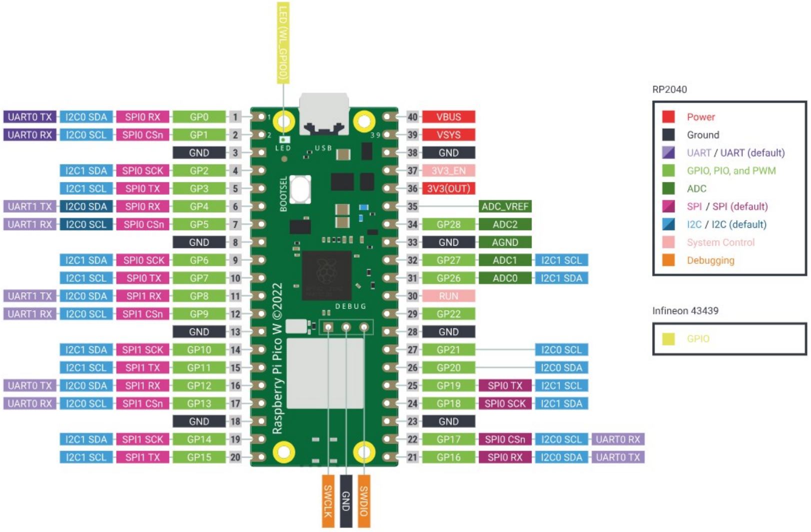


Figure A.1: Raspberry Pi Pico W pinout.

Figure A.2: Current sensor SCT-013.

A.2 Code developed for enabling MQTT communication between sensor node and Raspberry Pi

```python
import paho.mqtt.client as mqtt
import requests

THINGSPEAK_WRITE_APIKEY='2MDS0Q7YP9XWJWFR'
THINGSPEAK_URL='https://api.thingspeak.com/update?api_key='

MQTT_BROKER='localhost'
MQTT_PORT=1883
MQTT_topic_voltagePV='p2p/voltage'
MQTT_topic_currentPV='p2p/current'
MQTT_topic_potenciaPV='p2p/potencia'
MQTT_topic_voltageBESS='p2p/voltageBESS'
TOPICS={
  'p2p/voltage': 'field1',
  'p2p/current': 'field2' ,
  'p2p/potencia': 'field3' ,
  'p2p/voltageBESS': 'field5'
}
sensorData={
  'field1': None,
  'field2': None ,
  'field3': None,
  'field5': None

}
def on_connect(client, userdata, flags, rc):
  print(f"Conectando al broker... ",rc)
  for topic in TOPICS:
    client.subscribe(topic)
    print(f"Suscrito al topic {topic}")

#sendData to server JS
```

```
def sendDataAPI(valor):
  url="http://192.168.0.186:5000/sensor"
  data={"value":valor}
  try:
    response=requests.post(url,json=data)
    if response.status_code == 200:
      print(f"Dato enviado correctamente: {valor}")
    else:
      print(f"ERROR codigo: {respone.status_code}")
  except Exception as e:
    print(f"Error al enviar datos {e}")
  print("_____")
def on_message(client, userdata, msg):
  try:
    topic = msg.topic
    payload=msg.payload.decode()
    print(f"{topic}=> {payload}")

    if topic in TOPICS:
      field=TOPICS[topic]
      sensorData[field]=payload
      payload_to_send={
        'api_key':  THINGSPEAK_WRITE_APIKEY
      }
    for f,val in sensorData.items():
      if val is not None:
        payload_to_send[f]=val

    response=requests.post(THINGSPEAK_URL,params=payload_to_send)
    if response.status_code==200:
      print("Dato enviado a ThingSpeak: ", payload_to_send)
    else:
      print("Error to send ThingSpeak: ", response.text)

    #sendToAPI
    sendDataAPI(payload_to_send)
```

```


  except Exception as e:
    print("Error ",e)

client = mqtt.Client()
client.on_connect=on_connect
client.on_message=on_message

client.connect(MQTT_BROKER, MQTT_PORT, 60)
client.loop_forever()
```

A.3 Main script for obtain access token from ’ewelink’

```
require('dotenv').config();
import eWeLink from 'ewelink-api-next'

// https://dev.ewelink.cc/
// Login
// Apply to become a developer
// Create an application

const _config = {
  appId: process.env.EWELINK_APPID, // App ID, which needs to be configured in the eWeLink open platform
  appSecret: process.env.EWELINK_APPSECRET, // App Secret, which needs to be configured in the eWeLink open platform
  region: 'us', //Feel free, it will be automatically updated after login
  requestRecord: true, // Request record, default is false
  // logObj: console, // Log object, default is console
}

if (!_config.appId || !_config.appSecret) {
  throw new Error('Please configure appId and appSecret')
}

export const client = new eWeLink.WebAPI(_config)
export const wsClient = new eWeLink.Ws(_config);

export const redirectUrl = 'http://127.0.0.1:8000/redirectUrl' // Redirect URL, which needs to be configured in the eWeLeLink open platform

// Generate random strings
export const randomString = (length) => {
  return [...Array(length)].map(_=>(Math.random()*36|0).toString(36)).join('');
```

```
}
```

A.4 Script used to get data from Sonoff using ’ewelink’ API

```
const express = require('express');
const cors = require('cors');
const ewelink = require('ewelink-api');
const fs = require('fs'); // Importa el módulo 'fs'
require('dotenv').config();

const app = express();
app.use(cors()); // Permitir solicitudes desde React
app.use(express.json());

const connection = new ewelink({
    at: process.env.EWELINK_AT,
    region: process.env.EWELINK_REGION,
})
//device information
const testDevice = async () => {
  try {
    const device = await connection.getDevice(process.env.DEVICE_ID);
    console.log('Dispositivos:', device);

    // Escribe el objeto device en un archivo JSON
    fs.writeFile('device.json', JSON.stringify(device, null, 2), (err) => {
        if (err) {
          console.error('Error al escribir el archivo JSON:', err.message);
        } else {
          console.log('Información del dispositivo guardada en "device.json"');
        }
    });

  } catch (error) {
```

```
    console.error('Error al obtener dispositivos:', error.message);
  }
};

//daily used
const getDevicePowerUsage = async () => {
    try {
        const usage = await connection.getDevicePowerUsage(process.env.DEVICE_ID);
        console.log('Ahora el powerUsage')
        console.log(usage);
    } catch (error) {
        console.error('Error al obtener informacion del dispositivo: ', error.message);
    }
}

testDevice();

getDevicePowerUsage();

//route for used in frontend
app.get('/api/device', async (req, res) => {
  try {
    const connection = new ewelink({
      at: process.env.EWELINK_AT,
      region: process.env.EWELINK_REGION,
    });
    const device = await connection.getDevice(process.env.DEVICE_ID);
    res.json(device);
  } catch (error) {
    res.status(500).json({ error: error.message });
  }
});

```

```
//route for access monthly data used in frontend
app.get('/api/mensual', async (req, res) => {
  try {
    const connection = new ewelink({
      at: process.env.EWELINK_AT,
      region: process.env.EWELINK_REGION,
    });
    const deviceMensual = await connection.getDevicePowerUsage(process.env.DEVICE_ID);
    res.json(deviceMensual);
  } catch (error) {
    res.status(500).json({ error: error.message });
  }
});


// Server in port 5000
const PORT = process.env.PORT || 5000;
app.listen(PORT, () => console.log(`Servidor corriendo en el puerto ${PORT}`));
```

A.5 Smart Contract for P2P energy trading - Decentralized case

```
// SPDX-License-Identifier: MIT
pragma solidity ^0.8.0;

contract Marketplace {
    address public owner;

    uint public productCount = 0;
    uint public productCount_buyer = 0;

    mapping(uint => Product) public products;
    mapping(uint => ProductBuyer) public products_buyer;

    struct Product {
        uint id;
        uint price;
        string energy;
        address payable owner;
        bool purchased;
    }

    struct ProductBuyer {
        uint id;
        uint price;
        string energy;
        address payable owner;
        bool fulfilled;
    }

    event ProductCreated(
        uint id,
        uint price,
        string energy,
```

```
        address payable owner,
        bool purchased
    );

    event ProductPurchased(
        uint id,
        uint price,
        string energy,
        address payable owner,
        bool purchased
    );

    event ProductSoldToBuyer(
        uint id,
        uint price,
        string energy,
        address payable buyer,
        address payable seller
    );

    constructor() {
        owner = msg.sender;
    }

    function createProduct(uint _price, string memory _energy) public {
        require(_price > 0, "Product price must be greater than zero");
        require(bytes(_energy).length > 0, "Energy must be specified");

        productCount++;
        products[productCount] = Product(productCount, _price, _energy, payable(msg.sender), false);

        emit ProductCreated(productCount, _price, _energy, payable(
```

```
msg.sender), false);
    }

    function createProduct_buyer(uint _price, string memory _energy) public {
        require(_price > 0, "Price must be greater than zero");
        require(bytes(_energy).length > 0, "Energy must be specified");

        productCount_buyer++;
        products_buyer[productCount_buyer] = ProductBuyer(productCount_buyer, _price, _energy, payable(msg.sender), false);

        emit ProductCreated(productCount_buyer, _price, _energy, payable(msg.sender), false);
    }

    function purchaseProduct(uint _id) public payable {
        Product memory _product = products[_id];
        address payable _seller = _product.owner;

        require(_product.id > 0 && _product.id <= productCount, "Invalid product ID");
        require(msg.value >= _product.price, "Not enough Ether to cover price");
        require(!_product.purchased, "Already purchased");
        require(_seller != msg.sender, "Buyer cannot be the seller");

        _product.owner = payable(msg.sender);
        _product.purchased = true;
        products[_id] = _product;

        (bool success, ) = _seller.call{value: msg.value}("");
        require(success, "Transfer failed");
```

```

        emit ProductPurchased(_id, _product.price, _product.energy, payable(msg.sender), true);
    }

    function sellToBuyerRequest(uint _id) public payable{
        ProductBuyer memory _request = products_buyer[_id];

        require(_request.id > 0 && _request.id <= productCount_buyer, "Invalid buyer request ID");
        require(!_request.fulfilled, "Request already fulfilled");
        require(_request.owner != msg.sender, "Cannot sell to your own request");

        (bool success, ) = _request.owner.call{value: _request.price}("");
        require(success, "Payment failed");

        _request.fulfilled = true;
        products_buyer[_id] = _request;

        emit ProductSoldToBuyer(
            _id,
            _request.price,
            _request.energy,
            _request.owner,
            payable(msg.sender)
        );
    }
}
```

Listing A.1: Smart Contract for P2P energy trading decentralized case

A.6 Oracle code

```

const { ethers } = require("ethers");
const mqtt = require("mqtt");

const GANACHE_URL = "http://127.0.0.1:8545";
const CONTRACT_ADDRESS = "0x800F27A616c8F4471a18a11AABc9b9c7A22D7A22";

const contractJson = require('./abi/contracts/Marketplace.json');
const ABI = contractJson.abi;

const MQTT_BROKER = "http://192.168.0.193:1883";
const MQTT_TOPIC_ENERGY = "p2p/energy";

const provider = new ethers.JsonRpcProvider(GANACHE_URL);
const contract = new ethers.Contract(CONTRACT_ADDRESS, ABI, provider);
const mqttClient = mqtt.connect(MQTT_BROKER);
let ultimaTransaccionIndex = 0;

const fs = require("fs");
const path = require("path");
const transaccionesFile = path.join(__dirname, "transacciones.json");

let enviadas = [];

if (fs.existsSync(transaccionesFile)) {
  try {
    const saved = JSON.parse(fs.readFileSync(transaccionesFile));
    enviadas = saved.enviadas || [];
  } catch (e) {
    console.error("Error leyendo transacciones.json:", e.message);
  }
```

```
}

mqttClient.on("connect", () => {
  console.log("Conectado al broker MQTT");

  setInterval(async () => {
    try {
      const total = await contract.getCantidadTransacciones();

      for (let i = 0; i < total; i++) {
        if (enviadas.includes(i)) continue; // ya se envió

        const [id, price, energy, buyer, seller] = await contract.getTransaccion(i);
        console.log(`Transacción nueva #${id}: ${energy}kWh de ${seller} → ${buyer}`);

        mqttClient.publish(MQTT_TOPIC_ENERGY, energy);
        enviadas.push(i);

        fs.writeFileSync(transaccionesFile, JSON.stringify({ enviadas }));
      }
    } catch (error) {
      console.error("Error al leer transacciones:", error.message);
    }
  }, 10000); // cada 10 segundos
});
```

Listing A.2: Oracle code for decentralized and centralized market

Bibliography

[1] Ministry of Energy, “Mapa de vulnerabilidad energética,” [Online]. Available: https://www.energia.gob.cl/sites/default/files/documento_de_metodologia_y_resultados_0.pdf, 2019, accessed: 29-Agu-2024.

[2] Solcor Chile, “Chile logra récord de energías renovables con 93,5% de participación,” [Online]. Available: https://solcorchile.com/record-de-energias-renovables-chile/, 2023, accessed: 29-Agu-2024.

[3] Ministry of Energy, “Ernc y otro record: generación eléctrica en base a este tipo de energia llego al 41% en lo que va de 2024,” [Online]. Available: https://energia.gob.cl/noticias/nacional/ernc-y-otro-record-generacion-electrica-en-base-este-tipo-de-energia-llego-al-41-en-lo-que-va-de-2024, 2024, accessed: 29-Agu-2024.

[4] H. Almasalma, J. Engels, and G. Deconinck, “Peer-to-peer control of microgrids,” *arXiv preprint arXiv:1711.04070*, 2017.

[5] J. Salles-Mardones, A. Flores-Maradiaga, R. Barraza, and M. A. Ahmed, “Sensitivity analysis of peer-to-peer photovoltaic energy trading in a community microgrid in chile,” *Journal of Modern Power Systems and Clean Energy*, 2024.

[6] Energy Partnership Chile - Germany, “Prospection in energy digitalization in chile,” [Online]. Available: https://energypartnership.cl/fileadmin/chile/media_elements/Studies/

20210818_Prospection_in_Energy_Digitalization_in_Chile_Full_Study.pdf, 2021, accessed: 13-Jan-2025.

[7] M. de Energía de Chile, “Energía 2050: Política energética de chile,” [Online]. Available: https://www.energia.gob.cl/sites/default/files/energia_2050_-_politica_energetica_de_chile.pdf, 2015, accessed: 12-Mar-2025.

[8] C. Solar, “Casa solar - programa de acceso a energía solar para viviendas,” [Online]. Available: https://www.casasolar.cl/, 2025, accessed: 12-Mar-2025.

[9] M. de Energía de Chile, “Ruta de la luz - ministerio de energía de chile,” [Online]. Available: https://energia.gob.cl/mini-sitio/ruta-de-la-luz, 2019, accessed: 13-Agu-2024.

[10] O. Jogunola, Y. Tsado, B. Adebisi, and M. Hammoudeh, “Virtelect: A peer-to-peer trading platform for local energy transactions,” *IEEE Internet of Things Journal*, vol. 9, no. 8, pp. 6121–6133, 2021.

[11] K. Ravivarma and B. Lokeshgupta, “A peer-to-peer energy trading model for community microgrids with energy management,” *Peer-to-Peer Networking and Applications*, pp. 1–17, 2024.

[12] Y. Liu, L. Wu, and J. Li, “Peer-to-peer (p2p) electricity trading in distribution systems of the future,” *The Electricity Journal*, vol. 32, no. 4, pp. 2–6, 2019.

[13] A. Aoun, M. Adda, A. Ilinca, M. Ghandour, and H. Ibrahim, “Comparison between blockchain p2p energy trading and conventional incentive mechanisms for distributed energy resources—a rural microgrid use case study,” *Applied Sciences*, vol. 14, no. 17, p. 7618, 2024.

[14] J. Lin, M. Pipattanasomporn, and S. Rahman, “Comparative analysis of auction mechanisms and bidding strategies for p2p solar transactive energy markets,” *Applied energy*, vol. 255, p. 113687, 2019.

[15] ——, “Comparative analysis of blockchain-based smart contracts for solar electricity exchanges,” in *2019 IEEE Power & Energy Society Innovative Smart Grid Technologies Conference (ISGT)*. IEEE, 2019, pp. 1–5.

[16] C. Long, J. Wu, C. Zhang, L. Thomas, M. Cheng, and N. Jenkins, “Peer-to-peer energy trading in a community microgrid,” in *2017 IEEE power & energy society general meeting*. IEEE, 2017, pp. 1–5.

[17] M. I. Azim, W. Tushar, T. K. Saha, C. Yuen, and D. Smith, “Peer-to-peer kilowatt and negawatt trading: A review of challenges and recent advances in distribution networks,” *Renewable and Sustainable Energy Reviews*, vol. 169, p. 112908, 2022.

[18] C. Zhang, J. Wu, Y. Zhou, M. Cheng, and C. Long, “Peer-to-peer energy trading in a microgrid,” *Applied energy*, vol. 220, pp. 1–12, 2018.

[19] R. Trivedi, S. Patra, Y. Sidqi, B. Bowler, F. Zimmermann, G. Deconinck, A. Papaemmanouil, and S. Khadem, “Community-based microgrids: Literature review and pathways to decarbonise the local electricity network,” *Energies*, vol. 15, no. 3, p. 918, 2022.

[20] S. Park, S. Park, S.-P. Yun, K. Lee, B. Kang, M.-i. Choi, H. Jang, and S. Park, “Design and implementation of a futuristic ev energy trading system (feets) connected with buildings, pv, and ess for a carbon-neutral society,” *Buildings*, vol. 13, no. 3, p. 829, 2023.

[21] S. Suthar, S. H. C. Cherukuri, and N. M. Pindoriya, “Peer-to-peer energy trading in smart grid: Frameworks, implementation methodologies, and demonstration projects,” *Electric Power Systems Research*, vol. 214, p. 108907, 2023.

[22] F. Condon, P. Franco, J. M. Martínez, A. M. Eltamaly, Y.-C. Kim, and M. A. Ahmed, “Energyauction: Iot-blockchain architecture for local peer-to-peer energy trading in a microgrid,” *Sustainability*, vol. 15, no. 17, p. 13203, 2023.

[23] M. R. Alam, M. St-Hilaire, and T. Kunz, “Peer-to-peer energy trading among smart homes,” *Applied energy*, vol. 238, pp. 1434–1443, 2019.

[24] S. Knudsen, S. Majumder, and A. K. Srivastava, “Securely implementing and managing neighborhood solar with storage and peer to peer transactive energy,” *arXiv preprint arXiv:2302.11753*, 2023.

[25] M. Pipattanasomporn, S. Rahman, and M. Kuzlu, “Blockchain-based solar electricity exchange: Conceptual architecture and laboratory setup,” in *2019 IEEE power & energy society innovative smart grid technologies conference (ISGT)*. IEEE, 2019, pp. 1–5.

[26] Z. Jing, M. Pipattanasomporn, and S. Rahman, “Blockchain-based negawatt trading platform: Conceptual architecture and case studies,” in *2019 IEEE PES GTD Grand International Conference and Exposition Asia (GTD Asia)*. IEEE, 2019, pp. 68–73.

[27] M. Pipattanasomporn, M. Kuzlu, and S. Rahman, “A blockchain-based platform for exchange of solar energy: Laboratory-scale implementation,” in *2018 international conference and utility exhibition on green energy for sustainable Development (ICUE)*. IEEE, 2018, pp. 1–9.

[28] M. Kuzlu, M. Pipattanasomporn, L. Gurses, and S. Rahman, “Performance analysis of a hyperledger fabric blockchain framework: Throughput, latency and scalability,” in *2019 IEEE International Conference on Blockchain (Blockchain)*, 2019, pp. 536–540.

[29] F. A. Niloy, M. A. Nayeem, M. M. Rahman, and M. N. U. Dowla, “Blockchain-based peer-to-peer sustainable energy trading in microgrid using smart contracts,” in *2021 2nd International Conference on Robotics, Electrical and Signal Processing Techniques (ICREST)*. IEEE, 2021, pp. 61–66.

[30] J. Gupta, S. Jain, S. Chakraborty, V. Panchenko, A. Smirnov, and I. Yudaev, “Advancing sustainable energy transition: blockchain and peer-to-peer energy trading in india’s green revolution,” *Sustainability*, vol. 15, no. 18, p. 13633, 2023.

[31] A. M. Eltamaly and M. A. Ahmed, “Performance evaluation of communication infrastructure for peer-to-peer energy trading in community microgrids,” *Energies*, vol. 16, no. 13, p. 5116, 2023.

[32] M. A. Sayed, M. M. Ahmed, W. Azlan, and L. W. Kin, “Peer to peer solar energy sharing system for rural communities,” *Cleaner Energy Systems*, vol. 7, p. 100102, 2024.

[33] S. Shan, S. Yang, V. Becerra, J. Deng, and H. Li, “A case study of existing peer-to-peer energy trading platforms: calling for integrated platform features,” *Sustainability*, vol. 15, no. 23, p. 16284, 2023.

[34] V. E. B.V., “Vandebron - groene energie uit nederland,” [Online]. Available: https://vandebron.nl/, accessed: 22-Mar-2025.

[35] Piclo Energy, “Piclo Energy - Enabling a flexible, decarbonised energy system,” [Online]. Available: https://www.piclo.energy/, accessed: 22-Mar-2025.

[36] sonnen Group, “sonnencommunity,” [Online]. Available: https://sonnengroup.com/sonnencommunity/, accessed: 22-Mar-2025.

[37] Powerledger, “Powerledger - blockchain-powered renewable energy solutions,” [Online]. Available: https://powerledger.io/, accessed: 22-Mar-2025.

[38] V. AB, “Vattenfall,” [Online]. Available: = https://group.vattenfall.com/about-us, accessed: 22-Mar-2025.

[39] SunContract, “Suncontract - blockchain-based p2p energy trading platform,” [Online]. Available: https://suncontract.org/, accessed: 22-Mar-2025.

[40] R. P. Da Costa, C. F. M. Almeida, M. E. M. Udaeta, A. L. Municio, V. T. Nascimento, and F. J. B. Laurindo, “Energy commercialization proposition into a p2p framework in micro-grids for brazilian energy communities,” in *2022 IEEE International Conference on Power Systems and Electrical Technology (PSET)*. IEEE, 2022, pp. 280–289.

[41] M. J. A. Baig, M. T. Iqbal, M. Jamil, and J. Khan, "Iot and blockchain based peer to peer energy trading pilot platform," in *2020 11th IEEE Annual Information Technology, Electronics and Mobile Communication Conference (IEMCON)*. IEEE, 2020, pp. 0402–0406.

[42] ——, "Peer-to-peer energy trading in a micro-grid using internet of things and blockchain," *Electron. J*, vol. 25, pp. 39–49, 2021.

[43] ——, "A low-cost, open-source peer-to-peer energy trading system for a remote community using the internet-of-things, blockchain, and hypertext transfer protocol," *Energies*, vol. 15, no. 13, p. 4862, 2022.

[44] ——, "Blockchain-based peer-to-peer energy trading system using open-source angular framework and hypertext transfer protocol," *Electronics*, vol. 12, no. 2, p. 287, 2023.

[45] Y. Takeda, Y. Nakai, T. Senoo, and K. Tanaka, "Designing a user-centric p2p energy trading platform: A case study—higashi-fuji demonstration," *Energies*, vol. 14, no. 21, p. 7289, 2021.

[46] F. Bandeiras, Á. Gomes, M. Gomes, and P. Coelho, "Exploring energy trading markets in smart grid and microgrid systems and their implications for sustainability in smart cities," *Energies*, vol. 16, no. 2, p. 801, 2023.

[47] M. J. A. Baig, M. T. Iqbal, M. Jamil, and J. Khan, "Design and implementation of an open-source iot and blockchain-based peer-to-peer energy trading platform using esp32-s2, node-red and, mqtt protocol," *Energy reports*, vol. 7, pp. 5733–5746, 2021.

[48] C. Long, J. Wu, Y. Zhou, and N. Jenkins, "Peer-to-peer energy sharing through a two-stage aggregated battery control in a community microgrid," *Applied energy*, vol. 226, pp. 261–276, 2018.

[49] K. S. Alam, A. D. Kaif, and S. K. Das, "A blockchain-based optimal peer-to-peer energy trading framework for decentralized energy management with in a virtual

power plant: Lab scale studies and large scale proposal," *Applied Energy*, vol. 365, p. 123243, 2024.

[50] T. Deepa, N. Saraswathi, S. Hariprasad, K. Praveen, P. Elamurugan, and V. Dinesh, "Design and implementation of blockchain based peer to peer energy trading platform," in *Journal of Physics: Conference Series*, vol. 2335, no. 1. IOP Publishing, 2022, p. 012059.

[51] Y. Saleem, N. Crespi, M. H. Rehmani, and R. Copeland, "Internet of things-aided smart grid: technologies, architectures, applications, prototypes, and future research directions," *Ieee Access*, vol. 7, pp. 62 962–63 003, 2019.

[52] M. A. Iqbal, S. Hussain, H. Xing, and M. A. Imran, *Enabling the internet of things: fundamentals, design and applications*. John Wiley & Sons, 2020.

[53] E. Mengelkamp, J. Gärttner, K. Rock, S. Kessler, L. Orsini, and C. Weinhardt, "Designing microgrid energy markets: A case study: The brooklyn microgrid," *Applied energy*, vol. 210, pp. 870–880, 2018.

[54] SONOFF, "Sonoff official website," [Online]. Available: https://sonoff.tech/, 2025, accessed: 31-Mar-2025.

[55] MathWorks, "Thingspeak - iot analytics and cloud platform," [Online]. Available: https://thingspeak.mathworks.com/pages/learn_more, 2025, accessed: 31-Mar-2025.

[56] B. Mahapatra and A. Nayyar, "Home energy management system (hems): Concept, architecture, infrastructure, challenges and energy management schemes," *Energy Systems*, vol. 13, no. 3, pp. 643–669, 2022.

[57] J. S. Choi, "Energy management agent frameworks: Scalable, flexible, and efficient architectures for 5g vertical industries," *IEEE Industrial Electronics Magazine*, vol. 15, no. 1, pp. 62–73, 2020.

[58] ——, “A hierarchical distributed energy management agent framework for smart homes, grids, and cities,” *IEEE Communications Magazine*, vol. 57, no. 7, pp. 113–119, 2019.

[59] C. Zhang, “Peer-to-peer energy trading in electrical distribution networks,” Ph.D. dissertation, Cardiff University, 2017.

[60] IEEE Standards Association, “The evolution of wi-fi technology and standards,” [Online]. Available: https://standards.ieee.org/beyond-standards/the-evolution-of-wi-fi-technology-and-standards/, 2024, accessed: 04-Mar-2025.

[61] R. Molenaar. (n.d.) Introduction to ethernet. [Online]. Available: https://networklessons.com/cisco/ccna-routing-switching-icnd1-100-105/introduction-to-ethernet. Accessed: 06-Jul-2025.

[62] Meta Platforms, Inc., “React – reference documentation,” [Online]. Available: https://react.dev/reference/react, 2025, accessed: 09-Jul-2025.

[63] Taranveer Singh Anttal, “Smart home dataset with weather information,” [Online]. Available: https://www.kaggle.com/datasets/taranvee/smart-home-dataset-with-weather-information, 2019, accessed: 05-Jun-2025.

[64] H. Al-Breiki, M. H. U. Rehman, K. Salah, and D. Svetinovic, “Trustworthy blockchain oracles: review, comparison, and open research challenges,” *IEEE access*, vol. 8, pp. 85 675–85 685, 2020.

[65] D. Murray, L. Stankovic, and V. Stankovic, “An electrical load measurements dataset of united kingdom households from a two-year longitudinal study,” *Scientific data*, vol. 4, no. 1, pp. 1–12, 2017.

[66] L. Datastore, “Photovoltaic (pv) solar panel energy generation data.”