UNIVERSIDAD EAFIT

Vigilada Mineducación

GAME THEORY MODELING FOR DECENTRALIZED PEER-TO-PEER SOLAR ENERGY MARKET IN COLOMBIAN NANOGRIDS

Author:

Tomás Henao Ramírez [a1]

Type of work:

Degree Work

Advisor, teacher:

Jhon Jairo García Rendón

[a]**EAFIT University, 050022, CO**

School of Economics and Finance

Masters in economics

[1] Tomás Henao Ramírez. Tel: +57 31765 68505
E-mail address: thenaor@eafit.edu.co

Abstract

As microgeneration increases, the centralized model of electricity generation will be significantly altered. One of the new models being investigated is the notion of a peer-to-peer electricity market in which prosumers can market their electricity exports to any other household. This new kind of transactive energy market, and community or collective self-consumption, offer new models for trading energy locally. Over the past 10 years, there has been significant growth in the amount of academic literature and trial projects examining how these energy trading models might function. The results show that P2P energy trading provides significant financial and technical benefits to the community and is emerging as an alternative to cost-intensive energy storage systems. This paper investigates a possible game theoretic model for Colombian nanogrids and proposes a new algorithm for automating the sale and purchase of electricity in this market, aiming to optimize the market while providing increased control to householders. It is found that nanogrids may improve financial viability for solar systems at the residential level, concluding that the future for solar residential prosumers is beyond isolated self-consumption.

Keywords: Peer-to-Peer Energy Trading, Blockchain, Game Theory, Microgrid, Decentralization

1. Introduction

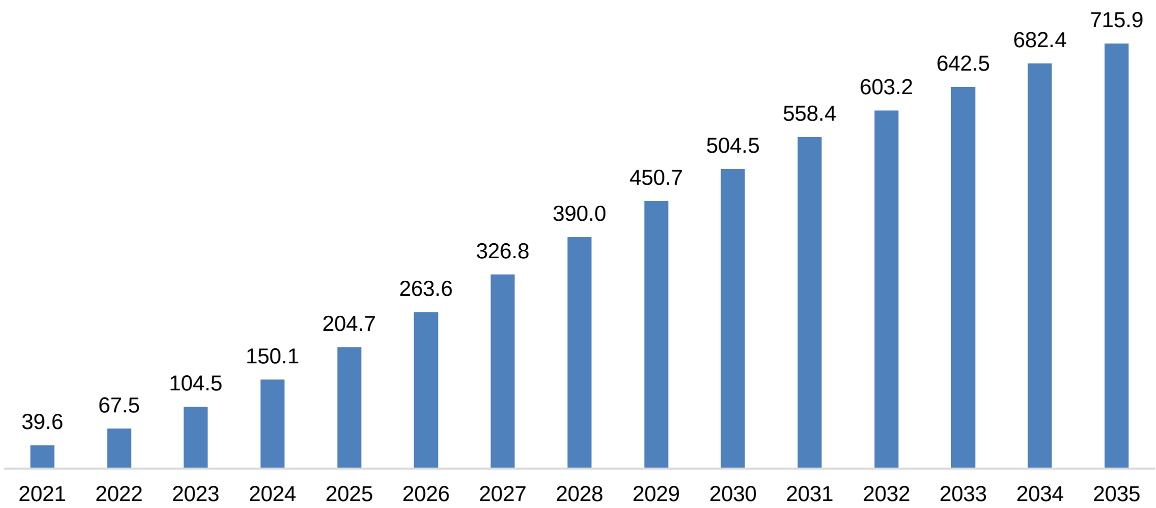
The human dependence on fossil energy resources has led to many issues, the chief among them being the emission of greenhouse gases and the resultant climate change (Solomon, Plattner, & Knutti, 2009). With finite reserves of fossil fuels and the environmental damage they cause, it has become a hindrance to economic growth and development in most third-world countries. In recent years, the scientific community and world governments have been focused on finding better mechanisms to help us wean off fossil fuels and their associated dangers. According to Zhou, Ci, Li, & Yang (2017), over 50% of the world's energy needs could be met using renewable resources. They argue that to achieve this, renewable energy resources must be used on two fronts: large-scale centralized installations (such as wind or solar farms) and large-scale distributed generators (DG). Historically, most economies have relied on a unidirectional energy model, where centralized facilities supply the economy's energy demand. However, energy markets are undergoing a transition, with the current electrical system evolving and new products and services emerging, as well as the arrival of new agents. In other words, the traditional centralized markets for electricity are migrating towards more distributed markets. This shift is being driven by factors such as the rise of smart networks, the internet of things, and the emergence of the prosumer concept. These changes require a new approach to managing electricity networks and transactions between the various stakeholders. The widespread use of distributed generation (DG) and distributed energy systems (DES) is already a global trend, which represents a significant challenge for the electric power industry, that has traditionally been based on centralized power generation, but this is no longer feasible in a world of distributed generation.

Nowadays, power generation does not just come from a sole source. There is a growing portion of power generation distributed throughout the grid. That is, the agents are trading power in two or more directions, causing problems in a network that was never designed to do this, not only from the hardware side, in terms of cabling and transformers, but also in terms of the control architecture.

In Fig. 1, it is possible to analyze the projection of the growth of DG systems according to the Mining-Energy Planning Unit (UPME) in Colombia, where it is estimated that by the year 2035, there will be an installed capacity of around 715.9 MW-year, which will require an investment of approximately one billion dollars.

This is being replicated globally, where a host of distributed generation resources are visible wanting to connect to the market, from photovoltaic farms to wind generation and residential rooftop solar panels.

Fig. 1: Installed capacity of the Distributed Generation systems in Colombia (MWp)



Source: *Mining-Energy Planning Unit (UPME, 2021).*

The increasing deployment of distributed generators with intelligent infrastructures enables residential consumers to harness the energy and inject it into distribution systems (Paudel, Chaudhari, Long, & Beng Gooi, 2019). This advancement changes residential consumers into prosumers (small energy-consuming producers). They are capable of producing, consuming, and sometimes also have demand response capacities (Kanchev, Lu, Colas, Lazarov, & Francois, 2011). A group of prosumers can be integrated as a prosumer energy community. The small-scale power system in a house is known as a prosumer nanogrid (Ekneligoda & Weaver, 2014). This paper uses the terms "Prosumer" and "Nanogrid" interchangeably, however, several nanogrids serving in close proximity can be combined to form a community microgrid.

For example, in many developed countries, energy operators are responsible for not only selling energy but also renting transmission lines so that prosumers can inject energy into the grid through net metering programs. Currently, there are 70 countries in the world with mandatory net metering policies (Soto, Bosman, Wollega, & Leon-Salas, 2020). However, these policies can discourage the installation of photovoltaic panels as they increase transaction costs and reduce returns on investment. If governments want to implement effective policies for a rapid and non-intrusive transition to low-CO2 energy production, they must work towards a more open and decentralized electricity grid, where new forms of compensation are found for residential energy prosumers, which will require new market approaches to “set prices, decentralize and make more flexible the energy market and the governance of energy infrastructure”, as stated (Soto, Bosman, Wollega, & Leon-Salas, 2020).

In recent years, alternatives to the traditional top-down approach have gained relevance in academic discussions. These peer-to-peer (P2P) markets are demonstrating their potential to democratize energy generation and markets by allowing local renewable energy producers to sell directly to consumers, without the need for intermediaries. In addition, P2P markets are effective in reducing peak electricity demand, reducing maintenance and operation costs, and improving the reliability of the electrical system (Morstyn, Farrell, Darby, & McCulloch, 2018).

Since 2014, the Colombian government has created a legal framework[2] to encourage the development, research, and investment in renewable energy projects. This has generated incentives for individuals to participate in the production of energy through renewable sources, thus allowing the sale of surpluses to the electricity grid (Guerra Posada & Ortega Arango, 2017). However, there is still no platform that

[2] *Law 1715 of 2014, decree 2143 of 2015, resolution 1283 of 2016, decree 348 of 2017, resolution 121 of August 28 - 2017 and resolution 174 of 2021 issued by the Energy and Gas Regulation Commission (CREG).*

encompasses all market agents and also supports massive energy and money transactions, in real-time, in a safe, decentralized, and effortless way. Some public and private projects are already exploring the viability of this type of peer-to-peer market for the Colombian context, as we will see later in section 5.

The problem lies in the fact that an underdeveloped theoretical and regulatory panorama was identified for the Colombian market. In addition to this, generation, transmission, and distribution are not included in current P2P models since most of these studies consider microgrids as a system where the main actors are prosumers and consumers. In this way, most of the research on microgrids focuses on maximizing benefits for the user and maintaining the energy balance of microgrids but does not analyze the market from the perspective of all its agents and their possible interactions (Soto, Bosman, Wollega, & Leon-Salas, 2020).

It is concluded that, in favor of the Colombian electricity market, it will be pertinent to evaluate the possible implementation of a P2P market and model its impact by including consumers and prosumers more actively in the wholesale market, which has shown that, in this context, with education and adequate regulation, they contribute to the improvement of the production balance and balanced energy consumption (Zhang, Wu, Zhou, Cheng, & Long, 2018).

2. Justification

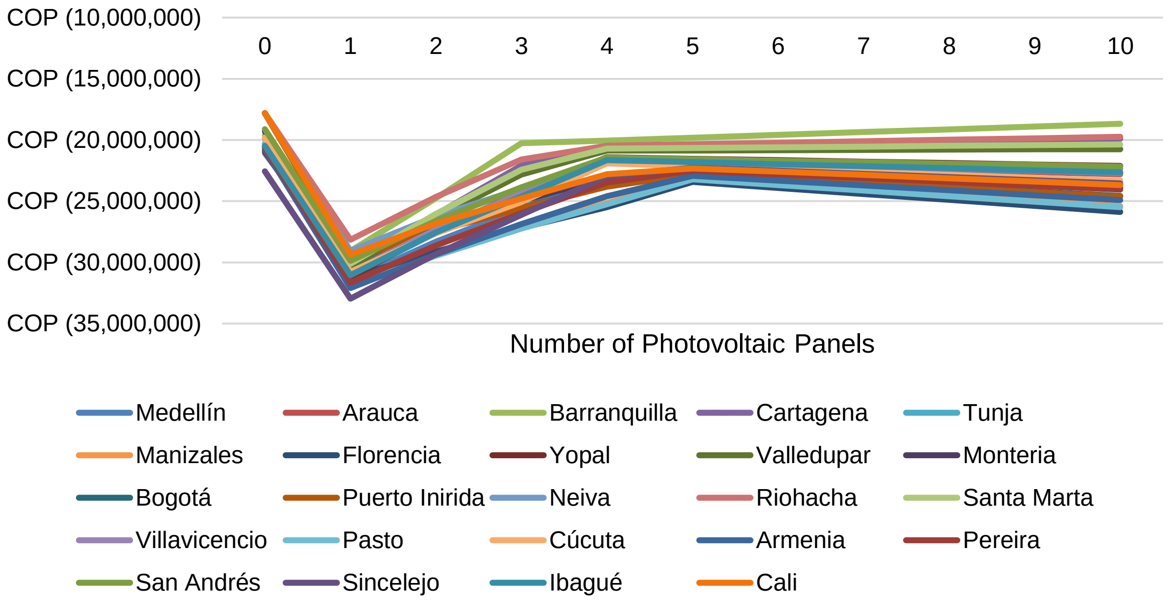
There are many motivations for house owners to install renewable-based distributed generators, such as environmental benefits, financial incentives, and reducing electricity bills (Kirthiga, Daniel, & Gurunathan, 2013). However, as Fig. 2 shows, the net present value for solar systems with an installed capacity of less than 4kWp does not necessarily grow with the number of installed Photovoltaic Panels (PVs). This is due to current regulations. Based on CREG 174 Resolution of 2021, when a prosumer generates surpluses, there are two main possible outcomes:

1) The network's energy consumption is bigger than production surpluses at the end of the month. In this case, the price per kWh the prosumer will receive from the network for the surpluses injected into the network will be equal to the unit cost per kWh charged by the utility company less the commercialization margin or service fee.
2) The network's energy consumption is lower than production surpluses at the end of the month. In this case, the price per kWh the prosumer will receive from the network for the surpluses injected into the network will be equal to the generation price in the energy spot market.

Prices for small-scale solar projects are relatively low in situation 2) because of two main factors: I. scale economics of big energy producers and II. more than 70% of the energy produced in Colombia is produced through hydroelectric plants. As shown in Fig. 4, the Levelized cost of hydroelectricity is lower than solar photovoltaic. Unless there is a climate issue affecting the generation price in the energy spot market, this will tend to be lower than the Levelized cost of a small-scale solar project.

Based in what was mentioned earlier, it will only make economic sense with the current regulation mostly for only three main Colombian cities: Barranquilla, Cartagena and Sincelejo, the latter only when certain conditions are met. This is mainly because as the Fig. 3 shows, Barranquilla and Cartagena have the best and the third best, respectively, solar irradiation ($\frac{kWh}{m^2}$) annual average in the data base. A solar system will be economically viable for both of these cities beginning with a system of 6 PVs. For Sincelejo's situation, a solar system will be economically viable for a system with 5 and 6 PVs, because it has the highest price per kWh in the data base but starting from 7 PV's current market conditions make it not economically and financially viable.

Fig. 2: Net Present Value of Solar Systems by Number of PVs in Main Colombian Municipalities[3]



Source: *own elaboration.*

Although nanogrid P2P markets are not currently regulated in Colombia, it will be shown in section 5 that P2P markets have been very successful in other countries when it comes to tackling Distributed Energy Resources (DER).

Automating these markets and making them more secure and transparent is where blockchain technology comes in, as it provides a new way of exchanging value efficiently, safely, and quickly between peers without the need for an intermediary (Schär, 2020).

Blockchain is making its way in the world as a form of exchange between peers that really works and the possibility of applying this technology in other fields such as medicine is being explored (Dimitrov, 2019), property registration (Ali, Nadeem, Alzahrani, & Jan, 2019), P2P money exchange (He, et al, 2018), crowdfunding (Arifin, Arshad, & Muneeza, 2018) and P2P energy trading (Kavousi-Fard, Almutairi, Al-Sumaiti, & Farughian, 2021).

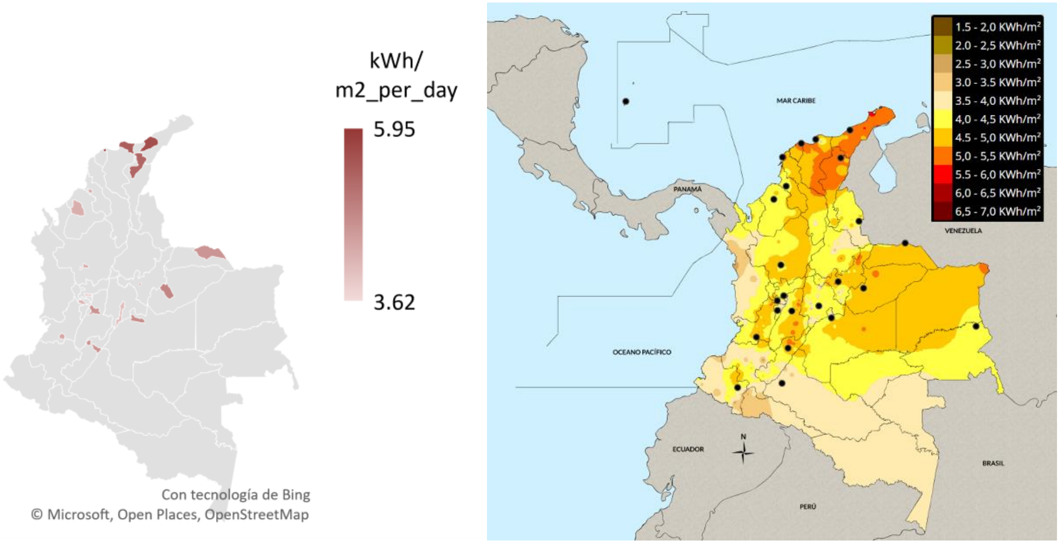
Currently, most power trading is one-way. Electricity is transmitted from large-scale generators to consumers over long distances, while the flow of cash is the other way around. However, in recent years with the sharp fall in the cost of photovoltaic panels and wind sources (see Fig. 4), the possibility has arisen for more people to acquire this type of technology at the residential level. If this trend continues, the number of people willing to generate their own energy will increase in the coming years. This poses challenges for governments to be prepared for this trend and have an efficient system that allows the participation of the various actors in the sector in an organized and safe manner.

In Colombia, the electricity sector was restructured in 1994 with laws 142 and 143, creating a competitive market called the Wholesale Energy Market (MEM). The MEM is today regulated by the Commission for the Regulation of Energy and Gas (CREG), and participants include generators, transmitters, distributors, marketers, intensive consumers of electricity, and non-regulated users. The MEM's purpose is to exchange large blocks of electrical energy in the National Interconnected System (SIN) at efficient prices. The MEM is divided into two segments: 1. Bilateral contracts and 2. The energy exchange. Bilateral contracts are a free-market negotiation scheme between suppliers and demanders, while the energy exchange is short-term and seeks to establish energy prices for the following day. The energy

[3] Methodology for the construction of this figure will be fully explained in Appendix 1.

exchange segment requires the mandatory participation of all registered generators and explicit rules for listing and declaration of availability (Super Intendencia de Servicios Públicos Domiciliarios, 2021).

Fig. 3: Mean Global Irradiation Received on the Surface by Main Colombian Municipalities[4]



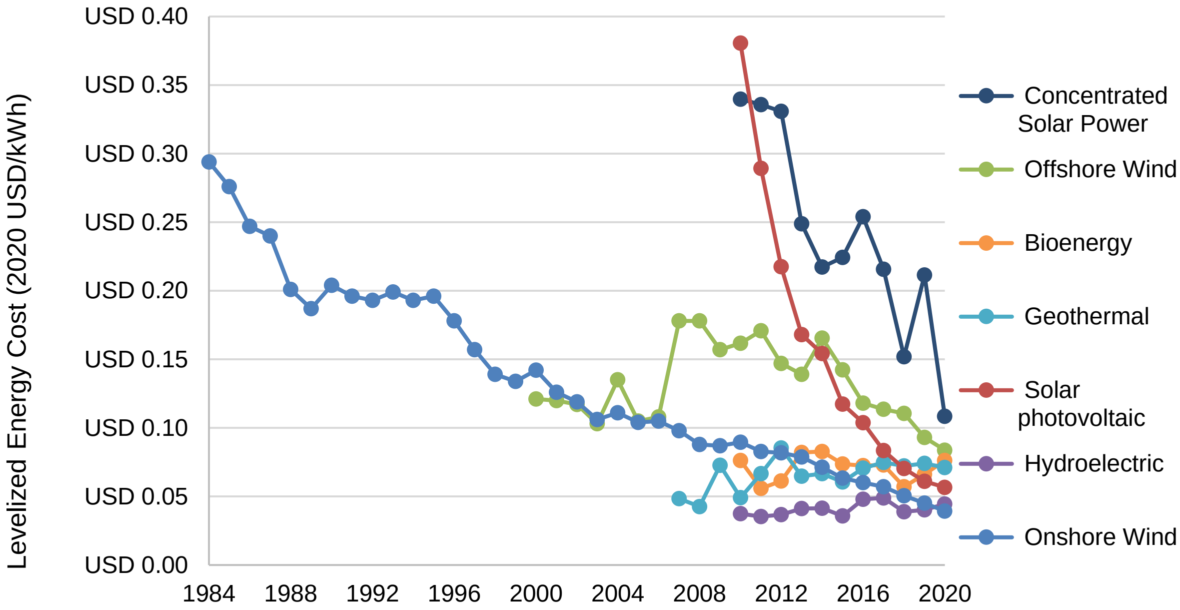
Source: *Atlas of Solar, Ultraviolet and Ozone Radiation of Colombia* (IDEAM-UPME, 2022).

The existence of bilateral contracts in Colombia allows for the existence of retail marketers, who serve some end-users and provide them with billing services. These two agents enter into energy contracts where the price is established without state intervention, this mechanism being the closest in the Colombian market to a P2P trade, but it lacks not only technological but regulatory development, to become a P2P market.

On the other hand, the MEM is managed by XM, who is in charge of dealing with the transactions of the agents, providing services such as registration of consumption and location measurement systems; settlement and billing of energy exchanges by agents in the Energy Exchange; a collection of the money resulting from the transactions carried out in the Energy Exchange as well as International Electricity Transactions and, finally, collection of national and regional transmission services to deliver them to the transmission agents and distributors for the use of their networks (Castaño Duque, 2020).

[4] http://atlas.ideam.gov.co/visorAtlasRadiacion.html

Fig. 4. Levelized Cost of Energy by Technology[5]



Source: *International Renewable Energy Agency (IRENA, 2020)*

Most of the energy produced and consumed in Colombia is traded on the Energy Exchange Market. This market is managed by XM, which validates and settles the transactions. However, this market is not a real-time market, and the operation of the system is conducted within regulated times defined by the CREG. In other words, the Colombian energy market has great opportunities for improvement toward a less unilateral and centralized market.

CREG Resolution 174 of 2021 provides an opportunity for Colombia to explore the potential of a P2P energy market. This market would allow for multidirectional trade within a local geographic area and the massive arrival of energy prosumers would provide a more decentralized and open electricity network. In fact, Colombia has an interesting development ahead in terms of the retail market and the integration of small prosumers into the network, where those who are coming to the market have a challenge when it comes to selling their surpluses locally, because in certain cases the information is asymmetric.

In the article by Li, Bahramirad, Paaso, Yan & Shahidehpour (2019), it is concluded that Blockchain technologies embedded in transactive energy will play an important role in the evolution of traditional energy distribution systems to active distribution networks.

3. Objectives

3.1 General objective

To develop a game theory modeling for retail nanogrids that enables a P2P solar energy market in the Colombian context, leveraging on the use of blockchain technology.

3.2 Specific objectives

1. To develop a game theory model that fits the characteristics of the Colombian context, including the different agents in the nanogrids, distributed generation, and interactions between the nanogrids and the SIN.

[5] *Levelized Cost of Energy (LCOE) estimates the average cost per unit of power generated over the lifetime of a new power plant. Fig. 2 presents the information measured in United States dollars (USD) for the year 2020 per kilowatt-hour.*

2. To develop a decision algorithm that simulates the market operation and automates decision making in an optimal way.
3. Conclude on the efficiency of this automated market configuration is, explain how blockchain technology enables its replicability and to make policy recommendations that allow the implementation of regulatory sandboxes in the future.

4. Theoretical framework

The most significant feature of Blockchain is that it does not need a trusted central system and can operate to exchange information between nodes in a decentralized environment. The reconciliation trend that must be managed between nodes by means of a consensus algorithm can be accelerated due to the elimination of the central authority in the Blockchain structure. In other words, in addition to reaching higher speeds than a centralized information network, the data transmitted by the nodes in this process will be cryptographic to improve the reliability and security of the information. To summarize, the Blockchain system has key comparative advantages over a centralized database insofar as: 1- in the Blockchain process, operations are validated and authorized based on a verification procedure managed by a consensus algorithm, and 2- the Blockchain system does not need architecture to connect nodes in the network and organizes them in a peer-to-peer structure, which makes the process transparent and fast (Kavousi-Fard, Almutairi, Al-Sumaiti, & Farughian, 2021).

Peer-to-peer (P2P) platforms have been proposed by the academic community for a couple of years, receiving all kinds of developments. Among the pioneers in addressing the exchange of electricity between peers for the creation of an electricity market are Inam, Strawser, Afridi, Ram & Perreault (2015). Under their proposal, people who can buy power from renewable energy generation sources, such as solar panels, can sell electricity to people who may not own one of these generation sources directly or who may have access to electricity but need more electricity at certain times. In that paper, they describe a power management unit (PMU) that enables these ad-hoc microgrids to exist and provides affordable electricity. Morstyn et al, (2018) faced the problem of how to encourage coordination between the different distributed energy resources, owners, and consumers with adverse characteristics. This is how they proposed the concept of Federated Power Plants, which is a virtual power plant formed through P2P transactions between self-organized prosumers, addressing social, institutional, and economic issues facing strategies to coordinate virtual power plants.

Likewise, Thomas & McCulloch (2019) propose a P2P energy market platform that coordinates trade between prosumers with heterogeneous preferences. This introduces the new concept of energy classes, which allow energy to be treated as a heterogeneous product, depending on the attributes of its source (generation technology, location in the network, and reputation of the prosumer). In this P2P market associated with the wholesale electricity market, the costs associated with losses and depreciation of batteries are minimized, while providing added value by taking into account individual preferences according to the source/destination of the energy that is used/consumed/produced. The backward-horizon model predictive control allows prosumers to adjust their planned energy flows based on the wholesale price of energy and have up-to-date renewable generation and load predictions.

In conclusion, it was found that the vast majority of studies on P2P energy trading platforms have been based mainly on platform architectures and on security and scalability tests.

Thakur & Breslin (2020) state that a Path-based funds transfer (PBT) in Blockchain offline channel networks or in credit networks that uses a path between offline channels to transfer funds between peers that do not have mutual channels. Presents a routing algorithm for PBT to find a suitable route for PBT execution. The problems with benchmark-based routing algorithms for PBT runs are: (1) PBTs across hubs can cause privacy issues as some benchmarks can collude to find the sender and receiver of a PBT, (2) Landmarks can be attacked with DoS or Eclipse attacks. The unavailability of reference points can lead to a high PBT failure rate, and (3) the unavailability of nodes for PBT execution creates cuts in the trees maintained by reference point-based routing protocols, which will lead to the failure of the PBT run. The contributions of Thakur & Breslin (2020) are associated with the development of a distributed algorithm to find peer-maintained subgraphs, the protocol preserves the privacy of the sender and receiver of a PBT. Also, the proof of the proposed protocol is secure against adversary peers that initially agree to participate in the PBT execution and included in the trees or subgraphs computed by the landmark-based routing algorithm. They show that trees built by landmark-based algorithms require more frequent reconstruction as values in individual channels change over time compared to the subgraphs that the pairs must maintain.

Another methodology to deal with this type of market is through optimization. As an example, we have the framework for P2P energy exchange and coordination proposed by Zhou, Ci, Li & Yang (2017). This technique aims to achieve flexible and efficient distributed energy management and control. There users are equipped with distributed generators (DG), distributed energy storage systems (DES) and smart meters; P2P power sharing is supported, where users can buy/sell electricity from/to the utility and their neighbors. The energy sharing and coordination problem is formulated as a convex optimization problem with the aim of minimizing the economic cost to users. Subsequently, a distributed algorithm is proposed, in combination with the alternate direction multipliers method (ADMM). Taking a real-world dataset on renewable energy and real-time electricity price, both analytical and numerical results show the technical efficacy and the proposed algorithm in terms of not only fast convergence in a time interval, but also of an economic saving in an outstanding way for a long-term application.

Another alternative analyzed in terms of how to deal with the problem of a P2P market for energy contemplates Blockchain initiatives. Münsing, Mather & Moura (2017) presented an architecture for P2P energy markets, where they ensured that operational restrictions are respected and that payments are made fairly, without relying on a centralized utility or microgrid aggregator. In addition to this, they demonstrated how to address issues of trust, security, and transparency through the use of Blockchain and smart contracts, two emerging technologies that can facilitate decentralized coordination between untrusting agents, being the first to examine their use to facilitate distributed optimization and control. Using the Alternating Direction Multipliers Method (ADMM), they presented a decentralized optimal power flow (OPF) model for scheduling a combination of batteries, configurable loads, and deferrable loads in an electrical distribution network. Distributed Energy Resources (DER) perform local optimization steps, and a smart contract on the blockchain serves as the coordinator of the ADMM, allowing the validity and optimization of the solution to be verified. Optimal programming is securely stored on the blockchain, and payments can be made automatically, securely, and without the need for trust, removing the obligation of a microgrid operator.

Vangulick, Cornélusse & Ernst (2018) state that energy communities and peer-to-peer energy exchanges will play an important role in the energy transition and decentralization of the energy market. Its objective was to determine the design that should allow a Distribution System Operator (DSO) to accept peer-to-peer energy exchanges based on a distributed ledger supported on Blockchain technology. However, the Blockchain proposed in this work, specifically for energy communities, has characteristics that are not compatible with the main existing Blockchain technologies based on Bitcoin and Ethereum, mainly because its consensus method is based on *Proof of Work* instead on *Proof of Stake* and therefore these technologies do not satisfy the timing requirements of the market. In line with this, Aitzhan & Svetinovic (2018) are concerned about the privacy of energy consumption and trading data, so they implement a *Proof-of-Concept* protocol for a decentralized energy trading system using Blockchain technology, multiple signatures, and encrypted anonymous message streams, allowing peers to anonymously trade energy prices and commercially transact in a secure ecosystem. They carry out case studies to analyze security and performance evaluation within the context of the obtained security and privacy requirements, demonstrating that the system is resistant to attacks by protecting user information.

Cali & Fifield (2019) present a comprehensive review of Blockchain technology applications related to P2P energy trading and propose a comprehensive multi-layer energy model architecture for P2P energy trading implementations where the use of blockchain technology is integrated. Furthermore, this study shows an Ethereum-based Blockchain testbed that exhibits Blockchain concepts and how they can be used in the field of P2P energy trading within a commodity microgrid using a sample use case scenario. They conclude that P2P energy trading allows consumers to become electricity prosumers in a more efficient, reliable, and profitable way. On the other hand, Andoni et al (2019) review more than 140 research projects and Startups from which they build a map of the potential and relevance of this technology and analyze its potential application in peer-to-peer trading. In this same year, Li, Greenwood, & Kassem (2019) recognize that the Blockchain and its applications are increasingly investigated as one of the components of the digital transformation of the construction industry and its response to different challenges. There, they conducted a detailed literature review on Blockchain and Distributed Ledger Technologies (DLT) where they cover possible use cases in 7 different industries including energy. In this they highlight that the energy market is in transformation towards an intelligent market. In other words, they affirm that until recently energy has been marketed by the main energy producers that have led the market and set their prices. They mention the work of Murkin, Chitchyan, & Byrne (2016) who claim that large energy producers represent 94% of energy production within the market. However, they refer to the study carried out by the research service of the European parliament by Šajn (2016) who states that due to the fall in the cost of renewable technologies and the increase in the behavior of prosumers, this market is opening up to offer more opportunities for individual and residential electricity producers, mainly those who use photovoltaic solar panels in their homes and who produce excesses of what they need to supply their homes, to sell it to the national grid or to their neighbors. Citing Castellanos, Coll-Mayor, & Notholt (2017), they conclude that currently transactions are carried out through large producers or state companies, however, micro-networks managed through DLT are making this exchange possible in a decentralized manner directly from the prosumer to the consumer.

Hayes, Thakur & Breslin (2020) present a methodology that aims to address the problem of the lack of measurement of the potential impacts of P2P commerce on distribution networks. In this way, they perform a co-simulation of energy distribution networks and local peer-to-peer energy trading platforms. This simulation of the distribution system is interconnected with a peer-to-peer energy trading platform, which employs a Blockchain-based distributed double auction trading mechanism. The presented co-simulation approach is demonstrated using a case study of a typical European suburban distribution network. The paper demonstrates that this approach can be used to analyze the impacts of peer-to-peer power trading on network operational performance. Finally, they suggest that a moderate level of peer-to-peer trading does not have significant impacts on the network's operational performance.

Finally, Kavousi-Fard et al (2021), assure that the centralized structure based on the current energy market needs a hierarchical and independent system to determine the conventional price and the power between the actors that participate in the market. However, for the developments of modern power systems, it is necessary that the market structure is driven to obtain a P2P design in the power market. In this way, the security of data exchange between market participants can be one of the most important challenges within the structure of the P2P energy market. For this, they propose a P2P market between microgrids and smart grids, considering as agents the operators of wind turbines, solar panels, tidal turbines, and storage units. This market works through a Blockchain consensus algorithm, and they measure its performance, even in the presence of cyberattacks. In this way, they show that the responses of this peer-to-peer market are very close to the results of the centralized market (less than 1% difference), even under cyberattacks. It is something very telling since they manage to demonstrate that the consensus algorithm works even when it is put under attack.

Blockchain technology is a revolutionary innovation with the ability to transform many existing traditional systems with secure, distributed, transparent and collaborative dynamics while empowering users (Abeyratne & Monfared, 2016). Blockchain technology first made headlines as the basis for new types of financial transactions, beginning with Bitcoin in 2009. By 2020, the PwC professional services network expects Blockchain-based systems to reduce or eliminate many points of friction for a large number of business transactions; individuals and businesses will be able to exchange a wide range of digitized or digitally represented assets and securities with anyone else (Forbes, 2016).

Blockchain has emerged as a new area of venture capital that has caught the attention of banks, governments, and commercial companies. Blockchain is about to become the most exciting invention after the Internet; while the latter connects the world to enable new business models based on online processes, the former helps solve the trust problem more efficiently through Network Computing (Zhao, Fan, & Yan, 2016). They are supported by digital currencies like Bitcoin and have far-reaching consequences for all aspects of modern society. Blockchain technology is essentially a database of assets that can be shared over a network between multiple locations, regions, or institutions. Also, Blockchain has the ability to run autonomous scripts, this is the concept of smart contract; data-driven code that can represent a testable logic application and help automate a set of system rules (Huckle, Bhattacharya, White, & Beloff, 2016).

The operation of Blockchain technology is based on a chain of blocks that allows to implement a distributed, public, and immutable database based on a growing sequence of nodes. This database inherently provides node fault tolerance, robustness against tampering, and being public represents transparency. The uses of this technology are potentially immense and for this reason it is considered one of the technologies with the greatest disruptive potential in recent years. The possibility of having a distributed and immutable database after the fact has a variety of practical benefits that are just beginning to appear. Cryptocurrencies were its first successful application thanks to the security and transparency needs of payment systems and the ability to eliminate intermediaries. However, in the future, Blockchain technology may be found in a wide variety of contexts and systems. In this sense, and as a starting point, we can consider the use cases in scenarios such as the Internet of Things (IoT) and Big Data (Dolader Retamal, Bel Roig, & Muñoz Tapia, 2009).

Another way of approaching this kind of problems is using models of game theory. Zhang, Wu, Cheng, Zhou & Long (2016) proposed an architecture model to present the design and interoperability aspects of components for P2P energy trading in a microgrid. A specific P2P business model was introduced in a reference network-connected micro network based on the architecture model. The core component of a bidding system, called Elecbay, was also proposed and simulated using game theory. They conclude that P2P energy trading is capable of balancing local generation and demand, thus it has the potential to allow a great penetration of renewable energy sources in the electricity grid. Zhang et al (2018), design a P2P energy exchange platform and perform simulations using game theory. They tested the results in a low voltage microgrid showing that P2P power trading can further facilitate local balancing of power generation as well as improvement in power consumption. On the other hand, Paudel et al (2019) establish a game theory model where buyers can adjust the behavior of their energy consumption based on the price and quantity of energy offered by sellers. These pose two separate competitions within the negotiation process: 1) price competition between sellers, modeled as a non-cooperative game; and 2) sellers selection competition among buyers, modeled with theory of evolutionary games. The interaction between buyers and sellers is also modeled by means of a Stackelberg game. In order for there to be a state of equilibrium in each of the games, the use of iterative algorithms for the implementation of the games is proposed. The proposed method is applied to a small community microgrid with photovoltaic and energy storage systems. The simulation results show the convergence of the algorithms and the effectiveness of the proposed model to handle P2P energy trading.

From these game-theoretic modeling, it can be concluded that P2P energy trading provides important financial and technical benefits to the community and is emerging as an alternative to expensive energy storage systems. Moreover, in Colombian context, better energy models represent an opportunity to reduce poverty, carbon dioxide emissions, and adapt new technologies that give greater autonomy to citizens in the production and distribution of energy.

In closing, the fact that most of the literature on this topic focuses on applied research in the United States and other developed countries is recognized as a major shortcoming, so there is an opportunity to expand the P2P literature in this area for the future of the underdeveloped world in a country like Colombia.

5. Background

The pace of technological and business innovation has accelerated in recent decades, making it difficult to develop business models that support sustainable profitability over time. In particular, the Internet allows the creation of new business models with an immediate global reach (Teece & Linden, 2017). However, the Internet itself lacks means of payment, corporate structures and forms of association that deny the separation of the digital world from the real world (Lérida & Pérez, 2016). Blockchain is a distributed ledger that provides security and ease of access around the world, allowing transactions with information or value without the need for a trusted third party such as a bank or government. Therefore, Blockchain is a new network that is moving from the Internet of information to the Internet of value and is said to have the disruptive ability to change business processes and models.

As seen in section 4, the problem highlighted in advance has already been addressed in other countries of the world and under different approaches. This section will describe some applied projects that achieved a certain degree of success and already have some partial response related to the object of research or simply served as pioneers to continue research in the area.

The concept of "Blockchain" appeared together with cryptocurrencies, that is, it is established as a term where cryptocurrency is a “Peer to Peer” digital exchange system in which a specific data encryption model is used to generate and distribute transaction logs on the network. Cryptocurrencies have a similarity in terms of the application of the P2P market in energy systems since there is a need for adequate information management, providing efficient, profitable, reliable, and secure systems, all motivated by the protection of financial transactions (Silva Valdés, 2019).

Some projects are recognized that are at the forefront of the Wholesale Energy Market - MEM, such is the case of the project designed by Kalms et al. (2018) called Power compensation simulation platform in commodified networks established by the P2P scheme. The proposal is framed within the institutional program H2020 LCE-2014-3 of the European Union, whose company is made up of nine shareholders from four countries and come from both the research context and the business sector. The main focus of intent is to manifest the work of a smart power system combined by advanced communications devices (ICTs), local markets, and transformative action shapers. The organization is based on a P2P scheme (Peer to Peer). According to Kalms et al. (2018) in this way: “The integration of flexibility in demand and the optimized operation of decentralized energy sources (DER) in the distribution network are guaranteed, so that quality, stability, and security are maintained. and at the same time a balance is achieved in the flow of forces (Kalms et al, 2018, pag. 03).

In Germany, the **PeerEnergyCloud** project was started with the ideal of creating an e-commerce platform connecting residential producers with local consumers, based on cloud information technology. They set out their research on different fronts such as innovative recording and forecasting procedures for device-specific electricity consumption in order to establish a virtual market for energy trading and develop value-added services within a microgrid (Brandherm, Baus, & Frey, 2012). The initiative was not very successful and newer, more novel approaches took the lead in the following years, but it helped to set the stage for the conversation of the possibility of a P2P market for energy in Europe.

Piclo, is a clear example of this. This is a project developed in the United Kingdom that began in 2013 with the mission of providing the world with cheap, clean, and abundant electricity. The project already has six scientific publications, of which two are from the last year. The first of these two explores the extent to which the flexibility of a market can contribute to reducing the need to invest in traditional solutions, and the second analyzes the value, and the impact on the system as a whole, of flexible demand in a zero-carbon scenario for the UK. Lastly, with their Open Utility platform, they estimate profits of around 30% for producers included in this type of flexible and accessible market (Piclo, 2021).

Subsequently, the European Commission (EC) supported and financed the **P2P SmarTest** project in order to “investigate and demonstrate a smarter electricity distribution system integrated with advanced ICT, regional markets and innovative business models” (P2P - SmarTest, 2015). This was supposed to employ Peer-to-Peer (P2P) approaches guaranteeing the integration and flexibility of the demand side, as well as the optimal functioning of the Distributed Energy Resources and other resources within the network, with the purpose of maintaining the balance of energy second by second, the quality and security of the supply. The project lasted 2 years and was completed in December 2017, serving as a prelude to other more successful projects.

In the Netherlands, the platform developed by the **Vandebron** project is enabling consumers to purchase energy directly from independent renewable energy generators. This intelligent application allows energy to be traded safely, optimally, and appropriately under a P2P model that enables access to renewable sources even when the sun is not shining or the wind is blowing (Vandebron, 2021).

sonnenCommunity in Germany is taking a different approach. The economic model of this project differs from those mentioned above since it works as a subscription model of 19.99 euros per month.

The system is made up of a community of owners of solar batteries and photovoltaic systems, where the surpluses generated are not injected into the conventional electricity grid, but into a virtual energy reserve that serves other members at times when they cannot produce enough power due to bad weather. Everything works through a central software which is in charge of connecting and monitoring all members of the sonnenCommunity, while balancing energy supply and demand (Sonnen, 2021).

In the Americas, the case of the **Yeloha** startup company is widely known by the community of renewable energy users, particularly solar energy. Its founders aimed to create a democratized smart grid, where everyone could access affordable solar power in minutes, and all sunlit properties would be used for solar power production. In that order of ideas, they created a solar exchange network from a web platform designed to allow those who wanted to buy, but did not have a suitable roof, could buy solar energy from those who produced an excess on their roofs. Yeloha eventually closed in 2016 because the funding needed to massively grow the prosumer network could not be raised (Rosner, 2016).

The case of projects such as the **Brooklyn Microgrid** has suffered a different fate. This, through Exergy (the data platform founded by the project) works as an energy Marketplace that allows transactions of surplus solar energy generated locally within the communities of New York. Using Blockchain technology and other types of innovative initiatives, it facilitates and records the transactions carried out. This initiative clearly seeks that prosumer, energy cooperatives, consumers and any agent that involves energy transactions do not have to go to a third party, it is only enough to belong to a network and thus transact energy through the local Marketplace platform (Brooklyn Microgrid, 2021).

Recently, both public and private developments began in terms of energy P2P in Colombia. There was a P2P energy pilot project called Transactive Energy Colombia Initiative and led by the EIA University, EPM, ERCO Energy, NEU Energy and University College London (UCL) where the objective was to carry out a pilot test for one year with fourteen residential users and three prosumers, each one different socioeconomic conditions, through a virtual platform to try to visualize which are the most relevant energy attributes for users (renewable, local, independent), and according to its characteristics, develop a mobile app so that people can carry out transactions between them, collect data of interest to probably issue recommendations on regulatory matters to allow the development of these markets in Colombia and, finally, the design of business models so that these markets can scale commercially.

Blockchain protocols are already used by XM, the Colombian electricity market administrator, who has recently invested in the technology to bring transparency to the energy and emission markets. They achieve this through a public-private mix and Blockchain technology authorized, audited, and certified by EBsec (Enterprise Blockchain Security Council), which is an alliance, initially of four companies that operate in cybersecurity, Blockchain and cryptography.

6. Methodology

As mentioned, this study sought to take advantage of solar energy resources and the existence of interconnected nanogrids to create an economic model that enables decentralized and automatic peer-to-peer transactions. They are achieved through the creation of an automatic decision algorithm that takes data in real-time, optimizing the actions of consumers and prosumers. The latter will reside in a Blockchain through a smart contract, thus removing the transactional burden for users of having to operate day to day, making optimal decisions on price auctions, and bringing with it benefits of blockchain technology such as operational transparency, immutability, and replicability of the smart contract. Not forgetting that it will also save consumers money and generate better prices for prosumers because the energy is consumed locally.

6.1 Major Contributions

Main contributions of this study are summarized as follows:

1) A novel game-theoretic model is proposed for P2P energy trading using direct interactions between buyers and sellers in a nanogrid considering the DER capability and privacy of prosumers.
2) The game-theoretic model used considers two simultaneous games. A non-cooperative multistage game, which includes investment decisions and market settlement and a repeated game that takes these P2P solar energy market to a limited time horizon. The algorithm will optimize decisions of the grid based on Paretian Equilibriums.
3) A decision algorithm is proposed to automate decision making with real time data.
4) Blockchain technology is proposed as a way to store this algorithm in a smart contract and as a way to keep transactions in a secure, decentralized, and transparent way.

6.2 Model conditions

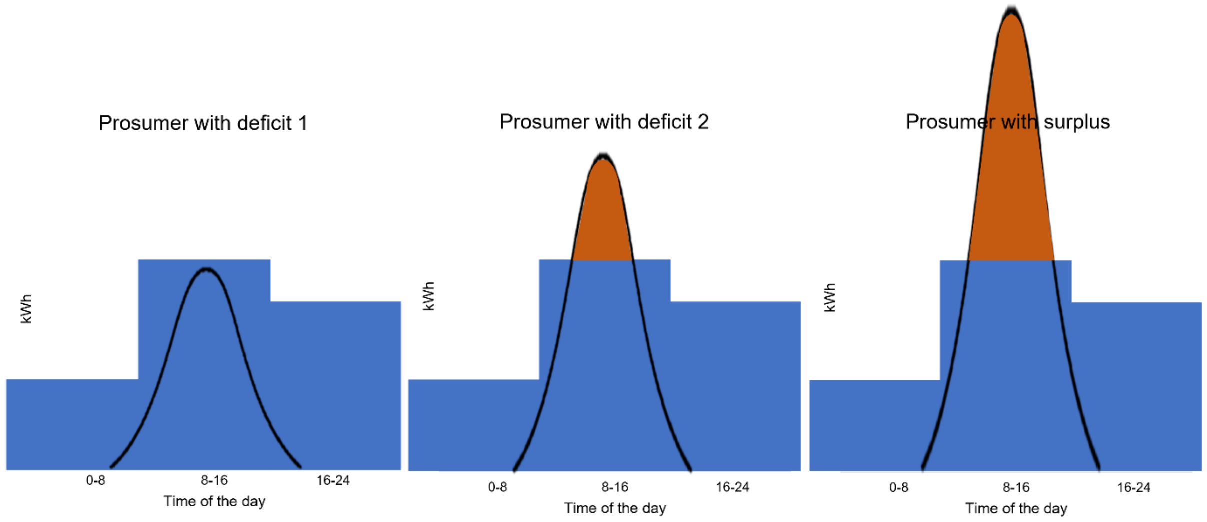
In order to model a P2P market for the Colombian context, it is important to define certain conditions:

i. Based on October 2021 CREG's 174 Resolution:
    a. Small-scale self-generator (prosumer): Self-generator with installed or nominal capacity equal to or less than 100kW. However, this study will not consider projects with an installed capacity higher that 4kWp, mainly because of three reasons:
        i. Space availability is set to a maximum value of 30mts^2.
        ii. Ninety percent of Colombian households consume less than 300 kWh/month.
        iii. Peak capacity of solar panels is set to 470Wp, so it would be needed around 10 solar panels to reach this peak capacity of 4kWp, which means around 30mts^2 of space availability, assuming that each panel has an approximate area of 2.18mt^2 and that the minimum area between the sides of two panels is 0.18mt^2, so that they do not overlap each other.
ii. According to Law 1715 of 2014 called: "invest and earn with energy", there are four main tax benefits to Colombian prosumers of Unconventional Renewable Energy Sources (URES):
        i. Special deduction in determining income tax: taxpayers declaring income tax who directly make new expenditures on research, development and investment for the production and use of energy from URES or efficient energy management, will have the right to deduct up to 50% of the value of the investments. The value to be deducted annually cannot exceed 50% of the taxpayer's net income.
        ii. Accelerated depreciation: expense that the law allows to be deductible at the time of declaring income tax, for a proportion of the value of the asset that cannot exceed 20% per year.
        iii. Exclusion of goods and services from VAT: for the purchase of goods and services, equipment, machinery, elements and/or national or imported services.
        iv. Exemption from customs duties: exemption from the payment of Import Tariff Rights for machinery, equipment, materials, and supplies destined exclusively for pre-investment and project investment work with URES.

    Only benefits iii. and iv. will be considered in this study.
iii. There are three investment decisions consumers that want to turn into prosumers have to face (these are shown in Fig. 5.):
    1) Prosumer with deficit 1 (PD_1): invest in a project with an installed or nominal capacity equal or less to their peak daylight consumption.
    2) Prosumer with deficit 2 (PD_2): invest in a project with an installed or nominal capacity greater than their peak daylight consumption but less than their total daily consumption.
    3) Prosumer with surplus (PS): invest in a project with an installed or nominal capacity greater than their total daily consumption.

    The only thing that changes between investment decisions is the number of photovoltaic panels (NPV), and therefore, peak capacity, and total cost of the system.
iv. Based on these definitions, PD_1 will not inject any surpluses to the network, PD_2 will inject less than what he consumes from the network and PS injects more than he consumes from the network.

Fig. 5. Type of prosumers



Source: *own elaboration.*

v. Prosumer may not have battery energy storage systems since deploying energy storage systems in the residential level is costly and does not allow to recover the initial investment in the period of time considered of 25 years.

vi. Initial investments for a solar project consider fixed and variable costs:
   1) Variable costs: photovoltaic panels, aluminum structure, wiring and accessories, insurance, engineering, logistics, construction and permits (ELCP).
   2) Fixed costs: 3kW microinverter, monitoring system, bidirectional meter, RETIE certification and UPME procedures.

vii. The PV system of a prosumer is connected to the load and AC system through DC/AC converter which is also known as PV inverter.

viii. All agents in the nanogrid are connected to each other through the bi-directional power and communication links, and the whole nanogrid is connected to the upstream utility grid via a one grid connection point.

ix. Smart bidirectional meters are installed at each participant.

x. Each prosumer has a local workstation with an energy management system called prosumer energy monitoring system (P-EMS).

xi. P2P energy trading algorithm is integrated with the P-EMS software.

xii. The smart meter measures the prosumer's generation, consumption, and energy transaction with other prosumers or with the network and sends information to the local workstation for processing.

xiii. It is assumed that the P2P market operator is the same as the network operator and has the task of assisting energy trading in the P2P market and charges a service fee for doing it.

xiv. Since the prosumers are serving nearby demand and the amount of energy traded in the P2P market is small, we assume that transmission losses and transmission cost are negligible.

xv. Smart meters are capable of supplying the smart contract with real time data that connect with the workstations, and these are powerful enough to carry out the computational tasks.

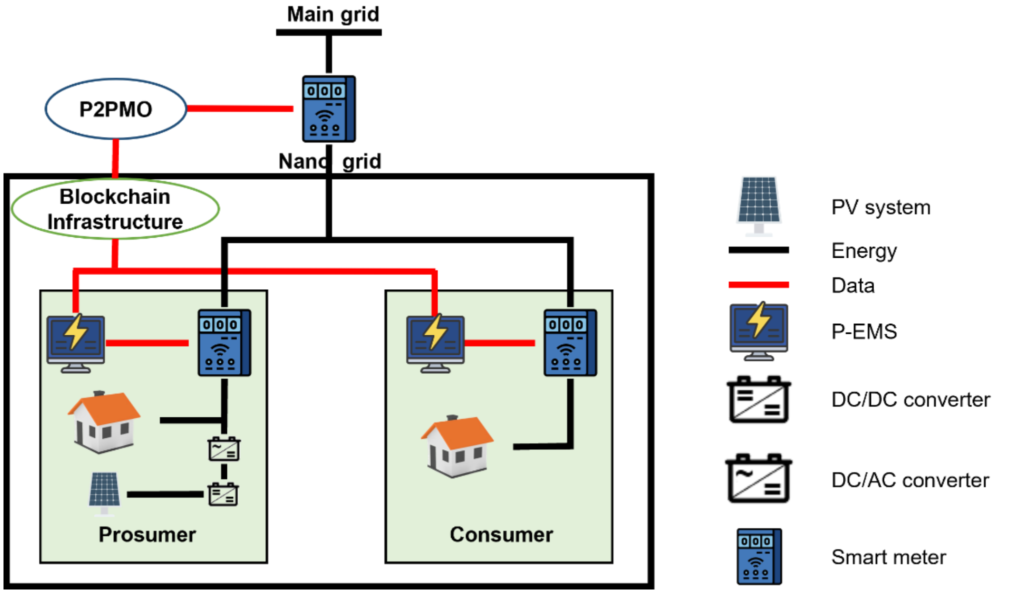
xvi. During the trading process, all the communication tasks are done through the smart meters, and computations are performed in local workstations.

xvii. The detailed working processes of smart meters, communication systems and physical infrastructures in the community microgrid are beyond the scope of this paper.

xviii. We assume that the total operation time is divided into different slots of equal interval Δt. In this study we have considered $\Delta t = 1$ day.

6.3 Nomenclature

Fig. 6: Structure of the proposed market model



Source: own elaboration based on (Paudel, Chaudhari, Long, & Beng Gooi, 2019)

As can be seen in Fig. 6, in the proposed market there will be 3 types of agents, which will be:

1. **Local solar energy prosumers:** local residential prosumers that are in charge of offering their surplus energy production to the nanogrid and supplying the market at the local level. They can be of three different types as explained earlier.
2. **Consumers:** local residential consumers that are energy users in the P2P market for residential use, that is, for non-industrial consumption. These are connected to the P2P market through micro networks. They lack production but have the possibility of becoming prosumers.
3. **Network Operators or Peer-to-peer Market Operators (NO or P2PMO):** they are in charge of enabling Blockchain structure for secure P2P transactions, as well as ensuring the proper functioning of the nanogrid.

In turn, there are two types of grids:

1. **Nanogrid:** is the one that allow P2P trading at the local level and enables access to real time data. It consists of no more than 10 players, between prosumers and consumers.
2. **Main grid**: is the main grid that is also known as National Interconnected System (SIN, for its acronym in Spanish).

Indexes

- **Subindex $\boldsymbol{i}$,** player, with $i \in I$.
- **Subindex $\boldsymbol{t}$,** time index with $t = \{1, \dots, T\}$.
- **Subindex $\boldsymbol{j}$**, Investment decision in the first stage. $j = \{NC, PD1,\ PD2,\ PS\}$.

Constants

- $\boldsymbol{R^{loss}}$: $PV\ Related\ Power\ Loss$, is the efficiency loss (0.7% per year is considered) of silicon solar cells.
- $\boldsymbol{Q}$: $Direct\ Irradiation,$ is the amount of solar radiation received per unit area by a surface that always remains perpendicular (or normal) to rays coming in a straight line from the direction of the sun at its current position in the sky.
- $\boldsymbol{U_t^{PV}}$: $PV\ Capacity$, measured in Watts or kW, it is considered to be 470W, based on industry data and the PV reference Jinko 470 Wp Photovoltaic Panel.

- $\boldsymbol{PR}$: $Performance\ Ratio$, is fixed at 80% which is commonly used in solar power performance analysis literature (Boddapati & Daniel, 2020).
- $\boldsymbol{T}$: PV's useful life, which is set to 25 years.

All constants are strictly greater than 0.

Variables

- $\boldsymbol{\chi}$: $Solar\ radiation$, is the set of electromagnetic radiation emitted by the Sun.
- $\boldsymbol{NPV}$: $Number\ of\ Photovoltaic\ Solar\ Panels$ needed for the system. These are devices formed by a set of photovoltaic cells that take advantage of sunlight to produce electricity.
- $\boldsymbol{UC}$: total network operator unit cost (UC) per kWh.
- $\boldsymbol{C}$: total network operator commercialization (C) service fee.
- $\boldsymbol{C_{NG}}$, nanogrid commercialization (CNG) service fee***.***
- $\boldsymbol{G}$: energy generation (G) price on the sport market.
- $\boldsymbol{DMC_j}$: daily maintenance cost (DMC) of the PV system.
- $\boldsymbol{kWh_{P,i,j}}$: total player i energy production (P) in investment decision j.
- $\boldsymbol{kWh_{DN,i,j}}$: energy produced by player i and delivered to the network (DN) in investment decision j.
- $\boldsymbol{kWh_{DC,i}}$: total player i daylight energy consumption (DC).
- $\boldsymbol{kWh_{NC,i}}$: total player i nighttime energy consumption (NC).
- $\boldsymbol{kWh_{TC,i}}$: total player i energy consumption (TC).
- $\boldsymbol{kWh_{NCD,i,j}}$: total player i network daylight energy consumption (NCD) in investment decision j.
- $\boldsymbol{kWh_{NCN,i,j}}$: total player i network nighttime energy consumption (NCN) in investment decision j.
- $\boldsymbol{kWh_{TNC,i,j}}$: total player i network energy consumption (TNC) in investment decision j.
- $\boldsymbol{kWh_{NGC,i,j}}$: total player i nanogrid energy consumption (NGC) in investment decision j.

Actions sets

- $Actions\ (A)\ for\ t = 1: \{Net\ Consumer\ (NC),\ Prosumer\ with\ deficit\ 1\ (PD1),$ $Prosumer\ with\ deficit\ 2\ (PD2),\ Prosumer\ with\ surplus\ (PS)\ \}$
- $A\ for\ t > 1: \{High\ Price\ (HP),\ Medium\ Price\ (HP), Accept\ (A),\ Reject\ (R)\}$

Further conditions

b. $HP > MP$: this means that High Price will always be higher than Medium Price.

c. $UC = G + T + D + C + PR + R$, were, based on CREG 012 of 2020, G: purchase cost or generation cost of energy, T: energy transportation charge, D: charge for energy distribution, C: commercialization or trading margin, PR: energy losses, R: restrictions.

d. $UC > HP + C_{NG} > HP > UC - C$: there will be no incentives for the price offeror to offer a price above UC because he can always buy energy to the network at that price. That is why, the highest price offered by the Net Consumer will be between UC and $UC - C$, which the latter will be the highest price paid by the network for the energy surpluses delivered to the network in prosumer with deficit 2 situation.

e. $UC - C > MP + C_{NG} > MP > G$: there will be no incentives for the price offeror to offer a price below G because he knows that he will be always rejected by the prosumer, because, as will be mentioned, this is the lowest price that a prosumer can get from the network.

f. $Net\ Consumer: kWh_{P,i,j} = 0$. A Net Consumer will be an agent that only consumes energy, therefore has no production.

g. $Prosumer\ with\ deficit\ 1\ (PD_1): kWh_{P,i,j} > 0\ \wedge\ kWh_{DC,i} > kWh_{P,i,j}$. This follows the explanation given above.

h. $Prosumer\ with\ deficit\ 2\ (PD_2): kWh_{P,i,j} > 0\ \wedge\ kWh_{DC,i} < kWh_{P,i,j} \wedge\ kWh_{TC,i} > kWh_{P,i,j}$. This follows the explanation given above.

i. $Prosumer\ with\ surplus\ (PS): kWh_{P,i,j} > 0\ \wedge\ kWh_{DC,i} < kWh_{P,i,j} \wedge\ kWh_{TC,i} < kWh_{P,i,j}$. This follows the explanation given above.

j. As explained earlier, when the prosumer sells his surplus to the network and there are two possible outcomes based on CREG 174 Resolution of 2021:
   1) $kWh_{TNC,i} > kWh_{DN,i}$, where the prosumer may pay to the network $UCkWh_{TNC,i} - (UC - C)kWh_{DN,i}$. The latter part of the equation is called energy credit.
   2) $kWh_{TNC,i} < kWh_{DN,i}$, where the prosumer may receive from the network $G\left(kWh_{DN,i} - kWh_{TNC,i}\right) - CkWh_{TNC,i}$.

k. $kWh_{TC,i} = kWh_{DC,i} + kWh_{NC,i}$. Total consumption can be analyzed as the sum of daylight consumption and nighttime consumption.

l. $kWh_{TNC,i,j} = kWh_{NCD,i,j} + kWh_{NCN,i,j}$. Total network consumption can be analyzed as the sum of daylight consumption and nighttime consumption.

m. $kWh_{TC,i} = kWh_{TNC,i} \vee kWh_{TC,i} = kWh_{NGC,i,j} + kWh_{TNC,i} \vee kWh_{P,i,j} - kWh_{DN,i,j} \vee kWh_{P,i,j} - kWh_{NGC,i,j} \vee kWh_{P,i,j} - (kWh_{DN,i,j} + kWh_{NGC,i,j})$. Total consumption can occur in five ways:
   1) Total consumption equals total consumption from the network.
   2) Total consumption equals the sum of nanogrid's total consumption and total consumption from the network.
   3) Total consumption equals energy production less energy delivered to the network.
   4) Total consumption equals energy production less energy delivered to the nanogrid.
   5) Total consumption equals energy production less the sum of energy delivered to the nanogrid and the network.

n. When $j = \{PD2 \vee PS\}$:
   1) $kWh_{NCD,i,j} = 0$. When a prosumer decides to invest in a PD2 or a PS system, his daylight production covers his energy demand, and he has no need to consume energy from the network in daylight.
   2) $kWh_{TNC,i,j} = kWh_{NCN,i,j} = kWh_{TC,i} - kWh_{DC,i}$. All the consumption from the network that a PD2 or PS prosumer does is at nighttime.
   3) $kWh_{TNC,i,PD2} = kWh_{TNC,i,PS}$. Total energy consumption is equal for both type of prosumers.

o. $R_{0,i,PD1} < R_{0,i,PD2} < R_{0,i,PS}$. The initial investment for a system with a higher installed capacity is higher than for one with a lower capacity.

p. There will be two main stages. $t = 1: Investment\ decision, t = 2: P2P\ market\ settlement$.

q. $t = 2$ turns into a repeated game towards PV's useful life.

6.4 Game-theoretic model with two players

Let $N = \{1, 2\}$ and the set of actions when $t = 1$, there is an investment decision to make which is if the agent wants to keep being a consumer or if he wants to turn into a prosumer and if so, he has to decide which of the three types to be, as shown in Fig. 7.:

Fig. 7. Investment decision stage *(t=1)*

Player 1 (rows) / Player 2 (columns)

	(NC)	(PD1)	(PD2)	(PS)
(NC)	0, 0	0, $-R_{0,2,PD1}$	0, $-R_{0,2,PD2}$	0, $-R_{0,2,PS}$
(PD1)	$-R_{0,1,PD1}$, 0	$-R_{0,1,PD1}$, $-R_{0,2,PD1}$	$-R_{0,1,PD1}$, $-R_{0,2,PD2}$	$-R_{0,1,PD1}$, $-R_{0,2,PS}$
(PD2)	$-R_{0,1,PD2}$, 0	$-R_{0,1,PD2}$, $-R_{0,2,PD1}$	$-R_{0,1,PD2}$, $-R_{0,2,PD2}$	$-R_{0,1,PD2}$, $-R_{0,2,PS}$
(PS)	$-R_{0,1,PS}$, 0	$-R_{0,1,PS}$, $-R_{0,2,PD1}$	$-R_{0,1,PS}$, $-R_{0,2,PD2}$	$-R_{0,1,PS}$, $-R_{0,2,PS}$

Source: *own elaboration.*

Here, when both players choose (NC, PD1), or (PD2, PS) there is no possibility for the existence of a P2P market, because neither player is going to generate surpluses to sell to the other or each player will generate surpluses, so they will have to sell them to the network. Therefore, both players will have a fixed payment in the second stage:

- h_1 = (NC, NC) = (NC, PD1) = $\varepsilon_i = -UCkWh_{TC,i}$
- h_1 = (PD1, NC) = (PD1, PD1) = $\lambda_i = -UC\left(kWh_{TC,i} - kWh_{P,i,PD1}\right) - DMC_{PD1}$
- h_1 = (PD2, PD2) = (PD2, PS) = $\rho_i = -UCkWh_{TNC,i,PD2} + (UC - C)kWh_{DN,i,PD2} - DMC_{PD2}$
- h_1 = (PS, PD2) = (PS, PS) = $\phi_i = G\left(kWh_{DN,i,PS} - kWh_{TNC,i,PS}\right) - CkWh_{TNC,i,PS} - DMC_{PS}$

Here, when player i choose (NC ∨ PD1) while the other chooses (PD2 ∨ PS) there are appropriate conditions for the existence of a P2P market, therefore both players will face a repeated game in the second stage:

Fig. 8. P2P Market Settlement *(t=2)*

Player 1 (rows) / Player 2 (columns)

h_1 = (NC , PD2)	(A)	(R)
(HP)	a_1, b_2	ε_1, ϖ_2
(MP)	c_1, d_2	ε_1, ϖ_2

h_1 = (PD1 , PD2)	(A)	(R)
(HP)	e_1, f_2	λ_1, ϖ_2
(MP)	g_1, h_2	λ_1, ϖ_2

h_1 = (NC , PS)	(A)	(R)
(HP)	i_1, j_2	ε_1, σ_2
(MP)	k_1, l_2	ε_1, σ_2

h_1 = (PD1 , PS)	(A)	(R)
(HP)	m_1, n_2	λ_1, σ_2
(MP)	o_1, p_2	λ_1, σ_2

h_1 = (PD2 , NC)	(HP)	(MP)
(A)	b_1, a_2	d_1, c_2
(R)	ϖ_1, ε_2	ϖ_1, ε_2

h_1 = (PD2 , PD1)	(HP)	(MP)
(A)	f_1, e_2	h_1, g_2
(R)	ϖ_1, λ_2	ϖ_1, λ_2

h_1 = (PS , NC)	(HP)	(MP)
(A)	j_1, i_2	l_1, k_2
(R)	σ_1, ε_2	σ_1, ε_2

h_1 = (PS , PD1)	(HP)	(MP)
(A)	n_1, m_2	p_1, o_2
(R)	σ_1, λ_2	σ_1, λ_2

Source: *own elaboration.*

Where:

- $a_1 = -(HP + C_{NG})kWh_{NGC,1,NC} - UC(kWh_{TC,1} - \ kWh_{NGC,1,NC})$; $kWh_{NGC,1,NC} = kWh_{NCD,1,NC} - (kWh_{P,2,PD2} - kWh_{DC,2})$

- $b_2 = (HP)kWh_{NGC,1,NC} + (UC - C)(kWh_{P,2,PD2} - kWh_{DC,2} - kWh_{NGC,1,PD1}) - UCkWh_{TNC,2,PD2} - DMC_{PD2}$
- $c_1 = -(MP + C_{NG})kWh_{NGC,1,NC} - UC(kWh_{TC,1} - kWh_{NGC,1,NC})$
- $d_2 = (MP)kWh_{NGC,1,NC} + (UC - C)(kWh_{P,2,PD2} - kWh_{DC,2} - kWh_{NGC,1,PD1}) - UCkWh_{TNC,2,PD2} - DMC_{PD2}$
- $e_1 = -(HP + C_{NG})kWh_{NGC,1,PD1} - UC\left(kWh_{TC,1} - kWh_{NGC,1,PD1} - kWh_{P,1,PD1}\right) - DMC_{PD1}; kWh_{NGC,1,PD1} = kWh_{NCD,1,PD1} - (kWh_{P,2,PD2} - kWh_{DC,2})$
- $f_2 = (HP)kWh_{NGC,1,PD1} + (UC - C)(kWh_{P,2,PD2} - kWh_{DC,2} - kWh_{NGC,1,PD1}) - UCkWh_{TNC,2,PD2} - DMC_{PD2}$
- $g_1 = -(MP + C_{NG})kWh_{NGC,1,PD1} - UC\left(kWh_{TC,1} - kWh_{NGC,1,PD1} - kWh_{P,1}\right) - DMC_{PD1}$
- $h_2 = (MP)kWh_{NGC,1,PD1} + (UC - C)(kWh_{P,2,PD2} - kWh_{DC,2} - kWh_{NGC,1,PD1}) - UCkWh_{TNC,2,PD2} - DMC_{PD2}$
- $i_1 = -(HP + C_{NG})kWh_{NGC,1,NC} - UC\left(kWh_{TC,1} - kWh_{NGC,1,NC}\right); kWh_{NGC,1,NC} = kWh_{P,2,PS} - kWh_{DC,2}$

If $kWh_{P,2,PD2} - kWh_{NGC,1,NC} > kWh_{TC,2} \rightarrow \psi = 1. \psi = 0$ otherwise:

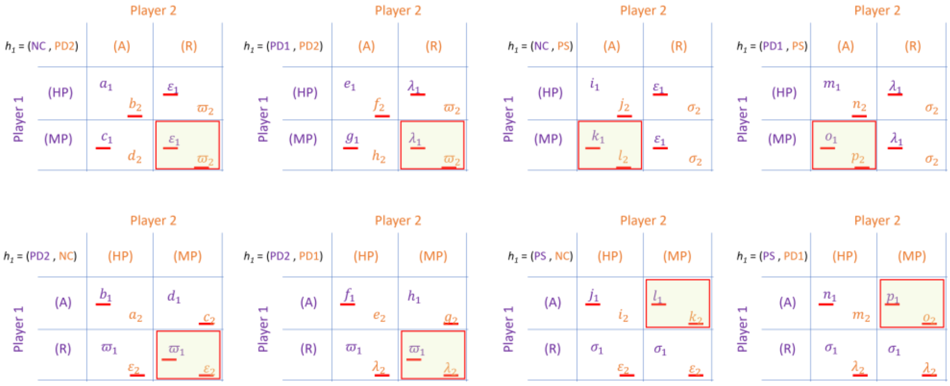
- $j_2 = (HP)kWh_{NGC,1,NC} + (1-\psi)[(UC - C)(kWh_{P,2,PS} - kWh_{DC,2} - kWh_{NGC,1,NC}) - UCkWh_{TNC,2,PS}] + \psi[G\left(kWh_{DN,2,PS} - kWh_{TNC,2,PS}\right) - CkWh_{TNC,2,PS}] - DMC_{PS}$
- $k_1 = -(MP + C_{NG})kWh_{NGC,1,NC} - UC\left(kWh_{TC,1} - kWh_{NGC,1,NC}\right); kWh_{NGC,1,NC} = kWh_{P,2,PS} - kWh_{DC,2}$
- $l_2 = (MP)kWh_{NGC,1,NC} + (1-\psi)[(UC - C)(kWh_{P,2,PS} - kWh_{DC,2} - kWh_{NGC,1,NC}) - UCkWh_{TNC,2,PS}] + \psi[G\left(kWh_{DN,2,PS} - kWh_{TNC,2,PS}\right) - CkWh_{TNC,2,PS}] - DMC_{PS}$
- $m_1 = -(HP + C_{NG})kWh_{NGC,1,PD1} - UC\left(kWh_{TC,1} - kWh_{NGC,1,PD1} - kWh_{P,1,PD1}\right) - DMC_{PD1}; kWh_{NGC,1,PD1} = kWh_{P,2,PS} - kWh_{DC,2} - kWh_{P,1,PD1}$
- $n_2 = (HP)kWh_{NGC,1,PD1} + (1-\psi)[(UC - C)(kWh_{P,2,PS} - kWh_{DC,2} - kWh_{NGC,1,PD1}) - UCkWh_{TNC,2,PS}] + \psi[G\left(kWh_{DN,2,PS} - kWh_{TNC,2,PS}\right) - CkWh_{TNC,2,PS}] - DMC_{PS}$
- $o_1 = -(MP + C_{NG})kWh_{NGC,1,PD1} - UC\left(kWh_{TC,1} - kWh_{NGC,1,PD1} - kWh_{P,1,PD1}\right) - DMC_{PD1}; kWh_{NGC,1,PD1} = kWh_{TC,1} - kWh_{P,1,PD1}$
- $p_2 = (MP)kWh_{NGC,1,PD1} + (1-\psi)[(UC - C)(kWh_{P,2,PS} - kWh_{DC,2} - kWh_{NGC,1,PD1}) - UCkWh_{TNC,2,PS}] + \psi[G\left(kWh_{DN,2,PS} - kWh_{TNC,2,PS}\right) - CkWh_{TNC,2,PS}] - DMC_{PS}$

Same equations will apply to the other player given homogeneity among player's payments. Furthermore, as it is shown in Appendix 1: $a_i \prec c_i$, $e_i \prec g_i$, $i_i \prec k_i$, $m_i \prec o_i$, $b_2 \succ \varpi_2$, $d_2 \prec \varpi_2$, $f_2 \succ \varpi_2$, $h_2 \prec \varpi_2$, $j_2 \succ \sigma_2$, $l_2 \succ \sigma_2$, $n_2 \succ \sigma_2$, $n_2 \succ \sigma_2$ and $p_2 \succ \sigma_2$.

6.5 Theoretical Findings

Based on Appendix 1 equations, assuming the existence of a P2P market, one can conclude that MP is a dominant strategy over HP when player i decided to play (NC, PD1). In other words, when analyzing player i payments, there is no possible value for δ that would make player i to play HP over MP when the other player chose to play (PD2, PS). Additionally, there are two possible Pure Strategy Nash Equilibriums (PSNE) in $t = 2$, as it is shown in Fig. 9:

Fig. 9: Pure Strategy Nash Equilibriums (PSNE) *(t=2)*



Source: *own elaboration.*

a. When player i plays PD2, PSNE will be {MP, R}.
b. When player i plays PS, PSNE will be {MP, A}.

However, when the condition a. holds, there is a Paretian inefficiency, because {MP, R} is dominated in Paretian sense by {HP, A}:

- For player 1:

$$-(HP + C_{NG})kWh_{NGC,1,j} - UC\left(kWh_{TC,1} - kWh_{NGC,1,j}\right) = -UCkWh_{TC,1}$$
$$-(HP + C_{NG})kWh_{NGC,1,j} - UCkWh_{TC,1} + UCkWh_{NGC,1,j} = -UCkWh_{TC,1}$$
$$(UC - HP - C_{NG})kWh_{NGC,1,j} = 0$$
$$UC > HP + C_{NG}$$

- For player 2:

$$(HP)kWh_{NGC,1,j} + (UC - C)(kWh_{P,2,PD2} - kWh_{DC,2} - kWh_{NGC,1,j}) - UCkWh_{TNC,2,PD2} - DMC_{PD2}$$
$$= -UCkWh_{TNC,2,PD2} + (UC - C)kWh_{DN,1,PD2} - DMC_{PD2}$$
$$(HP)kWh_{NGC,1,j} + (UC - C)\left(kWh_{P,2,PD2} - kWh_{DC,2} - kWh_{NGC,1,j}\right) = (UC - C)\left(kWh_{P,2,PD2} - kWh_{DC,2}\right)$$
$$(HP - (UC - C))kWh_{NGC,1,j} = 0$$
$$HP > UC - C$$

Furthermore, there is no possible way to find a theoretical multistage Nash equilibrium, because it will depend on parameter values. Nevertheless, we can simulate the market assuming values for the model parameters as we will see later.

On the other hand, when there is no P2P market, a PD1 solar system will be economically viable when this condition is met:

$$-\delta UCkWh_{TC,i}\left[\frac{1-\delta^{T+1}}{1-\delta}\right] < -R_{0,i,PD1} + \left[\frac{1-\delta^{T+1}}{1-\delta}\right]\left[-UC\left(kWh_{TC,i} - U_t^{PV}PRNPV_{PD1}\,\chi_t\right) - DMC_{PD1}\right] - \left[\frac{\delta(\delta + (T-1)\delta^{T+1} - T\delta^{T})}{(\delta-1)^2}\right]UCU_t^{PV}PRNPV_{PD1}\chi_t R^{loss}$$

We can conclude the same for PD2 and PS investment decisions:

$$-\delta UCkWh_{TC,i}\left[\frac{1-\delta^{T+1}}{1-\delta}\right] < -R_{0,i,PD2} + \delta\left[-UCkWh_{TNC,i,PD2} + (UC-C)kWh_{DN,i,PD2} - DMC_{PD2}\right]\left[\frac{1-\delta^{T+1}}{1-\delta}\right]$$

$$-\delta UCkWh_{TC,i}\left[\frac{1-\delta^{T+1}}{1-\delta}\right] < -R_{0,i,PS} + \delta\left[G\left(kWh_{DN,i,PS} - kWh_{TNC,i,PS}\right) - CkWh_{TNC,i,PS} - DMC_{PS}\right]\left[\frac{1-\delta^{T+1}}{1-\delta}\right]$$

However, as it was discussed previously, when a prosumer chooses to invest in a solar system, his returns will not be enough in most cases to cover the initial investment. Therefore, with the creation of a P2P market, we look for better prices both for prosumers and consumers, which is achieved, bringing higher returns. However, even with a P2P market, when ([PD2, NC], [A, MP]), we do not get higher prices for the prosumer compared to the main grid:

$$(MP)kWh_{NGC,2,NC} + (UC-C)(kWh_{P,2,PD2} - kWh_{DC,2} - kWh_{NGC,2,NC}) \cancel{- UCkWh_{TNC,1,PD2} - DMC_{PD2}} = \cancel{-UCkWh_{TNC,1,PD2}} + (UC-C)kWh_{DN,1,PD2} \cancel{- DMC_{PD2}}$$

$$(MP)kWh_{NGC,2,NC} \cancel{+ (UC-C)(kWh_{P,2,PD2} - kWh_{DC,2})} - (UC-C)kWh_{NGC,2,NC}) = \cancel{(UC-C)(kWh_{P,2,PD2} - kWh_{DC,2})}$$

$$(MP - UC + C)kWh_{NGC,2,NC} = 0$$
$$MP < UC - C$$

As it was shown above, this is a situation that one wants to avoid. Therefore, the use of blockchain technology, smart contracts, and automation in the nanogrid.

6.6 Classification of Prosumers as a Seller or Buyer

Using similar notation to Paudel, Chaudhari, Long, & Beng Gooi (2019) the generation-to-demand ratio (GDR) in daylight of a prosumer $i \in I$ in a given time period $t \in T$ is defined as:

$$GDR_i^t = \frac{kWh_{P,i,j}}{kWh_{TDC,i}}$$

Let $S = \{i \in I | GDR_n^t > 1\}$ represents the set of sellers at time slot t with index $i \in S$ and $S = |S|$ gives the total number of sellers at time t.
Let $B = \{i \in I | GDR_n^t < 1\}$ represents the set of buyers at time slot t with index $i \in B$ and $B = |B|$ gives the total number of buyers at time t.
Therefore, the amount of power the prosumer $i \in S$ can sell or export at time t is:

$$kWh_{ex,j}^i = (GDR_i^t - 1)kWh_{TDC,i}$$

The maximum amount of power the prosumer/consumer $i \in B$ can procure at time t is:

$$kWh_{im,j}^i = (1 - GDR_i^t)kWh_{TDC,i}$$

6.7 Utility Function

As it is widely used in the literature (Samadi, Mohsenian-Rad, Schober, Wong, & Jatskevich, 2010), the responses of different players to the various scenarios can be modeled by using the concept of utility function. The utility function is a method to quantify the level of satisfaction or happiness that player i receives when a certain amount of money is saved or received, compared with a situation where there is no nanogrid. For prosumers, the utility function will be a profit function which measures the gain respect the P2P non-existence situation. PD2 prosumer's utility function will be:

$$U_{i,PD2} = (HP)kWh_{NGC,i,j} + (UC - C)(kWh_{P,i,PD2} - kWh_{DC,i} - kWh_{NGC,i,j}) - UCkWh_{TNC,i,PD2} - [(UC - C)(kWh_{P,i,PD2} - kWh_{DC,i}) - UCkWh_{TNC,i,PD2}]$$

$$U_{i,PD2} = (HP)kWh_{NGC,i,j} + (UC - C)(kWh_{P,i,PD2} - kWh_{DC,i} - kWh_{NGC,i,j}) - (UC - C)(kWh_{P,i,PD2} - kWh_{DC,i})$$

$$U(kWh_{NGC,i,j})_{i,PD2} = (HP - UC + C)kWh_{NGC,i,j}$$

Utility function for PS prosumer's will be:

$$U(kWh_{NGC,i,j}, kWh_{P,i,PS}, kWh_{DC,i}, kWh_{TNC,i,j})_{i,PS} = (MP)kWh_{NGC,i,j} + (1-\psi)[(UC - C)(kWh_{P,i,PS} - kWh_{DC,i} - kWh_{NGC,i,j}) - UCkWh_{TNC,i,PS}] + \psi[G(kWh_{P,i,PS} - kWh_{DC,i} - kWh_{NGC,i,j}) - CkWh_{TNC,i,PS}] - [G(kWh_{P,i,PS} - kWh_{DC,i}) - CkWh_{TNC,i,PS}]$$

If $\psi = 1$:

$$= (MP)kWh_{NGC,i,j} + [G(kWh_{P,i,PS} - kWh_{DC,i} - kWh_{NGC,i,j}) - CkWh_{TNC,i,PS}] - [G(kWh_{P,i,PS} - kWh_{DC,i}) - CkWh_{TNC,i,PS}]$$

$$= (MP)kWh_{NGC,i,j} + [-GkWh_{NGC,i,j} + G(kWh_{P,i,PS} - kWh_{DC,i}) - CkWh_{TNC,i,PS}] - [G(kWh_{P,i,j} - kWh_{DC,i}) - CkWh_{TNC,i,PS}]$$

$$= (MP - G)kWh_{NGC,i,j}$$

If $\psi = 0$:

$$= (MP)kWh_{NGC,i,j} + [(UC - C)(kWh_{P,i,PS} - kWh_{DC,i} - kWh_{NGC,i,j}) - UCkWh_{TNC,i,PS}] - [G(kWh_{P,i,PS} - kWh_{DC,i}) - CkWh_{TNC,i,PS}]$$

$$= (MP - UC + C)kWh_{NGC,i,j} + (UC - C - G)(kWh_{P,i,PS} - kWh_{DC,i}) - (UC - C)kWh_{TNC,i,PS}$$

Prosumer's PD1 will have the following utility function:

$$U(kWh_{NGC,i,PD1})_{i,PD1} = UC(kWh_{TC,i} - kWh_{P,1,PD1}) - \left[(P_{NG} + C_{NG})kWh_{NGC,i,PD1} + UC\left(kWh_{TC,i} - kWh_{NGC,1,PD1} - kWh_{P,1,PD1}\right)\right]$$

$$U(kWh_{NGC,i,PD1})_{i,PD1} = (UC - P_{NG} - C_{NG})kWh_{NGC,i,PD1},$$

were P_{NG}: {HP ∨ MP}

Net consumer's utility will be:

$$U(kWh_{NGC,i,NC})_{i,NC} = UCkWh_{TC,i} - [(P_{NG} + C_{NG})kWh_{NGC,i,NC} + UC(kWh_{TC,i} - kWh_{NGC,i,NC})]$$

$$U(kWh_{NGC,i,NC})_{i,NC} = (UC - P_{NG} - C_{NG})kWh_{NGC,i,NC}$$

6.7 Social Welfare Function

The welfare function will measure the overall welfare of the nanogrid; therefore, it will be defined as follows:

$$W^{j,j} = U_{1,j} + U_{2,j}$$

7. Blockchain structure

Over time, technological revolutions have had a positive impact on development, growth, and innovation in both the public and private sectors, fostering change across industries, bringing innovative products and services, new ways to market, and changing the way companies create value for the market. While previous revolutions can be distinguished by how they deliver and gain value for customers, in this regard Blockchain, with its properties that makes it independent of trusted third parties, promises to benefit the community by fostering collaborative interest. At this point, we have shown that P2P markets without intervention, may end in a suboptimal equilibrium, and that leave us to conclude the need of a different market configuration that allows the market to reach this Paretian Equilibrium (PE) in a frictionless and secure way.

Blockchain technology as a basis for distributed ledger offers an innovative platform for a new decentralized and transparent transaction mechanism in industries and businesses. The legacy features of this technology enhance trust through transparency and traceability within any transaction of data, goods, and financial resources. Despite initial doubts about this technology, recently, governments and large corporations have been researching to adopt and improve this technology in various application domains, from finance, social and legal industries, to design, manufacturing, networking, and supply chain (Abeyratne & Monfared, 2016).

The Blockchain structure is based on a distributed, accessible, and fault-tolerant database in which each component or node can share its information while no node can perform specific control. This framework provides a highly secure alternative within a hostile environment, where different actors tend to penetrate the network to compromise data. In other words, the Blockchain system considers the existence of malicious behaviors related to attackers and attempts to disable their adversary strategies by using honest nodes, which are capable of high computational processing (Kavousi-Fard, Almutairi, Al-Sumaiti, & Farughian, 2021).

The main feature within the Blockchain is, as mentioned above, that it can operate to exchange information between nodes in a decentralized environment without the need for a central system that builds trust as seen in Fig. 7. That is, Blockchain generates appropriate conditions for systems without reciprocal trust between the parties.

On the other hand, the data transmitted by the nodes in this process will be cryptographic to improve the reliability of the information. As Kavousi-Fard, Almutairi, Al-Sumaiti, & Farughian (2021) claim, the Blockchain system has two key advantages compared to a centralized database: 1- operations are validated and authorized based on a verification procedure managed by a consensus algorithm and 2- it does not need architecture to connect nodes in the network and organizes them into a peer-to-peer structure (see Fig. 7.).

The three fundamental elements to ensure the efficiency of Blockchain technology are: a decentralized network, the consensus algorithm, and the cryptographic process.

7.1 Decentralized network

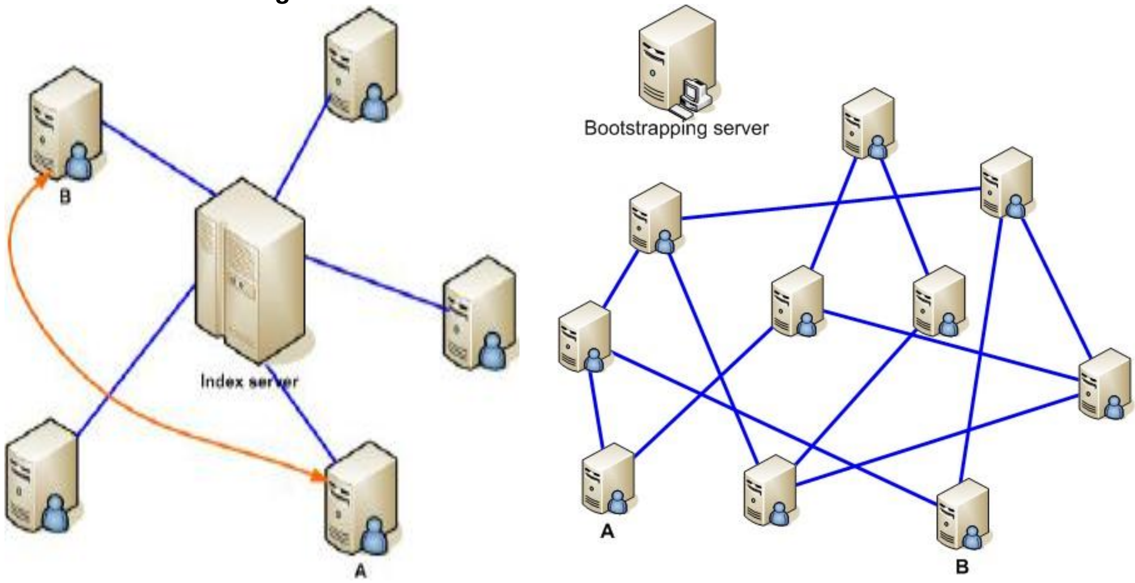
A decentralized network is basically made up of a network of computers or nodes, which lack an internal hierarchy. This network can be public or private and depending on this characteristic, it will be open to the entry of new nodes. The utility of a decentralized network is to improve the disclosure process of messages exchanged between nodes to retain the distributed records defined at each node. In other words, there is not a single source of information that contains all the records, but in a Blockchain system each node or computer that is constantly participating in the system also has a copy of the records, so if you want to sabotage the log history, all nodes within the network that have a copy which they constantly update should be attacked. In turn, the network protocol related to the Blockchain system allows the messages transferred from one node to other nodes to be broadcast in a decentralized structure. A public decentralized network should be realized keeping in mind a peer-to-peer structure in which nodes can join/leave the network, independently, as shown in Fig. 10. On the other hand, this network architecture is built in a robust way to reduce the failures of the nodes and connection between them.

7.1.1 Blockchain types

Blockchain types can be classified based on data access, the distinction between Blockchain types is the distributed ledger scheme and who can participate in the system (Viriyasitavat & Hoonsopon, 2018). In this way we have public, private and hybrid Blockchains:

Public Blockchain: they are open type, in which anyone can participate. All participants can freely access data and conduct transactions, but since numerous unverified users are participating, encryption and advanced verifications are needed, thus making network expansion slow and difficult. In addition, the public Blockchain forms a perfect distributed structure, and the network participants are pseudo-anonymous, therefore, it is not appropriate for financial services that need to be controlled by centralized information management systems (Oh & Shong, 2017). They also allow anyone to access and maintain the distributed ledger with permissions to validate integrity by running a consensus mechanism. A public Blockchain network is completely open and distributed; anyone can join, participate, and leave the system freely. Therefore, this system operates under unknown and unreliable nodes (Viriyasitavat & Hoonsopon, 2018).

Fig. 10: Centralized and unstructured P2P network



Source: Shahriar (2012).

Private Blockchain: in it the owner generates and manages the Blockchain. This is appropriate if the owner wishes to manage the Blockchain as the centralized system (Oh & Shong, 2017). Accounting books are shared and validated by a predefined group of nodes. The system requires initiation or validation from nodes that wish to be part of the system. Authorized nodes are responsible for maintaining consensus. Private blockchains are suitable for closed systems, where all nodes are completely trusted. Ultimately, it is the owner who has the ultimate authority to control access to authorized nodes (Viriyasitavat & Hoonsopon, 2018).

Hybrid Blockchain (Consortium): is the intermediate type of public and private Blockchain. Unlike Private Blockchain in which the owner has the authority, it is the pre-established nodes that have the authority in this type of Blockchain. Therefore, Hybrid Blockchain maintains a distributed structure while strengthening security through limited participation and solves the problem of slow transaction speed and network scalability issues raised in Public Blockchain. Therefore, Hybrid Blockchain could be used for transactions between financial institutions (Oh & Shong, 2017).

The hybrid Blockchain is suitable for semi-closed systems composed of a few agents, often organized in the form of a consortium. The degree of openness of the data varies, usually with access controls, defined by the consortium, to control access on both participants and the information within the Blockchain. This is why, a hybrid Blockchain is recommended for P2P transactions at a nanogrid level, in which every agent that is connected to the nanogrid will be a validator node and they will reach consensus as a community rather than in a centralized way. Every participant will have a copy of the ledger with all the transactions and new participants can be added if a consensus has been reached. In this hybrid Blockchain, the P2PMO will be in charge of validating transactions along with all nodes that are constantly providing decentralized information in real time, but the first has to ensure the functioning of the system and its transparency and that is why a service fee is charged. Even though the system is not completely open, the benefits of decentralization can be partially realized. Hyperledger Fabric, Ripple and Stellar are examples of Hybrid Blockchain implementations (Viriyasitavat & Hoonsopon, 2018).

According to (Viriyasitavat & Hoonsopon, 2018), regardless of the type of Blockchain, they all share the following similarities regarding the benefits offered by this technology:

- They operate in a P2P network that provides a certain degree of decentralization,
- Multiple nodes maintain the integrity of the ledger through consensus mechanisms,
- Data is stored on Blockchain which provides immutability, even when some nodes are faulty or malicious.

7.2 Consensus algorithm or protocol

In a simplified way, this is a rule that allows the nodes within the network to agree on how the new blocks of information are going to be written within the chain of blocks. That is, in the Blockchain process, the consensus protocol is implemented on a peer-to-peer (P2P) structure based on a decentralized network to validate the transactions distributed among the nodes before adding information blocks to the public ledgers at the network nodes. Based on a defined protocol, the messages are received in the P2P network and the transactions carried out between the nodes are recorded in the logbooks. By using the consensus protocol, it is guaranteed that new transactions can be added to the network without any conflict with the other valid transactions in the system. Furthermore, the consensus protocol is capable of causing locks and providing agreements on the integration of them. In turn, the new transactions are inserted into a block and sent to the Blockchain system for confirmation through the validation process, which allows new transactional data to be inserted, considering the number of transactions carried out (Kavousi-Fard, Almutairi, Al-Sumaiti, & Farughian, 2021).

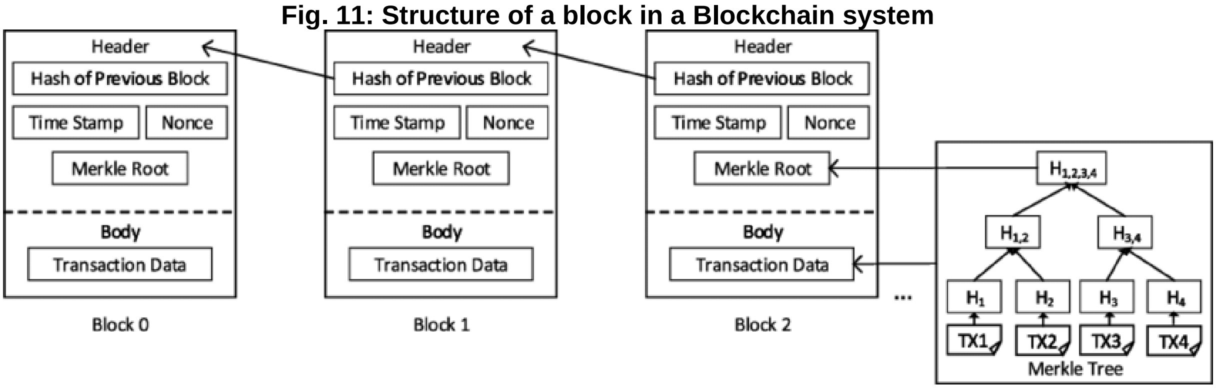
Moreover, taking up what Kavousi-Fard, Almutairi, Al-Sumaiti, & Farughian (2021) mentioned, consensus algorithms are generally defined based on fault-tolerant consensus. After publishing the information of the nodes within the network, a fault-tolerant consensus algorithm can ensure that all nodes reach an agreement (on a common value) and respond to all requests with the appropriate results. A consensus algorithm with N nodes must satisfy the following consensus objectives: completion, agreement, validity, and completeness. For termination, each non-defective node must finally settle on a result. Due to the agreement condition, all non-defective nodes will eventually converge to the same answer to satisfy the second objective. Validity means that all nodes must be evaluated by the validation procedure. Ultimately, network integrity is provided when each node's decision is confirmed by the response of the other nodes.

7.3 Cryptographic process

Cryptography can be defined as the art of secure communication in a hostile environment. It is what allows verifying messages and proving the authenticity of one's own messages, even under the existence of malicious players on the network. Cryptography is necessary, given the existence of the Blockchain characteristic of being a decentralized network where anyone can participate as a node in the network, this includes malicious actors. It's fine to enable peer-to-peer communication and new nodes to join the network, but it will require that peer-to-peer communication be unaltered. To ensure this, the Blockchain's distributed database maintains a growing list of records, which is defined as a block, and these are protected against malicious attackers through continuous verification. Each block consists of a list of transactions stored in the logbooks related to a node in a data structure, which can be seen by nodes attached to the P2P network. (Kavousi-Fard, Almutairi, Al-Sumaiti, & Farughian, 2021).

Fig. 11 represents a block structure in a Blockchain system. As can be seen in this figure, the block structure includes a set of transaction data, a timestamp, a Hash related to the previous block, a Nonce which is a number that appears only once, and finally the Merkle root which is an abbreviated form of the transaction tree diagram. In this way, the blocks are joined to organize a chain, where the hash generated by the previous blocks preserves the integrity of the Blockchain process. Upon receiving the data blocks, each node must have access to the data inserted in the data block. To do this, the block tag is embedded in the data block to indicate a unique hash function. Each tag expresses a hash generator defined for the nodes of the previous network. With this argument, the nodes will consider an encryption mechanism belonging to the block data tag to create previous/current hash (HAs) addresses and scramble them to limit access to the correct data. To clarify the $HA\ previous/current$, suppose the network includes some nodes, each of them generates a HA actual relative to hash function on iteration r and save a $HA\ previous$ which is generated and sent by neighboring nodes in the iteration $r-1$. Each node inserts the $HA\ current$ and $previous$ in its block tag and this process continues within a chain of nodes. The result of this process is reflected and presented in two concepts, that is, confirmation and validity of the data block. As for the encryption algorithm, any faulty node can be quickly recognized and nodes on the network will eventually update their data block and tag during the hash generation process. The HA's are defined in terms of 32-bit compound words with respect to various hash functions. In the case of Bitcoin, the $SHA-256$ is used, including letters and numbers $\{0:9, A:F\}$ (Kavousi-Fard, Almutairi, Al-Sumaiti, & Farughian, 2021).

Fig. 11: Structure of a block in a Blockchain system



Source: Ying-Chang (2020).

It is concluded that the incorporation of Blockchain consensus algorithms in P2P trading platforms may be the key to making distributed energy a reality. That is, unlike a centralized system, in a distributed system based on Blockchain, all network participants can have transparent access to information, with a facilitated or automated exchange of value, subtracting the need for a third party. In terms of security, due to its distributed structure, Blockchain cannot be hacked as easily as on a central server (Potts, Rennie, & Goldenfein, 2017). It is also expected to reduce the time of transactions, even converging to be in real time (Allidina, 2016). Lastly, each block is encrypted with a hash function that affects subsequent blocks, making any interference noticeable (Khaqqi, Sikorski, Hadinoto, & Kraft, 2018).

7.4 Nanogrid's Blockchain architecture and operation

The Blockchain architecture of the nanogrid enables a trustless environment that will optimize consumer and prosumer decisions by allowing the local consumption of energy and facilitating access to transactional data in real-time, reducing dependency on the main grid. In addition, it will achieve a distributed system composed of several independent nodes following the peer-to-peer (P2P) scheme, which manages a single record of all transactions and operations carried out.

Therefore, we can summarize the most outstanding reason why it is proposed the use of Blockchain technology:

- Durability: Decentralized networks eliminate single points of failure contrary to centralized systems. This distribution of risk among its nodes makes blockchains much more durable than centralized systems and better suited to prevent malicious attacks.
- Transparency: Each node in the network maintains an identical copy of a blockchain, allowing auditing and inspection of data sets in real time. This level of transparency makes network activities and operations highly visible, thereby reducing the need for trust.

- Immutability: the data stored in a distributed public Blockchain is practically immutable due to the need for validation by other nodes and traceability of changes. This allows users to operate with the highest degree of confidence, since the chain data is exact and unalterable.
- Process Integrity: Open-source distributed protocols by nature run exactly as written in code. Users can be sure that the actions described in the protocol are executed correctly and in a timely manner without the need for human intervention.

8. Automated P2P Energy Trading Between Consumers and Prosumers

The goal of automated P2P trading is to create the best possible outcomes for everyone involved by taking the guesswork out of pricing decisions and making it easier to trade. P2P energy trading is carried out in the following steps:

1) Prosumers register into the P2P market as sellers (S) or buyers (B), based on their investment decision, their GDR_i^t and installed peak capacity.
2) Prosumers are classified as PD1, PD2 or PS prosumers.
3) Net consumers register into the P2P market as buyers.
4) After grouping participants as sellers or buyers, P2PMO assigns a unique and encrypted identity and wallet with a public and a private key, to each buyer and seller, which maintains the anonymity of sellers and buyers ensuring privacy.
5) P2PMO share unique addresses to all participants of the nanogrid to establish direct communication.
6) Each anonymous seller and each anonymous buyer sign the Smart contract and P2P energy trading is ready to start.
7) Prices are set depending on the pricing mechanism at time t and oracle information about the Energy Exchange prices.
8) Finally, P2PMO receives information about prices and amount of energy traded anonymously among different participants, it validates transactions based on wallet balances of the buyers, then settle the financial transactions and update the new block that is to be added to the hybrid nanogrid blockchain.

8.1 Pricing Mechanism

Let assume that as shown above, prices can be between a minimum value and a maximum value, which for High Price (HP), the maximum value is UC and the minimum value is $UC - C$, the latter being the price that $PD2$ prosumers get from the network. In that sense, $C = UC - (UC - C)$ becomes the maximum trading margin that a prosumer can get from a consumer, or the potential savings for a consumer. For PS prosumers, trading margin will be given by $UC - C - G$.

Therefore, this starts to look like a trading model based on auctions or a networked trading model based on alternating offers bargaining. Now, let assume that consumers/buyers value their savings randomly (uniformly and independently distributed on $[0; 1]$) and prices are determined through an auction, i.e., energy surpluses are sold via a second-price auction. This is an auction where the highest bidder obtains the surplus that is demanding at time t and pays the highest bid among the bidders who are not getting the surpluses (with ties in the highest bid broken uniformly at random). When we have two or more buyers then it is a dominant strategy for each buyer to bid his or her value, and the corresponding revenue to the seller is the average between the amount sold to the highest bidder times the valuation price and the amount sold to the second highest bidder times the valuation price. As the number of buyers increase, but the number of sellers is fixed at one, then the seller will always sell his or her surpluses to the higher bidders, therefore getting the best prices possible. However, if we fix the number of buyers at a big number and we start to increase the number of sellers, then we get that as more energy is traded at lower valuations, so does the average price. We can therefore conclude that prices tend to be high when there is a low number of sellers relative to buyers, and prices tend to lower as long as there are more energy surpluses available in the market. This is a game with a similar configuration and described by Kranton & Minehart (2001).

As we commented earlier, it is beyond the scope of this study to know savings valuations of buyers, as well as putting a transactional burden to them of having to make daily price bids. Therefore, we can summarize the pricing mechanism with a decreasing function on the number of sellers relative to the number of total participants in the nanogrid:

- ✓ $HP_t = UC_t - C_t + \left[1 - \frac{S_{PD2,t}}{S_{PD2,t}+B_t}\right](C_t)$
- ✓ $MP_t = G_t + \left[1 - \frac{S_{PS,t}}{S_{PS,t}+B_t}\right](UC_t - C_t - G_t)$

The latter equations are similar to results found by Corominas-Bosch (2004) in his paper "On Two-Sided Network Markets", where he described a simple model of networks with bilateral bargaining. In this game, a link in the network represents the opportunity for a buyer and seller to bargain and potentially exchange a good. If a buyer and seller exchange at a price p, then the buyer receives a payoff of $1 - p$ and the seller a payoff of p. If an individual has several links, then there are several possible trading patterns. Thus, the network structure essentially determines the bargaining power of various buyers and sellers. In the first period, sellers simultaneously call out prices. A buyer can only select from the prices that she has heard called out by the sellers to whom she is linked. Buyers simultaneously respond by either choosing to accept some single price offer they received or to reject all price offers they received. If there are several sellers who have called out the same price and/or several buyers who have accepted the same price, and there is any discretion under the given network connections as to which trades should occur, then there is a careful protocol for determining which trades occur (which is designed to maximize the number of eventual transactions, but in this study a different algorithm will be used and it is described later). At the end of the period, trades are made and buyers and sellers who have traded are cleared from the market. This process repeats itself indefinitely until all remaining buyers and sellers are not linked to each other. Buyers and sellers are impatient and discount according to a common discount factor $0 < \delta < 1$. So a transaction at price p in period t is worth $\delta^t p$ to a seller and $\delta^t(1 - p)$ to a buyer.

In an equilibrium with very patient agents (so that is δ close to 1), there are effectively three possible outcomes for any given agent: either he or she gets most of the available gains from trade, or roughly half of the gains from trade, or a small portion of the available gains from trade. Which of these three cases ensues depends on that agent's position in the network. Some easy special cases are as follows. First, consider a seller linked to two buyers, who are only linked to that seller. Competition between the buyers to accept the price will lead to an equilibrium price of close to 1 if agents are sufficiently patient. So, the payoff to the seller in such a network will be close to 1, while the payoff to the buyers will be close 0.

This is reversed for a single buyer linked to two sellers. The latter equations use similar intuition to Hall's Theorem and Corominas-Bosch algorithm and classifies a price based on the number of buyers and sellers available for trading. When there is a set of sellers that is collectively linked to a larger set of buyers, sellers get payoffs of close to 1, and buyers get payoffs of close to 0; those configurations where the collective set of sellers is linked to a same-sized collective set of buyers, each get payoff of around 1/2; and those where sellers outnumber buyers, sellers get payoffs close to 0, and buyers get payoffs close to 1 (Jackson, 2008).

9. Blockchain Architecture and Operation

As mentioned earlier, participants will have to sign a smart contract that will be implemented and embedded in the system to provide trustless incentives that allow the Blockchain to control the progress of the energy trading algorithm.

9.1 Energy Trading Algorithm

Smart Contracts are basically computer programs that can automatically execute the terms of a contract. When a pre-established condition in a smart contract between participating entities is fulfilled, the parties involved in the contractual agreement can automatically make payments according to the contract in a transparent manner (Efanov & Roschin, 2018).

Before defining the algorithm, total nanogrid generation surpluses ($TNGS_{j,t}$) and total nanogrid consumers demand ($TNCD_t$) will be defined:

For players in $i \in S$, classified as sellers, then $TNGS_{j,t}$ will be equal to:

$$TNGS_{j,t} = \sum_{i=1}^{S} kWh_{P,i,j,t} - kWh_{TDC,i,t}$$

For players in $i \in B$, classified as buyers, then $TNCD_t$ will be equal to:

$$TNCD_t = \sum_{i=1}^{B} kWh_{TDC,i,t} - kWh_{P,i,j,t}$$

Note that only players that chose $(NC, PD1)$ will be classified as buyers, and therefore $TNCD_t \geq 0$.

Smart Contract SC1 Algorithm for energy trading settlement

Smart metering is executed locally by each device participating in the market. The results are passed to the smart contract SC1, which serves as a consensus mechanism. The algorithm iterates back and forth until it converges, at which point the schedule is saved to the billing ledger, which computes payments and automatically transfers funds from consumers to generators.

Inputs by source:
P2PMO: UC_t, C_t,
Nanogrid classification: $S_{PS,t}$, $S_{PD2,t}$, B_t
Oracle Inputs: G_t
Smart meters Input: $TNGS_{j,t}$, $TNCD_t$

Do

For $j = PS$:

If $TNGS_{j,t} \leq TNCD_t$ then distribute $\frac{TNGS_{j,t}}{B_t}$ to each buyer on the nanogrid at Paretian Equilibrium State Price MP_t.
Then consume from the main grid $TNCD_t - TNGS_{j,t}$.

Else distribute $\frac{TNCD_t}{B_t}$ to each buyer on the nanogrid at Paretian Equilibrium State Price MP_t and inject $TNGS_{j,t} - TNCD_t$ to the main grid at price G_t.

For $j = PD2$:

If $TNGS_{j,t} \leq TNCD_t$ then distribute $\frac{TNGS_{j,t}}{B_t}$ to each buyer on the nanogrid at Paretian Equilibrium State Price HP_t.
Then consume from the main grid $TNCD_t - TNGS_{j,t}$.

Else distribute $\frac{TNCD_t}{B_t}$ to each buyer on the nanogrid at Paretian Equilibrium State Price HP_t and inject $TNGS_{j,t} - TNCD_t$ to the main grid at price $UC_t - C_t$.

Prosumer utilities are distributed according to each seller contribution to $TNGS_{j,t}$.
Each transaction is recorded in

While $S_{j,t} \geq 1$ and $B_t \geq 1$.

In this sense, at the end of each month, consumers will owe money to prosumers for the energy they have generated, while both prosumers and consumers will have a credit with the utility company for the energy they've consumed from the grid. The smart contract will help to establish the prices and traded amounts for energy settlement according to the latter algorithm, and it will be embedded in the nanogrid architecture as it is shown in Fig. 12.

This immutable record generated by the smart contract, can also become the basis for reckoning payments when credits and debits for each node in the network are computed and securely saved as the updated account balances to the blockchain.
Many types of assets can be represented with Blockchain tokens, such as coins, stocks, real estate, certificates, fiat currency, and more. Since Blockchain technology is based on cryptography, such currencies are often referred to as cryptocurrencies. The best example is Bitcoin, which is the native currency of the Bitcoin blockchain (Nakamoto, 2008). The Bitcoin blockchain allows users to store and transfer bitcoins on a peer-to-peer network. Another example is Ether, which is the native currency of the Ethereum blockchain. Like the Bitcoin blockchain, the Ethereum blockchain allows users to store and transmit Ether on a peer-to-peer (P2P) network. Furthermore, the Ethereum blockchain can be used for smart contracts and decentralized applications that need to use Ether to pay for computing services provided by the Ethereum platform (Chen & Yan, 2018). Broadly speaking, what is really innovative about Blockchain is that its system allows the movements of tokens to be written in a large virtual ledger that works as a large accounting file for a currency. This book has proven to be unassailable and is based on being fully distributed and constantly updated with the new accounting entries that are produced.

If this system is paired with a cryptocurrency as discussed in (Killeen, 2015), this can form a complete payment system — removing the need for a utility or nanogrid operator to handle scheduling and billing. Although, as of now, this is not the case, and therefore in this study P2PMO will help to deal with transactions in two ways:

1) Consumers can charge their personal wallets with fiat currency through the P2PMO and automate payments depending on their consumption to transfer payments between accounts.
2) They can pay their energy bill including their nanogrid consumption, and there will be a credit in favor for prosumers for the next billing cycle, depending on their consumption.

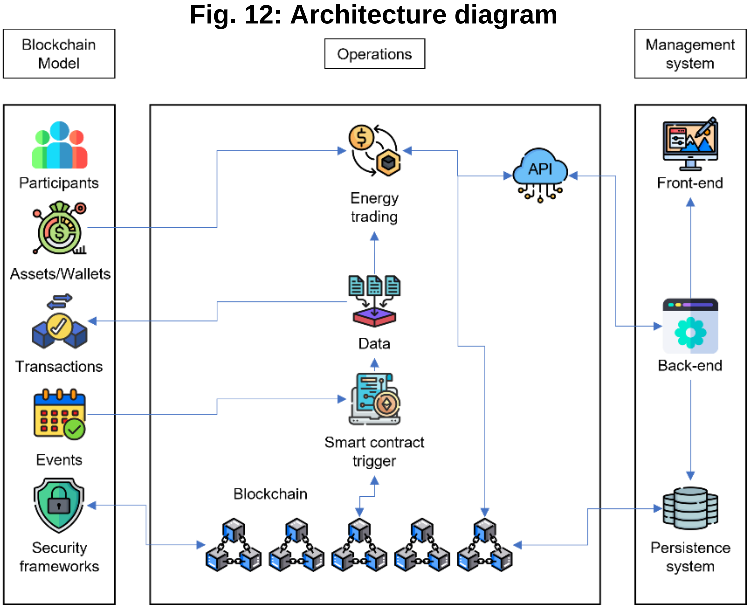
Transactions are the central element in a Blockchain network, whereby one network address sends a message to another network address. The final objective is that transactions of monetary units or tokens between users can be carried out safely. In this protocol, a transaction is made up of two main elements:

- Transaction outputs. It is the transfer of funds. Indicate the amount of funds to be transferred and the recipient of the funds.
- Transaction inputs. These are the funds that will be used for the transaction. These funds must come from a previous transaction. Therefore, in reality the inputs of a transaction will be references to outputs of previous transactions.

The sum of input amounts must be greater than or equal to the sum of output amounts. That is, the sum of the input funds must be equal to (or greater than) the sum of the output funds. In most cases a user will not have previous transactions whose added funds give exactly the amount that he wants to send to the transaction. What is done is to take as inputs previous transactions whose amount is higher than necessary, and in the transaction make the output of the funds that you want to send to the recipient, plus another output with the remaining amount (the change) in which the recipient it is the user himself who is making the transaction.

Full nodes maintain a local copy of the blockchain, starting at the genesis block. The local copy of the blockchain is constantly updated, as new blocks are found and used to extend the chain. As a node receives incoming blocks from the network, it will validate these blocks and then link them to the existing blockchain. To establish a link, a node will examine the header of the incoming block looking for the previous block hash, the shared record of transactions, and that the consensus to verify the transactions was carried out.

Fig. 12: Architecture diagram



Source: *own elaboration.*

10. Simulation results

This section presents the results of study simulation to assess the performance of proposed game-theoretic model for P2P energy trading in a prosumer-based community nanogrid. In addition to the conditions explained in section 6.2 the following configuration was used:

1) Location: Medellin, Colombia.
2) Number of players (I): 10.
3) 9 different scenarios were performed by simulation of the nanogrid, only changing the number of prosumers in each configuration.
4) Monthly solar radiation data were taken from IDEAM-UPME (2022), assuming a normal distribution with a standard deviation of 0.2245409 (which is the annual standard deviation recorded).
5) Similar energy demand characteristics were considered for microgrid participants. Thus, daily energy consumption for each player was set at 6.67 kWh, also assuming a normal distribution with a standard deviation of 0.667.
6) 50% of energy consumption is carried out during the day light and the other 50% at nighttime.
7) Both UC prices and C service fee were taken from EPM: Previous years energy prices (2021).
8) Energy Exchange Market prices (G) were retrieved from XM web page. Prices were taken from January 1, 2021 to December 31, 2021.
9) Each simulation contemplates the 365 days of 2021.
10) The area available for PVs was set at a maximum of 30mts^2 per prosumer/consumer.
11) PD1 players were considered to have a fixed amount of one PV.
12) PD2 players were considered to have a fixed amount of three PVs.
13) PS players were considered to have a flexible amount PVs between 4 and 10.
14) Nanogrid commercialization service fee is fixed at 0.1% of each energy transaction.
15) Both Social Welfare and prosumer/consumer utilities were calculated for each microgrid configuration.

The results showed that the model performed well in terms of reducing the overall dependency on the main network and increasing social welfare. Thanks to the fact that energy is being consumed locally, better prices were achieved for prosumers and consumers. After simulating scenarios where PS type prosumers partially used all of their available area, it was concluded that the greatest utility was achieved when PS prosumers used all of their available area. Therefore, in Fig. 10 there is a comparison of social welfare in different nanogrid configurations, assuming that PS prosumers use their total available area.

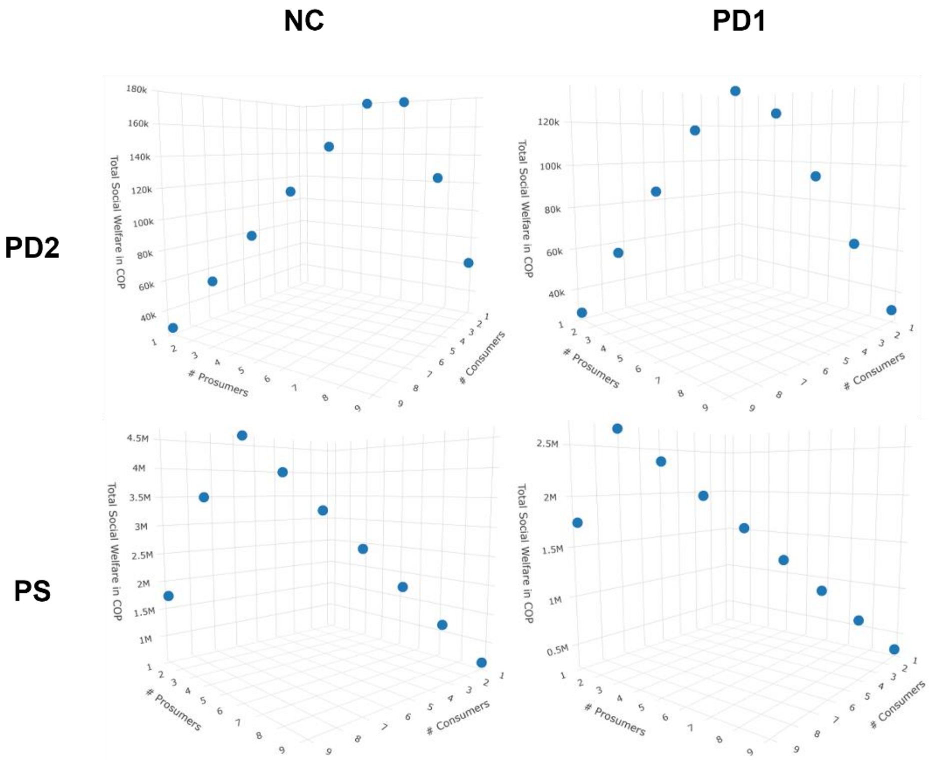
From Fig. 13, we can conclude that when all sellers are PD2 prosumers and all buyers are PD1 prosumers, the maximum social welfare will be achieved when there are 5 sellers and 5 buyers. However, annual social welfare is relatively low at about COP $134.000, where COP $66.100 will go to consumers and COP $67.900 will go to prosumers.

On the other hand, when all consumers lack power generation (NC), the maximum social welfare will be achieved when there are 7 sellers and 3 net consumers. Nevertheless, annual social welfare is still relatively low at about COP $176.004, where COP $122.504 will go to consumers and COP $53.500 will go to prosumers.

Now, when all sellers are PS prosumers and all buyers are PD1 prosumers, the maximum social welfare will be achieved when there are 2 sellers and 8 buyers. In this case, annual social welfare is much higher than those two cases analyzed earlier at about COP $ 2.655.350, where COP $ 738.343 will go to consumers and COP $ 1.917.006 will go to prosumers.

Secondly, when all buyers are net consumers, the maximum social welfare will be achieved when there are 3 sellers and 7 buyers. Moreover, annual social welfare will reach its peak in this configuration at about COP $ 4.554.710, where COP $ 1.683.256 will go to consumers and COP $ 2.871.454 will go to prosumers.

Fig. 13: Total Social Welfare comparison by nanogrid configuration

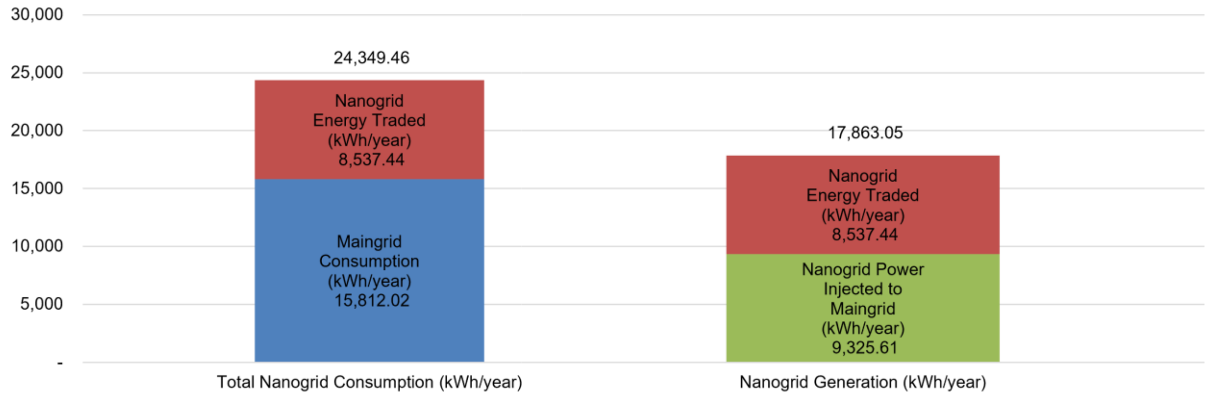


Source: *own elaboration.*

One can note that all of these points where social welfare is maximized, there are no incentives to deviate, and players will not be able to change their condition and improve their utility without worsening that of the others (this is shown in Appendix 1). Hence, we can conclude that these are both Paretian and Nash equilibriums of the game, based on the initial conditions. Also, when there are PD2 prosumers, the nanogrid will tend to have more prosumers than consumer and when there are PS prosumers it will be in the opposite direction. Now, comparing equilibriums between situations with PD1 consumers and net consumers, we conclude that nanogrids with net consumers will demand more power from the microgrid, thus leading to more energy transactions and a higher social welfare in comparison with situations where there are PD1 prosumers.

Finally, taking the situation where we get the highest social welfare [(NC:7, MP); (PS:3, A)], we get that around 48% of the microgrid power generation is being consumed locally and this means that dependency on the main grid is reduced by 35%, as it is shown in Fig. 14.

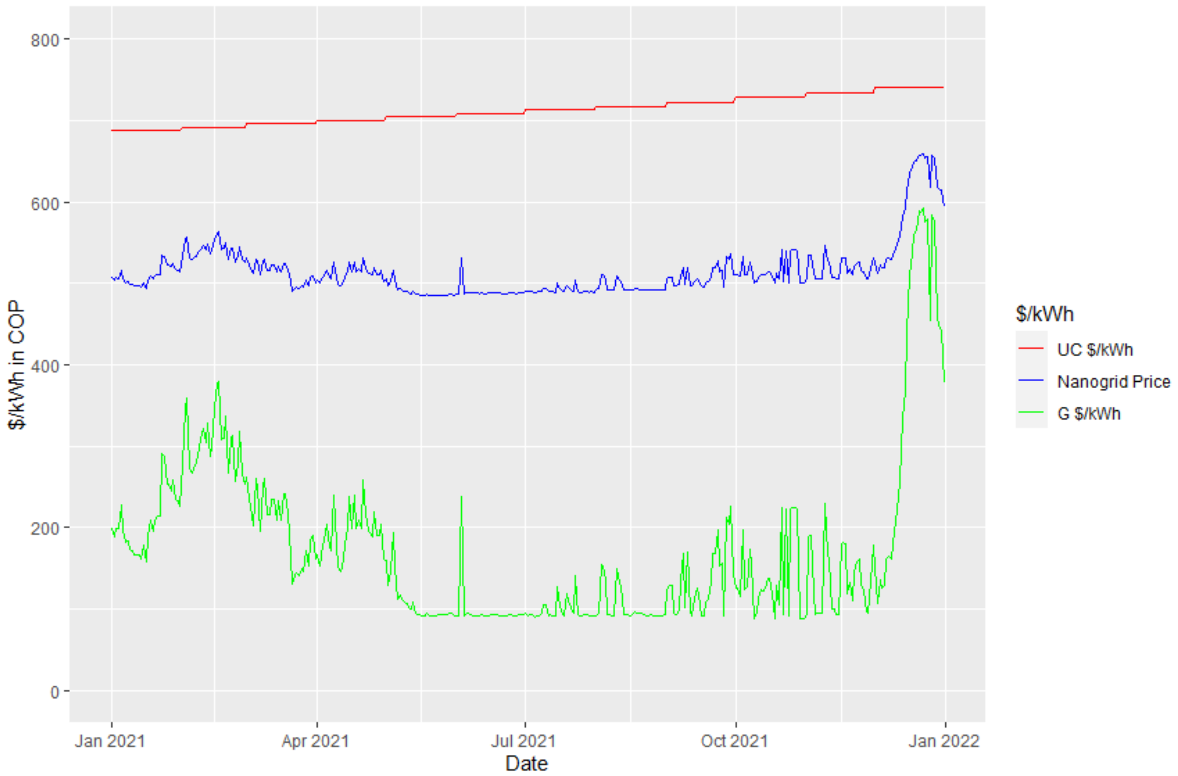
Fig. 14: Total Nanogrid Power Consumption and Generation (kWh/year)



Source: *own elaboration.*

Price wise, we get that, for the configuration [(NC:7, MP); (PS:3, A)], the nanogrid generates prices almost three times higher than the main grid, at COP $514.43, as shown in Fig. 15. Not only that, but we also get a reduction in price volatility relative to Energy Exchange Market prices. Furthermore, the area between the red line and the blue line will be the buyers' savings on the energy purchased in the nanogrid, around 27% on average; while the area between the blue line and the green line will be the sellers' profit on the energy traded within the nanogrid, around 296% higher prices compared to the ones received if there were not P2P energy trading.

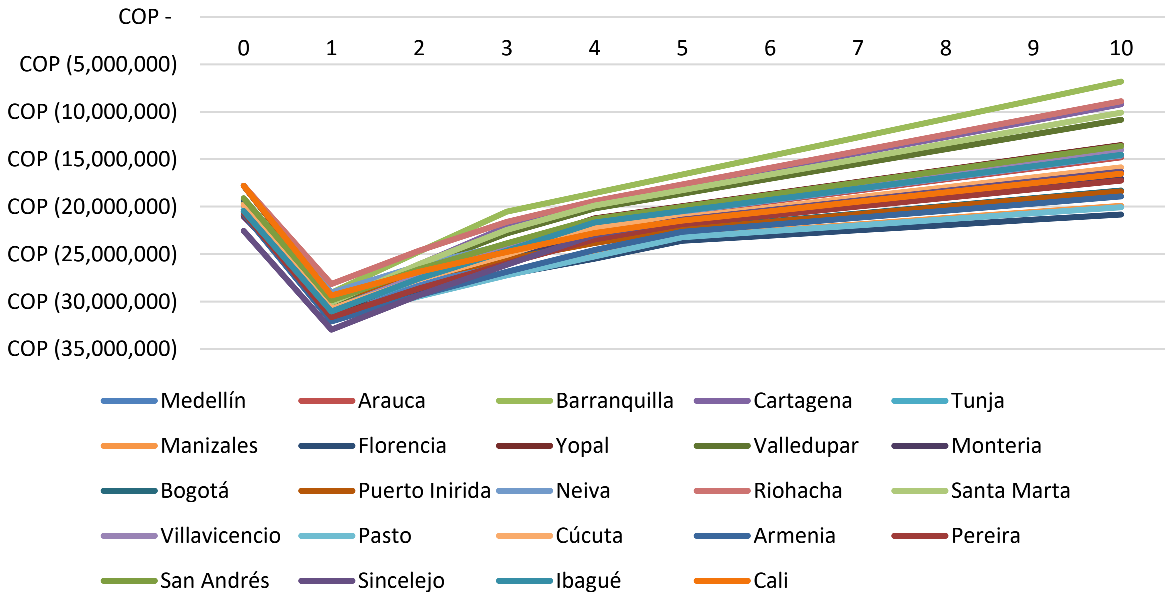
Fig. 15: Price comparison for [(NC:7, MP); (PS:3, A)]



Source: *own elaboration.*

This undoubtedly helps to improve net present values for solar systems at residential level as shown in Fig. 16, which now compared to Fig. 2 it is not a flat line but an increasing one. In other words, a P2P energy trading infrastructure can create sufficient economic incentives for a residential prosumer to invest in a bigger solar system with a higher number of PVs.

Fig. 16: Net Present Value of Solar Systems by Number of PVs in Main Colombian Municipalities assuming the existence of a P2P market [(NC:7, MP); (PS:3, A)]



Source: *own elaboration.*

With this P2P market configuration, we get that now it is economically and financially viable to residential prosumers in all Colombian main cities to invest in a 10 PV solar system compared to only consume energy from the main grid.

11. Conclusion

Electricity systems are decentralizing and digitalizing, which is opening up a world of new opportunities and functions that may be constrained by classical approaches to infrastructure regulation and consumer protection. Energy regulators are discussing the best ways to deal with these emerging phenomena, but several questions still need to be answered: should these new models be defined in a technology-neutral way or not? How should they be supported in a way that does not distort the market nor penalize passive consumers? How should network tariffs and the market design be eventually rearranged without unduly affecting regulated companies and undermining needed investments? How can we automate matching of demand and supply in the best way possible? Although, P2P energy trading is not legal yet, should we facilitate regulatory sandboxes?

Some principles that can be found in the successful examples of P2P energy markets in the world are the right for final customers to switch suppliers, the unbundling between competitive and monopolistic (i.e. regulated) activities, the development of efficient and reliable distribution grids, the promotion of renewables via explicit support measures rather than via implicit subsidies hidden in non-cost reflective network charges. However, more direct experience is needed to understand whether those principles are appropriate or not to an increasingly decentralized and digitalized energy system that must undertake a deep process of decarbonization in the next decades.

Although testing innovative technologies and business models is important, the current recourse to regulatory sandboxes may not always be the most effective way forward. The introduction of “pilot regulation” instead of regulatory pilots could avoid the undertaking of several idiosyncratic initiatives, each of them going in different directions and not easily scalable to the real world.

Energy companies seem to agree with this idea and highlight that technology is frequently not the main barrier to the implementation of new solutions. On the contrary, it is the absence of stakeholders’ involvement and consensus on the required changes to the policy and regulatory framework that often blocks innovation scale-up.

Finally, although it is only one of the elements characterizing these new energy models, technology will be fundamental in ensuring the necessary collection of data and the automation of several processes (think of smart meters, smart home hubs and the like). By doing this, it will allow people to be active in the energy system without being constantly “busy” with decisions on how to produce, trade and consume energy, a condition that is hardly attractive for most of us.

In this study, it was identified that in spite of Colombia’s immaturity or lack of clarification in policy and law, in terms of P2P energy trading regulation, there are some attempts done at the enterprise level. These are in early stages and a lot of research is still needed to achieve a more distributed and fair energy system. If something, one can conclude that current regulation needs to change its approach and encourage uptake of renewable energy resources by giving prosumers additional opportunities to sell their self-produced energy locally, in order to improve financial benefits.

Moreover, in this paper, we have proposed a game-theoretic model for real-time P2P energy trading in an agent-based community nanogrid. Agents in the community who engage in P2P trading are either sellers or buyers. The interaction between the sellers and buyers is modeled as a multistage and repeated game, and an iterative algorithm is proposed to reach consensus in the energy transactions. Additionally, the price is defined as a decreasing function of the number of prosumers in the nanogrid, following a double auction logic and in order to maintain local energy trading incentives as high as possible. The proposed method is applied to a small-scale community nanogrid with PVs, no energy storage systems, and a direct connection to the main grid. Simulation results show that the proposed model is effective in handling P2P energy trading in a community nanogrid, as evidenced by the significant increase in prices for energy sellers compared to the main grid, improving net present values for solar systems at residential level. Anyhow, this is just the beginning of the use of blockchain technology as a lever for a distributed and automatic economic system.

The presented model did not have prediction or forecasting characteristics, but rather will serve to theoretically measure the validity of P2P energy trading market in the Colombian context through parameters and variables, so that space is opened for the discussion of the possible entry of these P2P initiatives to the national energy market and serve as an advance for the regulatory environment.

In conclusion, Colombian regulators should start to analyze this type of initiatives and recognize that it is time to open up to the possibility of energy submarkets operating alongside traditional energy markets.

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Appendix 1

Prosumer energy production, LCOE and R_0

1. Prosumer production in investment decision j will be defined as:

$$kWh_{P,i,j} = U_t^{PV}\ PR\ NPV_j\ \chi_t$$

And the expected output for the lifetime of solar panels will be:

$$\sum_{t=1}^{T} kWh_{P,i,j} * (1 - R^{loss}(t-1))$$
$$= \sum_{t=1}^{T} kWh_{P,i,j} - kWh_{P,i,j}R^{loss}(t-1)$$
$$= TkWh_{P,i,j} - \sum_{t=1}^{T} kWh_{P,i,j}R^{loss}(t-1)$$
$$= TkWh_{P,i,j} - kWh_{P,i,j}R^{loss}\left[\frac{1}{2}(T-1)T\right]$$

2. On the other hand, the initial investment for a solar project, being UC: Unit Cost, will be defined as:

$$R_{0,i,j} = NPV(PV_{UC}) + Aluminum\ Structure_{UC}(NPV) + (U_t^{PV}\ PR\ NPV_j)Wiring\ and\ accesories_{UC} + Insurance + ELCP + 3kW\ Microinverter_{UC} + Monitoring\ system_{UC} + Bidirectional\ Meter_{UC} + RETIE\ Certification_{UC} + UPME\ Procedures_{UC}$$

3. Moreover, it is possible to define the present value of the total cost of a solar system in its useful life as follows:

$$TC_{PVS} = R_{0,i,j} + \sum_{t=1}^{T} \delta^t DMC_j$$

$$TC_{PVS} = R_{0,i,j} + \left[\frac{1-\delta^{T+1}}{1-\delta}\right] DMC_j$$

Therefore, one can conclude that the Levelized Cost of Energy (LCOE) for a solar system is equal to:

$$LCOE_{j,t} = \frac{R_{0,i,j} + \left[\frac{1-\delta^{T+1}}{1-\delta}\right] DMC_j}{TU_t^{PV}\ PR\ NPV_j\ \chi_t - U_t^{PV}\ PR\ NPV_j\ \chi_t R^{loss} \left[\frac{1}{2}(T-1)T\right]}$$

Review Annex 1 at the end of this document., where there is a table that calculates the LCOE for solar systems containing different numbers of PVs for Colombian main municipalities.

Second Stage $(t = 2)$ Equations

$$a_1 = -(HP + C_{NG})kWh_{NGC,1,NC} - UC(kWh_{TC,1} - kWh_{NGC,1,NC});\ kWh_{NGC,1,NC} = kWh_{NCD,1,NC} - (kWh_{P,2,PD2} - kWh_{DC,2})$$

$$b_2 = (HP)kWh_{NGC,1,NC} + (UC - C)(kWh_{P,2,PD2} - kWh_{DC,2} - kWh_{NGC,1,PD1}) - UCkWh_{TNC,2,PD2} - DMC_{PD2}$$

$$c_1 = -(MP + C_{NG})kWh_{NGC,1,NC} - UC(kWh_{TC,1} - kWh_{NGC,1,NC})$$

$$d_2 = (MP)kWh_{NGC,1,NC} + (UC - C)(kWh_{P,2,PD2} - kWh_{DC,2} - kWh_{NGC,1,PD1}) - UCkWh_{TNC,2,PD2} - DMC_{PD2}$$

$$e_1 = -(HP + C_{NG})kWh_{NGC,1,PD1} - UC\left(kWh_{TC,1} - kWh_{NGC,1,PD1} - kWh_{P,1,PD1}\right) - DMC_{PD1};\ kWh_{NGC,1,PD1} = kWh_{NCD,1,PD1} - (kWh_{P,2,PD2} - kWh_{DC,2})$$

$$f_2 = (HP)kWh_{NGC,1,PD1} + (UC - C)(kWh_{P,2,PD2} - kWh_{DC,2} - kWh_{NGC,1,PD1}) - UCkWh_{TNC,2,PD2} - DMC_{PD2}$$

$$g_1 = -(MP + C_{NG})kWh_{NGC,1,PD1} - UC\left(kWh_{TC,1} - kWh_{NGC,1,PD1} - kWh_{P,1}\right) - DMC_{PD1}$$

$$h_2 = (MP)kWh_{NGC,1,PD1} + (UC - C)(kWh_{P,2,PD2} - kWh_{DC,2} - kWh_{NGC,1,PD1}) - UCkWh_{TNC,2,PD2} - DMC_{PD2}$$

$$i_1 = -(HP + C_{NG})kWh_{NGC,1,NC} - UC\left(kWh_{TC,1} - kWh_{NGC,1,NC}\right);\ kWh_{NGC,1,NC} = kWh_{P,2,PS} - kWh_{DC,2}$$

If $kWh_{P,2,PD2} - kWh_{NGC,1,NC} > kWh_{TC,2} \rightarrow \psi = 1.\ \psi = 0$ otherwise:

$$j_2 = (HP)kWh_{NGC,1,NC} + (1 - \psi)[(UC - C)(kWh_{P,2,PS} - kWh_{DC,2} - kWh_{NGC,1,NC}) - UCkWh_{TNC,2,PS}] + \psi[G\left(kWh_{DN,2,PS} - kWh_{TNC,2,PS}\right) - CkWh_{TNC,2,PS}] - DMC_{PS}$$

$$k_1 = -(MP + C_{NG})kWh_{NGC,1,NC} - UC\left(kWh_{TC,1} - kWh_{NGC,1,NC}\right);\ kWh_{NGC,1,NC} = kWh_{P,2,PS} - kWh_{DC,2}$$

$$l_2 = (MP)kWh_{NGC,1,NC} + (1-\psi)[(UC-C)(kWh_{P,2,PS} - kWh_{DC,2} - kWh_{NGC,1,NC}) - UCkWh_{TNC,2,PS}] + \psi[G(kWh_{DN,2,PS} - kWh_{TNC,2,PS}) - CkWh_{TNC,2,PS}] - DMC_{PS}$$

$$m_1 = -(HP + C_{NG})kWh_{NGC,1,PD1} - UC(kWh_{TC,1} - kWh_{NGC,1,PD1} - kWh_{P,1,PD1}) - DMC_{PD1}; kWh_{NGC,1,PD1} = kWh_{P,2,PS} - kWh_{DC,2} - kWh_{P,1,PD1}$$

$$n_2 = (HP)kWh_{NGC,1,PD1} + (1-\psi)[(UC-C)(kWh_{P,2,PS} - kWh_{DC,2} - kWh_{NGC,1,PD1}) - UCkWh_{TNC,2,PS}] + \psi[G(kWh_{DN,2,PS} - kWh_{TNC,2,PS}) - CkWh_{TNC,2,PS}] - DMC_{PS}$$

$$o_1 = -(MP + C_{NG})kWh_{NGC,1,PD1} - UC(kWh_{TC,1} - kWh_{NGC,1,PD1} - kWh_{P,1,PD1}) - DMC_{PD1}; kWh_{NGC,1,PD1} = kWh_{TC,1} - kWh_{P,1,PD1}$$

$$p_2 = (MP)kWh_{NGC,1,PD1} + (1-\psi)[(UC-C)(kWh_{P,2,PS} - kWh_{DC,2} - kWh_{NGC,1,PD1}) - UCkWh_{TNC,2,PS}] + \psi[G(kWh_{DN,2,PS} - kWh_{TNC,2,PS}) - CkWh_{TNC,2,PS}] - DMC_{PS}$$

Same equations apply further but with the other player.

Second Stage $(t = 2)$ Pure Strategy Nash Equilibrium

$\boldsymbol{a_1 \prec c_1}$

$$-(HP + C_{NG})kWh_{NGC,1,NC} - UC(kWh_{TC,1} - kWh_{NGC,1,NC}) = -(MP + C_{NG})kWh_{NGC,1,NC} - UC(kWh_{TC,1} - kWh_{NGC,1,NC})$$

$$-HP - C_{NG} = -MP - C_{NG}$$

$$-HP < -MP$$

$\boldsymbol{e_1 \prec g_1}$

$$-(HP + C_{NG})kWh_{NGC,1,PD1} - UC(kWh_{TC,1} - kWh_{NGC,1,PD1} - kWh_{P,1,PD1}) - DMC_{PD1} = -(MP + C_{NG})kWh_{NGC,1,PD1} - UC(kWh_{TC,1} - kWh_{NGC,1,PD1} - kWh_{P,1}) - DMC_{PD1}$$

$$-HP < -MP$$

$\boldsymbol{i_1 \prec k_1}$

$$-(HP + C_{NG})kWh_{NGC,1,NC} - UC(kWh_{TC,1} - kWh_{NGC,1,NC}) = -(MP + C_{NG})kWh_{NGC,1,NC} - UC(kWh_{TC,1} - kWh_{NGC,1,NC})$$

$$-HP < -MP$$

$\boldsymbol{m_1 \prec o_1}$

$$-(HP + C_{NG})kWh_{NGC,1,PD1} - UC\left(kWh_{TC,1} - kWh_{NGC,1,PD1} - kWh_{P,1,PD1}\right) - DMC_{PD1} = -(MP + C_{NG})kWh_{NGC,1,PD1} - UC\left(kWh_{TC,1} - kWh_{NGC,1,PD1} - kWh_{P,1,PD1}\right) - DMC_{PD1}$$

$$-HP < -MP$$

$\boldsymbol{b_2 \succ \varpi_2}$

$$(HP)kWh_{NGC,1,NC} + (UC - C)(kWh_{P,2,PD2} - kWh_{DC,2} - kWh_{NGC,1,NC}) - \ UCkWh_{TNC,2,PD2} - DMC_{PD2} = -UCkWh_{TNC,2,PD2} + (UC - C)kWh_{DN,1,PD2} - DMC_{PD2}$$

$$(HP)kWh_{NGC,1,NC} + (UC - C)\left(kWh_{P,2,PD2} - kWh_{DC,2} - kWh_{NGC,1,NC}\right) = (UC - C)\left(kWh_{P,2,PD2} - kWh_{DC,2}\right)$$

$$(HP - (UC - C))kWh_{NGC,1,NC} = 0$$

$$HP > UC - C$$

$\boldsymbol{d_2 \prec \varpi_2}$

$$(MP)kWh_{NGC,1,NC} + (UC - C)(kWh_{P,2,PD2} - kWh_{DC,2} - kWh_{NGC,1,NC}) - \ UCkWh_{TNC,2,PD2} - DMC_{PD2} = -UCkWh_{TNC,2,PD2} + (UC - C)kWh_{DN,1,PD2} - DMC_{PD2}$$

$$(MP)kWh_{NGC,1,NC} + (UC - C)\left(kWh_{P,2,PD2} - kWh_{DC,2} - kWh_{NGC,1,NC}\right) = (UC - C)\left(kWh_{P,2,PD2} - kWh_{DC,2}\right)$$

$$(MP - (UC - C))kWh_{NGC,1,NC} = 0$$

$$MP < UC - C$$

$\boldsymbol{f_2 \succ \varpi_2}$

$$(HP)kWh_{NGC,1,PD1} + (UC - C)(kWh_{P,2,PD2} - kWh_{DC,2} - kWh_{NGC,1,PD1}) - \ UCkWh_{TNC,2,PD2} - DMC_{PD2} = -UCkWh_{TNC,2,PD2} + (UC - C)kWh_{DN,1,PD2} - DMC_{PD2}$$

$$(HP)kWh_{NGC,1,PD1} + (UC - C)(kWh_{P,2,PD2} - kWh_{DC,2} - kWh_{NGC,1,PD1}) = +(UC - C)(kWh_{P,2,PD2} - kWh_{DC,2})$$

$$(HP)kWh_{NGC,1,PD1} - (UC - C)kWh_{NGC,1,PD1} = 0$$

$$HP > UC - C$$

$\boldsymbol{h_2 \prec \varpi_2}$

$$(MP)kWh_{NGC,1,PD1} + (UC - C)(kWh_{P,2,PD2} - kWh_{DC,2} - kWh_{NGC,1,PD1}) - \ UCkWh_{TNC,2,PD2} - DMC_{PD2} = -UCkWh_{TNC,2,PD2} + (UC - C)kWh_{DN,1,PD2} - DMC_{PD2}$$

$$(MP)kWh_{NGC,1,PD1} + (UC - C)(kWh_{P,2,PD2} - kWh_{DC,2} - kWh_{NGC,1,PD1}) = +(UC - C)(kWh_{P,2,PD2} - kWh_{DC,2})$$

$$(MP)kWh_{NGC,1,PD1} - (UC - C)kWh_{NGC,1,PD1} = 0$$

$$MP < UC - C$$

$\boldsymbol{j_2 \succ \sigma_2}$

$$(HP)kWh_{NGC,1,NC} + (1 - \psi)[(UC - C)(kWh_{P,2,PS} - kWh_{DC,2} - kWh_{NGC,1,NC}) - \ UCkWh_{TNC,2,PS}] + \psi[G\big(kWh_{DN,2,PS} - kWh_{TNC,2,PS}\big) - CkWh_{TNC,2,PS}] - DMC_{PS}$$
$$= G\big(kWh_{DN,2,PS} - kWh_{TNC,2,PS}\big) - CkWh_{TNC,2,PS} - DMC_{PS}$$

When $\psi = 1$,

$$(HP)kWh_{NGC,1,NC} + G\big((kWh_{P,2,PS} - kWh_{DC,2} - kWh_{NGC,1,NC}) - kWh_{TNC,2,PS}\big) - CkWh_{TNC,2,PS} = G\big((kWh_{P,2,PS} - kWh_{DC,2}) - kWh_{TNC,2,PS}\big) - CkWh_{TNC,2,PS}$$

$$(HP)kWh_{NGC,1,NC} - GkWh_{NGC,1,NC} = 0$$

$$HP > G$$

$\boldsymbol{j_2 \succ \sigma_2}$

When $\psi = 0$,

$$(HP)kWh_{NGC,1,NC} + (UC - C)(kWh_{P,2,PS} - kWh_{DC,2} - kWh_{NGC,1,NC}) - \ UCkWh_{TNC,2,PS} = G\big((kWh_{P,2,PS} - kWh_{DC,2}) - kWh_{TNC,2,PS}\big) - CkWh_{TNC,2,PS}$$

$$(HP)kWh_{NGC,1,NC} + (UC - C)\big(kWh_{P,2,PS} - kWh_{DC,2} - kWh_{NGC,1,NC}\big) - G\left(\big(kWh_{P,2,PS} - kWh_{DC,2}\big) - kWh_{TNC,2,PS}\right) = (UC - C)kWh_{TNC,2,PS}$$

$$(HP)kWh_{NGC,1,NC} + (UC - C)kWh_{P,2,PS} - (UC - C)kWh_{DC,2} - (UC - C)kWh_{NGC,1,NC} - GkWh_{P,2,PS} + GkWh_{DC,2} + GkWh_{TNC,2,PS} = (UC - C)kWh_{TNC,2,PS}$$

$$(HP - UC + C)kWh_{NGC,1,NC} + (UC - C - G)kWh_{P,2,PS} - (UC - C - G)kWh_{DC,2} = (UC - C - G)kWh_{TNC,2,PS}$$

$$(HP - UC + C)kWh_{NGC,1,NC} + (UC - C - G)(kWh_{P,2,PS} - kWh_{DC,2}) = (UC - C - G)kWh_{TNC,2,PS}$$

$$(HP - UC + C)kWh_{NGC,1,NC} + (UC - C - G)(kWh_{TC,2} + kWh_{NGC,1,NC} + kWh_{DN,2,PS} - kWh_{DC,2}) = (UC - C - G)kWh_{TNC,2,PS}$$

$$(HP - UC + C)kWh_{NGC,1,NC} + (UC - C - G)(kWh_{TNC,2,PS} + kWh_{NGC,1,NC} + kWh_{DN,2,PS}) = (UC - C - G)kWh_{TNC,2,PS}$$

$$(HP - UC + C)kWh_{NGC,1,NC} + (UC - C - G)kWh_{NGC,1,NC} + (UC - C - G)kWh_{DN,2,PS} = 0$$

$$(HP - G)kWh_{NGC,1,NC} + (UC - C - G)kWh_{DN,2,PS} > 0$$

$\boldsymbol{l_2 \succ \sigma_2}$

$$(MP)kWh_{NGC,1,NC} + (1 - \psi)[(UC - C)(kWh_{P,2,PS} - kWh_{DC,2} - kWh_{NGC,1,NC}) - UCkWh_{TNC,2,PS}] + \psi[G\left(kWh_{DN,2,PS} - kWh_{TNC,2,PS}\right) - CkWh_{TNC,2,PS}] - DMC_{PS} = G\left(kWh_{DN,2,PS} - kWh_{TNC,2,PS}\right) - CkWh_{TNC,2,PS} - DMC_{PS}$$

When $\psi = 1$,

$$(MP)kWh_{NGC,1,NC} + G\left((kWh_{P,2,PS} - kWh_{DC,2} - kWh_{NGC,1,NC}) - kWh_{TNC,2,PS}\right) - CkWh_{TNC,2,PS} = G\left((kWh_{P,2,PS} - kWh_{DC,2}) - kWh_{TNC,2,PS}\right) - CkWh_{TNC,2,PS}$$

$$(MP)kWh_{NGC,1,NC} - GkWh_{NGC,1,NC} = 0$$

$$MP > G$$

$\boldsymbol{l_2 \succ \sigma_2}$

When $\psi = 0$,

$$(MP)kWh_{NGC,1,NC} + (UC - C)(kWh_{P,2,PS} - kWh_{DC,2} - kWh_{NGC,1,NC}) - UCkWh_{TNC,2,PS} = G\left((kWh_{P,2,PS} - kWh_{DC,2}) - kWh_{TNC,2,PS}\right) - CkWh_{TNC,2,PS}$$

$$(MP)kWh_{NGC,1,NC} + (UC - C)\left(kWh_{P,2,PS} - kWh_{DC,2} - kWh_{NGC,1,NC}\right) - G\left(\left(kWh_{P,2,PS} - kWh_{DC,2}\right) - kWh_{TNC,2,PS}\right) = (UC - C)kWh_{TNC,2,PS}$$

$$(MP)kWh_{NGC,1,NC} + (UC - C)kWh_{P,2,PS} - (UC - C)kWh_{DC,2} - (UC - C)kWh_{NGC,1,NC} - GkWh_{P,2,PS} + GkWh_{DC,2} + GkWh_{TNC,2,PS} = (UC - C)kWh_{TNC,2,PS}$$

$$(MP - UC + C)kWh_{NGC,1,NC} + (UC - C - G)kWh_{P,2,PS} - (UC - C - G)kWh_{DC,2} = (UC - C - G)kWh_{TNC,2,PS}$$

$$(HP - UC + C)kWh_{NGC,1,NC} + (UC - C - G)(kWh_{P,2,PS} - kWh_{DC,2}) = (UC - C - G)kWh_{TNC,2,PS}$$

$$(MP - UC + C)kWh_{NGC,1,NC} + (UC - C - G)(kWh_{TC,2} + kWh_{NGC,1,NC} + kWh_{DN,2,PS} - kWh_{DC,2}) = (UC - C - G)kWh_{TNC,2,PS}$$

$$(MP - UC + C)kWh_{NGC,1,NC} + (UC - C - G)(kWh_{TNC,2,PS} + kWh_{NGC,1,NC} + kWh_{DN,2,PS}) = (UC - C - G)kWh_{TNC,2,PS}$$

$$(MP - UC + C)kWh_{NGC,1,NC} + (UC - C - G)kWh_{NGC,1,NC} + (UC - C - G)kWh_{DN,2,PS} = 0$$

$$(MP-G)kWh_{NGC,1,NC}+(UC-C-G)kWh_{DN,2,PS}>0$$

$\boldsymbol{n_2 \succ \sigma_2}$

$$(HP)kWh_{NGC,1,PD1}+(1-\psi)[(UC-C)(kWh_{P,2,PS}-kWh_{DC,2}-kWh_{NGC,1,PD1})-\ UCkWh_{TNC,2,PS}]+\psi[G\big(kWh_{DN,2,PS}-kWh_{TNC,2,PS}\big)-CkWh_{TNC,2,PS}]-DMC_{PS}$$
$$=G\big(kWh_{DN,2,PS}-kWh_{TNC,2,PS}\big)-CkWh_{TNC,2,PS}-DMC_{PS}$$

When $\psi=1$,

$$(HP)kWh_{NGC,1,PD1}+G\big((kWh_{P,2,PS}-kWh_{DC,2}-kWh_{NGC,1,PD1})-kWh_{TNC,2,PS}\big)-CkWh_{TNC,2,PS}=G\big((kWh_{P,2,PS}-kWh_{DC,2})-kWh_{TNC,2,PS}\big)-CkWh_{TNC,2,PS}$$

$$(HP)kWh_{NGC,1,PD1}-GkWh_{NGC,1,PD1}=0$$

$$HP>G$$

$\boldsymbol{n_2 \succ \sigma_2}$

When $\psi=0$,

$$(HP)kWh_{NGC,1,PD1}+(UC-C)(kWh_{P,2,PS}-kWh_{DC,2}-kWh_{NGC,1,PD1})-\ UCkWh_{TNC,2,PS}=G\big((kWh_{P,2,PS}-kWh_{DC,2})-kWh_{TNC,2,PS}\big)-CkWh_{TNC,2,PS}$$

$$(HP)kWh_{NGC,1,PD1}+(UC-C)\big(kWh_{P,2,PS}-kWh_{DC,2}-kWh_{NGC,1,PD1}\big)-G\left(\big(kWh_{P,2,PS}-kWh_{DC,2}\big)-kWh_{TNC,2,PS}\right)=(UC-C)kWh_{TNC,2,PS}$$

$$(HP)kWh_{NGC,1,PD1}+(UC-C)kWh_{P,2,PS}-(UC-C)kWh_{DC,2}-(UC-C)kWh_{NGC,1,PD1}-GkWh_{P,2,PS}+GkWh_{DC,2}+GkWh_{TNC,2,PS}=(UC-C)kWh_{TNC,2,PS}$$

$$(HP-UC+C)kWh_{NGC,1,PD1}+(UC-C-G)kWh_{P,2,PS}-(UC-C-G)kWh_{DC,2}=(UC-C-G)kWh_{TNC,2,PS}$$

$$(HP-UC+C)kWh_{NGC,1,PD1}+(UC-C-G)(kWh_{P,2,PS}-kWh_{DC,2})=(UC-C-G)kWh_{TNC,2,PS}$$

$$(HP-UC+C)kWh_{NGC,1,PD1}+(UC-C-G)(kWh_{TC,2}+kWh_{NGC,1,PD1}+kWh_{DN,2,PS}-kWh_{DC,2})=(UC-C-G)kWh_{TNC,2,PS}$$

$$(HP-UC+C)kWh_{NGC,1,PD1}+(UC-C-G)(kWh_{TNC,2,PS}+kWh_{NGC,1,PD1}+kWh_{DN,2,PS})=(UC-C-G)kWh_{TNC,2,PS}$$

$$(HP-UC+C)kWh_{NGC,1,PD1}+(UC-C-G)kWh_{NGC,1,PD1}+(UC-C-G)kWh_{DN,2,PS}=0$$

$$(HP-G)kWh_{NGC,1,PD1}+(UC-C-G)kWh_{DN,2,PS}>0$$

$\boldsymbol{p_2 \succ \sigma_2}$

$$(MP)kWh_{NGC,1,NC} + (1-\psi)[(UC-C)(kWh_{P,2,PS} - kWh_{DC,2} - kWh_{NGC,1,NC}) - UCkWh_{TNC,2,PS}] + \psi[G(kWh_{DN,2,PS} - kWh_{TNC,2,PS}) - CkWh_{TNC,2,PS}] - DMC_{PS} = G(kWh_{DN,2,PS} - kWh_{TNC,2,PS}) - CkWh_{TNC,2,PS} - DMC_{PS}$$

When $\psi = 1$,

$$(MP)kWh_{NGC,1,NC} + G((kWh_{P,2,PS} - kWh_{DC,2} - kWh_{NGC,1,NC}) - kWh_{TNC,2,PS}) - CkWh_{TNC,2,PS} = G((kWh_{P,2,PS} - kWh_{DC,2}) - kWh_{TNC,2,PS}) - CkWh_{TNC,2,PS}$$

$$(MP)kWh_{NGC,1,NC} - GkWh_{NGC,1,NC} = 0$$

$$MP > G$$

$\boldsymbol{p_2 \succ \sigma_2}$

When $\psi = 0$,

$$(MP)kWh_{NGC,1,NC} + (UC-C)(kWh_{P,2,PS} - kWh_{DC,2} - kWh_{NGC,1,NC}) - UCkWh_{TNC,2,PS} = G((kWh_{P,2,PS} - kWh_{DC,2}) - kWh_{TNC,2,PS}) - CkWh_{TNC,2,PS}$$

$$(MP)kWh_{NGC,1,NC} + (UC-C)(kWh_{P,2,PS} - kWh_{DC,2} - kWh_{NGC,1,NC}) - G\left((kWh_{P,2,PS} - kWh_{DC,2}) - kWh_{TNC,2,PS}\right) = (UC-C)kWh_{TNC,2,PS}$$

$$(MP)kWh_{NGC,1,NC} + (UC-C)kWh_{P,2,PS} - (UC-C)kWh_{DC,2} - (UC-C)kWh_{NGC,1,NC} - GkWh_{P,2,PS} + GkWh_{DC,2} + GkWh_{TNC,2,PS} = (UC-C)kWh_{TNC,2,PS}$$

$$(MP-UC+C)kWh_{NGC,1,NC} + (UC-C-G)kWh_{P,2,PS} - (UC-C-G)kWh_{DC,2} = (UC-C-G)kWh_{TNC,2,PS}$$

$$(HP-UC+C)kWh_{NGC,1,NC} + (UC-C-G)(kWh_{P,2,PS} - kWh_{DC,2}) = (UC-C-G)kWh_{TNC,2,PS}$$

$$(MP-UC+C)kWh_{NGC,1,NC} + (UC-C-G)(kWh_{TC,2} + kWh_{NGC,1,NC} + kWh_{DN,2,PS} - kWh_{DC,2}) = (UC-C-G)kWh_{TNC,2,PS}$$

$$(MP-UC+C)kWh_{NGC,1,NC} + (UC-C-G)(kWh_{TNC,2,PS} + kWh_{NGC,1,NC} + kWh_{DN,2,PS}) = (UC-C-G)kWh_{TNC,2,PS}$$

$$(MP-UC+C)kWh_{NGC,1,NC} + (UC-C-G)kWh_{NGC,1,NC} + (UC-C-G)kWh_{DN,2,PS} = 0$$

$$(MP-G)kWh_{NGC,1,NC} + (UC-C-G)kWh_{DN,2,PS} > 0$$

Game payments for player 1 when there is no use of P2P market

- ν_1(NC, NC) = ν_1(NC, PD1) = ν_1([NC, PD2 ∨ PS], [HP ∨ MP, R]) = ν_1([NC, PS], [HP ∨ MP, R]) : $0 + \sum_{t=1}^{T} \delta^t(-UCkWh_{TC,1})$

$$= -\delta UCkWh_{TC,1}\left[1+\delta+\delta^2+\dots+\delta^T\right]$$

$$= -\delta UCkWh_{TC,1}\left[\frac{1-\delta^{T+1}}{1-\delta}\right]$$

- ν_1(PD1 , NC) = ν_1(PD1 , PD1) = ν_1([PD1, PD2], [HP ∨ MP, R]) = ν_1([PD1, PS], [HP ∨ MP, R]): $-R_{0,1,PD1}+\sum_{t=1}^{T}\delta^t\left[-UC\left(kWh_{TC,1}-kWh_{P,1,PD1}*(1-R^{loss}(t-1))\right)-DMC_{PD1}\right]$

$$= -R_{0,1,PD1}+\sum_{t=1}^{T}\delta^t\left[-UC\left(kWh_{TC,1}-kWh_{P,1,PD1}+kWh_{P,1,PD1}R^{loss}(t-1)\right)-DMC_{PD1}\right]$$

$$= -R_{0,1,PD1}+\sum_{t=1}^{T}\delta^t\left[-UC\left(kWh_{TC,1}-kWh_{P,1,PD1}\right)-DMC_{PD1}\right]-\sum_{t=1}^{T}\delta^t\,UCkWh_{P,1,PD1}R^{loss}(t-1)$$

$$= -R_{0,1,PD1}+\left[\frac{1-\delta^{T+1}}{1-\delta}\right]\left[-UC\left(kWh_{TC,1}-kWh_{P,1,PD1}\right)-DMC_{PD1}\right]-\left[\frac{\delta(\delta+(T-1)\delta^{T+1}-T\delta^T)}{(\delta-1)^2}\right]UCkWh_{P,1,PD1}R^{loss}$$

- ν_1(PD2,PD2) = ν_1(PD2,PS) = $-R_{0,1,PD2}+\delta\left[-UCkWh_{TNC,1,PD2}+(UC-C)kWh_{DN,1,PD2}-DMC_{PD2}\right]+\dots+$

$$= -R_{0,1,PD2}+\delta\left[-UCkWh_{TNC,1,PD2}+(UC-C)kWh_{DN,1,PD2}-DMC_{PD2}\right]\left[\frac{1-\delta^{T+1}}{1-\delta}\right]$$

- ν_1(PS,PD2) = ν_1(PS,PS) = $-R_{0,1,PS}+\delta\left[G\left(kWh_{DN,1,PS}-kWh_{TNC,1,PS}\right)-CkWh_{TNC,1,PS}-DMC_{PS}\right]+\dots+$

$$= -R_{0,1,PS}+\delta\left[G\left(kWh_{DN,1,PS}-kWh_{TNC,1,PS}\right)-CkWh_{TNC,1,PS}-DMC_{PS}\right]\left[\frac{1-\delta^{T+1}}{1-\delta}\right]$$

The same equations apply to player’s 2, given homogeneity.

Game payments for player 1 when there is use of P2P market settlement

1. (NC, PD1):

- ν_1([NC, PD2], [HP, A]): $0 + \delta\big(-(HP + C_{NG})kWh_{NGC,1,NC} - UC(kWh_{TC,1} - kWh_{NGC,1,NC})\big) + \cdots +$

$$= \delta\big(-(HP + C_{NG})kWh_{NGC,1,NC} - UC(kWh_{TC,1} - kWh_{NGC,1,NC})\big)\left[\frac{1-\delta^{T+1}}{1-\delta}\right];\ kWh_{NGC,1,NC} = kWh_{P,2,PD2} - kWh_{DC,2}$$

- ν_1([NC, PD2], [MP, A]):

$$0 + \delta\big(-(MP + C_{NG})kWh_{NGC,1,NC} - UC(kWh_{TC,1} - kWh_{NGC,1,NC})\big) + \cdots +$$

$$= \delta\big(-(MP + C_{NG})kWh_{NGC,1,NC} - UC(kWh_{TC,1} - kWh_{NGC,1,NC})\big)\left[\frac{1-\delta^{T+1}}{1-\delta}\right];\ kWh_{NGC,1,NC} = kWh_{P,2,PD2} - kWh_{DC,2}$$

$$\delta\big(-(HP + C_{NG})kWh_{NGC,1,NC} - UC(kWh_{TC,1} - kWh_{NGC,1,NC})\big)\left[\frac{1-\delta^{T+1}}{1-\delta}\right] = \delta\big(-(MP + C_{NG})kWh_{NGC,1,NC} - UC(kWh_{TC,1} - kWh_{NGC,1,NC})\big)\left[\frac{1-\delta^{T+1}}{1-\delta}\right]$$

$$-HP < -MP$$

- ν_1([PD1, PD2], [HP, A]): $-R_{0,1,PD1} + \delta\Big(-(HP + C_{NG})kWh_{NGC,1,PD1} - UC\big(kWh_{TC,1} - kWh_{NGC,1,PD1} - kWh_{P,1,PD1}(1 - R^{loss}(t-1))\big) - DMC_{PD1}\Big) + \cdots +$

$$= -R_{0,1,PD1} + \delta\Big(-(HP + C_{NG})kWh_{NGC,1,PD1} - UC\big(kWh_{TC,1} - kWh_{NGC,1,PD1} - kWh_{P,1,PD1}\big) - DMC_{PD1}\Big)\left[\frac{1-\delta^{T+1}}{1-\delta}\right] - \left[\frac{\delta(\delta + (T-1)\delta^{T+1} - T\delta^{T})}{(\delta-1)^2}\right]UCkWh_{P,1,PD1}R^{loss}$$

- ν_1([PD1, PD2], [MP, A]): $-R_{0,1,PD1} + \delta\Big(-(MP + C_{NG})kWh_{NGC,1,PD1} - UC\big(kWh_{TC,1} - kWh_{NGC,1,PD1} - kWh_{P,1,PD1}(1 - R^{loss}(t-1))\big) - DMC_{PD1}\Big) + \cdots +$

$$= -R_{0,1,PD1} + \delta\Big(-(MP + C_{NG})kWh_{NGC,1,PD1} - UC\big(kWh_{TC,1} - kWh_{NGC,1,PD1} - kWh_{P,1,PD1}\big) - DMC_{PD1}\Big)\left[\frac{1-\delta^{T+1}}{1-\delta}\right] - \left[\frac{\delta(\delta + (T-1)\delta^{T+1} - T\delta^{T})}{(\delta-1)^2}\right]UCkWh_{P,1,PD1}R^{loss}$$

$$-R_{0,1,PD1} + \delta\Big(-(HP + C_{NG})kWh_{NGC,1,PD1} - UC\big(kWh_{TC,1} - kWh_{NGC,1,PD1} - kWh_{P,1,PD1}\big) - DMC_{PD1}\Big)\left[\frac{1-\delta^{T+1}}{1-\delta} - \left[\frac{\delta(\delta+(T-1)\delta^{T+1}-T\delta^{T})}{(\delta-1)^2}\right]UCkWh_{P,1,PD1}R^{loss}\right] = -R_{0,1,PD1} + \delta\Big(-(MP + C_{NG})kWh_{NGC,1,PD1} - UC\big(kWh_{TC,1} - kWh_{NGC,1,PD1} - kWh_{P,1,PD1}\big) - DMC_{PD1}\Big)\left[\frac{1-\delta^{T+1}}{1-\delta}\right] - \left[\frac{\delta(\delta+(T-1)\delta^{T+1}-T\delta^{T})}{(\delta-1)^2}\right]UCkWh_{P,1,PD1}R^{loss}$$

$$-HP < -MP$$

Therefore, there is no possible value for δ that would make player 1 to play HP over MP.

2. (PD2, PS):

- v_1([PD2, NC], [A, HP]): $-R_{0,1,PD2} + \delta\big((HP)kWh_{NGC,2,NC} + (UC - C)(kWh_{P,2,PD2} - kWh_{DC,2} - kWh_{NGC,2,NC}) - \ UCkWh_{TNC,1,PD2} - DMC_{PD2}\big) + \cdots +$

$$= -R_{0,1,PD2} + \delta\big((HP)kWh_{NGC,2,NC} + (UC - C)(kWh_{P,2,PD2} - kWh_{DC,2} - kWh_{NGC,2,NC}) - \ UCkWh_{TNC,1,PD2} - DMC_{PD2}\big)\left[\frac{1 - \delta^{T+1}}{1 - \delta}\right]$$

- v_1([PD2, NC], [R, HP]): $-R_{0,1,PD2} + \delta\big(-UCkWh_{TNC,1,PD2} + (UC - C)kWh_{DN,1,PD2} - DMC_{PD2}\big) + \cdots +$

$$= -R_{0,1,PD2} + \delta\big(-UCkWh_{TNC,1,PD2} + (UC - C)kWh_{DN,1,PD2} - DMC_{PD2}\big)\left[\frac{1 - \delta^{T+1}}{1 - \delta}\right]$$

$$-R_{0,1,PD2} + \delta\big((HP)kWh_{NGC,2,NC} + (UC - C)(kWh_{P,2,PD2} - kWh_{DC,2} - kWh_{NGC,2,NC}) - \ UCkWh_{TNC,1,PD2} - DMC_{PD2}\big)\left[\frac{1 - \delta^{T+1}}{1 - \delta}\right]$$
$$= -R_{0,1,PD2} + \delta\big(-UCkWh_{TNC,1,PD2} + (UC - C)kWh_{DN,1,PD2} - DMC_{PD2}\big)\left[\frac{1 - \delta^{T+1}}{1 - \delta}\right]$$

We get $b_1 = \rho$, and as shown before: $b_1 > \rho$.

- v_1([PD2, NC], [A, MP]): $-R_{0,1,PD2} + \delta\big((MP)kWh_{NGC,2,NC} + (UC - C)(kWh_{P,2,PD2} - kWh_{DC,2} - kWh_{NGC,2,NC}) - \ UCkWh_{TNC,1,PD2} - DMC_{PD2}\big) + \cdots +$

$$= -R_{0,1,PD2} + \delta\big((MP)kWh_{NGC,2,NC} + (UC - C)(kWh_{P,2,PD2} - kWh_{DC,2} - kWh_{NGC,2,NC}) - \ UCkWh_{TNC,1,PD2} - DMC_{PD2}\big)\left[\frac{1 - \delta^{T+1}}{1 - \delta}\right]$$

- v_1([PD2, NC], [R, MP]): $-R_{0,1,PD2} + \delta\big(-UCkWh_{TNC,1,PD2} + (UC - C)kWh_{DN,1,PD2} - DMC_{PD2}\big) + \cdots +$

$$= -R_{0,1,PD2} + \delta\big(-UCkWh_{TNC,1,PD2} + (UC - C)kWh_{DN,1,PD2} - DMC_{PD2}\big)\left[\frac{1 - \delta^{T+1}}{1 - \delta}\right]$$

$$-R_{0,1,PD2} + \delta\big((MP)kWh_{NGC,2,NC} + (UC - C)(kWh_{P,2,PD2} - kWh_{DC,2} - kWh_{NGC,2,NC}) - \ UCkWh_{TNC,1,PD2} - DMC_{PD2}\big)\left[\frac{1 - \delta^{T+1}}{1 - \delta}\right]$$
$$= -R_{0,1,PD2} + \delta\big(-UCkWh_{TNC,1,PD2} + (UC - C)kWh_{DN,1,PD2} - DMC_{PD2}\big)\left[\frac{1 - \delta^{T+1}}{1 - \delta}\right]$$

We get $d_1 = \rho$, and as shown before: $b_1 < \rho$.

- v_1([PD2, PD1], [A, HP]): $-R_{0,1,PD2} + \delta\big((HP)kWh_{NGC,2,PD1} + (UC - C)(kWh_{P,2,PD2} - kWh_{DC,2} - kWh_{NGC,2,PD1}) - \ UCkWh_{TNC,1,PD2} - DMC_{PD2}\big) + \cdots +$

$$= -R_{0,1,PD2} + \delta\big((HP)kWh_{NGC,2,PD1} + (UC - C)(kWh_{P,2,PD2} - kWh_{DC,2} - kWh_{NGC,2,PD1}) - UCkWh_{TNC,1,PD2} - DMC_{PD2}\big)\left[\frac{1-\delta^{T+1}}{1-\delta}\right]$$

- v_1([PD2, PD1], [R, HP]): $-R_{0,1,PD2} + \delta\big(-UCkWh_{TNC,1,PD2} + (UC - C)kWh_{DN,1,PD2} - DMC_{PD2}\big) + \cdots +$

$$= -R_{0,1,PD2} + \delta\big(-UCkWh_{TNC,1,PD2} + (UC - C)kWh_{DN,1,PD2} - DMC_{PD2}\big)\left[\frac{1-\delta^{T+1}}{1-\delta}\right]$$

$$-R_{0,1,PD2} + \delta\big((HP)kWh_{NGC,2,PD1} + (UC - C)(kWh_{P,2,PD2} - kWh_{DC,2} - kWh_{NGC,2,PD1}) - UCkWh_{TNC,1,PD2} - DMC_{PD2}\big)\left[\frac{1-\delta^{T+1}}{1-\delta}\right]$$
$$= -R_{0,1,PD2} + \delta\big(-UCkWh_{TNC,1,PD2} + (UC - C)kWh_{DN,1,PD2} - DMC_{PD2}\big)\left[\frac{1-\delta^{T+1}}{1-\delta}\right]$$

We get $f_1 = \rho$, and as shown before: $f_1 > \rho$. So, we can conclude that player 1 will always Accepts HP offers if PD2 is chosen.

- v_1([PD2, PD1], [A, MP]): $-R_{0,1,PD2} + \delta\big((MP)kWh_{NGC,2,PD1} + (UC - C)(kWh_{P,2,PD2} - kWh_{DC,2} - kWh_{NGC,2,PD1}) - UCkWh_{TNC,1,PD2} - DMC_{PD2}\big) + \cdots +$

$$= -R_{0,1,PD2} + \delta\big((MP)kWh_{NGC,2,PD1} + (UC - C)(kWh_{P,2,PD2} - kWh_{DC,2} - kWh_{NGC,2,PD1}) - UCkWh_{TNC,1,PD2} - DMC_{PD2}\big)\left[\frac{1-\delta^{T+1}}{1-\delta}\right]$$

- v_1([PD2, PD1], [R, MP]): $-R_{0,1,PD2} + \delta\big(-UCkWh_{TNC,1,PD2} + (UC - C)kWh_{DN,1,PD2} - DMC_{PD2}\big) + \cdots +$

$$= -R_{0,1,PD2} + \delta\big(-UCkWh_{TNC,1,PD2} + (UC - C)kWh_{DN,1,PD2} - DMC_{PD2}\big)\left[\frac{1-\delta^{T+1}}{1-\delta}\right]$$

$$-R_{0,1,PD2} + \delta\big((MP)kWh_{NGC,2,PD1} + (UC - C)(kWh_{P,2,PD2} - kWh_{DC,2} - kWh_{NGC,2,PD1}) - UCkWh_{TNC,1,PD2} - DMC_{PD2}\big)\left[\frac{1-\delta^{T+1}}{1-\delta}\right]$$
$$= -R_{0,1,PD2} + \delta\big(-UCkWh_{TNC,1,PD2} + (UC - C)kWh_{DN,1,PD2} - DMC_{PD2}\big)\left[\frac{1-\delta^{T+1}}{1-\delta}\right]$$

We get $h_1 = \rho$, and as shown before: $h_1 < \rho$. So, we can conclude that player 1 will always Reject MP offers if PD2 is chosen.

- v_1([PS, NC], [A, HP]): $-R_{0,1,PS} + \delta(j_1) + \cdots +$

$$= -R_{0,1,PS} + \delta(j_1)\left[\frac{1-\delta^{T+1}}{1-\delta}\right]$$

- ν_1([PS, NC], [R, HP]): $-R_{0,1,PS} + \delta(\sigma_1) + \cdots +$

$$= -R_{0,1,PS} + \delta(\sigma_1)\left[\frac{1-\delta^{T+1}}{1-\delta}\right]$$

$$-R_{0,1,PS} + \delta(j_1)\left[\frac{1-\delta^{T+1}}{1-\delta}\right] = -R_{0,1,PS} + \delta(\sigma_1)\left[\frac{1-\delta^{T+1}}{1-\delta}\right]$$

We get $j_1 = \sigma_1$, and as shown before: $j_1 > \sigma_1$.

- ν_1([PS, NC], [A, MP]): $-R_{0,1,PS} + \delta(l_1) + \cdots +$

$$= -R_{0,1,PS} + \delta(l_1)\left[\frac{1-\delta^{T+1}}{1-\delta}\right]$$

- ν_1([PS, NC], [R, MP]): $-R_{0,1,PS} + \delta(\sigma_1) + \cdots +$

$$= -R_{0,1,PS} + \delta(\sigma_1)\left[\frac{1-\delta^{T+1}}{1-\delta}\right]$$

$$-R_{0,1,PS} + \delta(l_1)\left[\frac{1-\delta^{T+1}}{1-\delta}\right] = -R_{0,1,PS} + \delta(\sigma_1)\left[\frac{1-\delta^{T+1}}{1-\delta}\right]$$

We get $l_1 = \sigma_1$, and as shown before: $l_1 > \sigma_1$.

ν_1([PS, PD1], [A, HP]): $-R_{0,1,PS} + \delta(n_1) + \cdots +$

$$= -R_{0,1,PS} + \delta(n_1)\left[\frac{1-\delta^{T+1}}{1-\delta}\right]$$

ν_1([PS, PD1], [R, HP]): $-R_{0,1,PS} + \delta(\sigma_1) + \cdots +$

$$= -R_{0,1,PS} + \delta(\sigma_1)\left[\frac{1-\delta^{T+1}}{1-\delta}\right]$$

$$-R_{0,1,PS} + \delta(j_1)\left[\frac{1-\delta^{T+1}}{1-\delta}\right] = -R_{0,1,PS} + \delta(\sigma_1)\left[\frac{1-\delta^{T+1}}{1-\delta}\right]$$

We get $n_1 = \sigma_1$, and as shown before: $n_1 > \sigma_1$.

v_1([PS, PD1], [A, MP]): $-R_{0,1,PS} + \delta(p_1) + \cdots +$

$$= -R_{0,1,PS} + \delta(p_1)\left[\frac{1-\delta^{T+1}}{1-\delta}\right]$$

v_1([PS, PD1], [R, MP]): $-R_{0,1,PS} + \delta(\sigma_1) + \cdots +$

$$= -R_{0,1,PS} + \delta(\sigma_1)\left[\frac{1-\delta^{T+1}}{1-\delta}\right]$$

$$-R_{0,1,PS} + \delta(l_1)\left[\frac{1-\delta^{T+1}}{1-\delta}\right] = -R_{0,1,PS} + \delta(\sigma_1)\left[\frac{1-\delta^{T+1}}{1-\delta}\right]$$

We get $p_1 = \sigma_1$, and as shown before: $p_1 > \sigma_1$.

Fig. 2 Methodology

Parameters:

- T: 25 years.
- δ: 0.953 annually.
- kWh_{TC}: 2.400 kWh/year.

- C: 66.47, which is the average commercialization service fee charged by utility companies in 2021 based on Superservicios data[1], brought to present value with inflation data from Banrep[2].
- G: 173.73, which is the average generation price charged by utility companies in 2021 based on Superservicios data, brought to present value with inflation data from Banrep.
- UC: will depend on location, but it is also retrieved from 2021 Superservicios data.
- U_t^{PV}: 470 Wp.
- PR: 0.80 which is widely used in literature.
- NPV: will vary between 0 to 10.
- χ_t: will depend on location, but information from IDEAM-UPME (2022)[3] was used. Review Annex 2 at the end of this document.
- R^{loss}: 0.7% annually.
- DMC_j: is fixed at COP $1,345.326.
- PV_{UC}: COP $ 573,600.
- $Aluminum\ Structure_{UC}$: COP $150,000.
- $Wiring\ and\ accesories_{UC}$: COP $700,000.
- $Insurance$: 0.7% of solar system total cost before $ELCP$.
- $ELCP$: 38% of solar system total cost before $ELCP$.
- $3kW\ Microinverter_{UC}$: COP $1,328,571.
- $Monitoring\ system_{UC}$: COP $1,328,571.
- $Bidirectional\ Meter_{UC}$: COP $394,286.
- $RETIE\ Certification_{UC}$: COP $ 1,000,000.
- $UPME\ Procedures_{UC}$: COP $388,369.

Equations:

1. Payment for net consumers ($NPV = 0$) when there is no P2P energy market: $-\delta UCkWh_{TC}\left[\frac{1-\delta^{T+1}}{1-\delta}\right]$

[1] https://www.superservicios.gov.co/sites/default/files/inline-files/boletin_tarifario_energia_2_trim_2021_1.pdf
[2] https://www.banrep.gov.co/es/estadisticas/inflacion-total-y-meta
[3] http://atlas.ideam.gov.co/visorAtlasRadiacion.html

2. Payment for PD1 prosumers when there is no P2P energy market: $-R_{0,PD1} + \left[\frac{1-\delta^{T+1}}{1-\delta}\right]\left[-UC\left(kWh_{TC} - kWh_{P,PD1}\right) - DMC_{PD1}\right] - \left[\frac{\delta(\delta+(T-1)\delta^{T+1}-T\delta^{T})}{(\delta-1)^2}\right] UCkWh_{P,PD1}R^{loss}$.
3. Payment for PD2 prosumers when there is no P2P energy market: $-R_{0,PD2} + \delta\left[-UCkWh_{TNC,PD2} + (UC - C)kWh_{DN,PD2} - DMC_{PD2}\right]\left[\frac{1-\delta^{T+1}}{1-\delta}\right]$
4. Payment for PS prosumers when there is no P2P energy market: $-R_{0,PS} + \delta\left[G\left(kWh_{DN,1,PS} - kWh_{TNC,1,PS}\right) - CkWh_{TNC,PS} - DMC_{PS}\right]\left[\frac{1-\delta^{T+1}}{1-\delta}\right]$.

Total Social Welfare comparison by nanogrid configuration

Where Paretian and Nash equilibrium are highlighted in light orange.

(NC, PD2)

Consumers	Prosumers	Social Welfare	Prosumer Utility	Consumer Utility
9	1	COP 28,982	COP 26,445	COP 2,537
8	2	COP 58,617	COP 47,538	COP 11,079
7	3	COP 87,953	COP 62,406	COP 25,546
6	4	COP 116,651	COP 70,937	COP 45,713
5	5	COP 146,084	COP 74,023	COP 72,061
4	6	COP 174,475	COP 70,720	COP 103,755
3	7	COP 176,004	COP 53,500	COP 122,504
2	8	COP 124,229	COP 25,172	COP 99,056
1	9	COP 61,971	COP 6,278	COP 55,693

(PD1, PD2)

Consumers	Prosumers	Social Welfare	Prosumer Utility	Consumer Utility
9	1	COP 28,982	COP 26,445	COP 2,537

8	2	COP 58,617	COP 47,538	COP 11,079
7	3	COP 87,953	COP 62,406	COP 25,546
6	4	COP 116,264	COP 70,702	COP 45,562
5	5	COP 134,000	COP 67,901	COP 66,099
4	6	COP 123,895	COP 50,220	COP 73,675
3	7	COP 95,244	COP 28,952	COP 66,292
2	8	COP 63,573	COP 12,882	COP 50,691
1	9	COP 31,570	COP 3,198	COP 28,371

(PD1, PS with 10 PVs)

Consumers	Prosumers	Social Welfare	Prosumer Utility	Consumer Utility
9	1	COP 1,747,033	COP 1,280,592	COP 466,441
8	2	COP 2,655,350	COP 1,917,006	COP 738,343
7	3	COP 2,342,656	COP 1,483,448	COP 859,208
6	4	COP 2,004,849	COP 1,088,050	COP 916,799
5	5	COP 1,674,907	COP 757,407	COP 917,500
4	6	COP 1,338,027	COP 484,000	COP 854,027
3	7	COP 1,003,050	COP 272,101	COP 730,950
2	8	COP 667,558	COP 120,698	COP 546,860
1	9	COP 331,374	COP 29,953	COP 301,421

(NC, PS with 10 PVs)

Consumers	Prosumers	Social Welfare	Prosumer Utility	Consumer Utility
9	1	COP 1,750,169	COP 1,276,797	COP 473,371

8	2	COP 3,504,452	COP 2,129,326	COP 1,375,126
7	3	COP 4,554,710	COP 2,871,454	COP 1,683,256
6	4	COP 3,932,566	COP 2,134,807	COP 1,797,760
5	5	COP 3,281,484	COP 1,484,322	COP 1,797,162
4	6	COP 2,623,404	COP 949,225	COP 1,674,179
3	7	COP 1,967,171	COP 533,790	COP 1,433,381
2	8	COP 1,310,363	COP 237,004	COP 1,073,359
1	9	COP 652,806	COP 59,030	COP 593,776

Consumers	Prosumers	Main grid Consumption (kWh/year)	Nanogrid Consumption (kWh/year)	Nanogrid Generation (kWh/year)	Nanogrid Injection (kWh/year)	Nanogrid Trading (kWh/year)
9	1	19,614	24,349	5,954	1,218	4,736
8	2	15,098	24,349	11,909	2,657	9,252
7	3	15,812	24,349	17,863	9,326	8,537
6	4	17,037	24,349	23,817	16,505	7,313
5	5	18,248	24,349	29,772	23,670	6,102
4	6	19,471	24,349	35,726	30,848	4,878
3	7	20,692	24,349	41,680	38,023	3,657
2	8	21,912	24,349	47,635	45,197	2,438
1	9	23,135	24,349	53,589	52,374	1,215

ANNEX 1: LCOE according to number of PVs

Municipality	Department	LCOE according to number of PVs									
		1	2	3	4	5	6	7	8	9	10
Medellín	Antioquia	COP 1,150.13	COP 634.13	COP 462.14	COP 376.14	COP 324.54	COP 290.14	COP 265.57	COP 247.14	COP 232.81	COP 221.34
Arauca	Arauca	COP 1,079.25	COP 595.06	COP 433.66	COP 352.96	COP 304.54	COP 272.26	COP 249.20	COP 231.91	COP 218.46	COP 207.70
Barranquilla	Atlántico	COP 837.80	COP 461.93	COP 336.64	COP 273.99	COP 236.41	COP 211.35	COP 193.45	COP 180.03	COP 169.59	COP 161.23
Cartagena	Bolívar	COP 897.96	COP 495.10	COP 360.81	COP 293.67	COP 253.38	COP 226.52	COP 207.34	COP 192.95	COP 181.76	COP 172.81
Tunja	Boyacá	COP 1,070.54	COP 590.25	COP 430.16	COP 350.11	COP 302.08	COP 270.06	COP 247.19	COP 230.04	COP 216.70	COP 206.02
Manizales	Caldas	COP 1,323.51	COP 729.73	COP 531.80	COP 432.84	COP 373.46	COP 333.88	COP 305.60	COP 284.39	COP 267.90	COP 254.71
Florencia	Caquetá	COP 1,378.28	COP 759.93	COP 553.81	COP 450.75	COP 388.92	COP 347.69	COP 318.25	COP 296.16	COP 278.99	COP 265.25
Yopal	Casanare	COP 1,031.19	COP 568.56	COP 414.35	COP 337.24	COP 290.98	COP 260.14	COP 238.10	COP 221.58	COP 208.73	COP 198.45
Valledupar	Cesar	COP 944.23	COP 520.61	COP 379.40	COP 308.80	COP 266.44	COP 238.20	COP 218.03	COP 202.90	COP 191.13	COP 181.71
Monteria	Córdoba	COP 1,173.96	COP 647.27	COP 471.71	COP 383.93	COP 331.26	COP 296.15	COP 271.07	COP 252.26	COP 237.63	COP 225.93
Bogotá	Cundinamarca	COP 1,234.84	COP 680.84	COP 496.18	COP 403.84	COP 348.44	COP 311.51	COP 285.13	COP 265.34	COP 249.95	COP 237.64
Puerto Inirida	Guainía	COP 1,239.79	COP 683.57	COP 498.16	COP 405.46	COP 349.84	COP 312.76	COP 286.27	COP 266.40	COP 250.95	COP 238.59
Neiva	Huila	COP 1,071.90	COP 591.00	COP 430.70	COP 350.55	COP 302.46	COP 270.40	COP 247.50	COP 230.33	COP 216.97	COP 206.28
Riohacha	La Guajira	COP 889.42	COP 490.39	COP 357.38	COP 290.88	COP 250.97	COP 224.37	COP 205.37	COP 191.12	COP 180.03	COP 171.17
Santa Marta	Magdalena	COP 922.40	COP 508.57	COP 370.63	COP 301.66	COP 260.28	COP 232.69	COP 212.98	COP 198.20	COP 186.71	COP 177.51
Villavicencio	Meta	COP 1,049.51	COP 578.66	COP 421.71	COP 343.23	COP 296.15	COP 264.76	COP 242.33	COP 225.52	COP 212.44	COP 201.98
Pasto	Nariño	COP 1,332.14	COP 734.49	COP 535.27	COP 435.66	COP 375.90	COP 336.05	COP 307.59	COP 286.25	COP 269.65	COP 256.37
Cúcuta	Norte de Santander	COP 1,122.00	COP 618.62	COP 450.83	COP 366.94	COP 316.60	COP 283.04	COP 259.07	COP 241.09	COP 227.11	COP 215.92
Armenia	Quindío	COP 1,267.46	COP 698.82	COP 509.28	COP 414.51	COP 357.65	COP 319.74	COP 292.66	COP 272.35	COP 256.56	COP 243.92
Pereira	Risaralda	COP 1,184.05	COP 652.84	COP 475.77	COP 387.23	COP 334.11	COP 298.70	COP 273.40	COP 254.43	COP 239.67	COP 227.87
San Andrés	Archipiélago de San Andrés	COP 1,034.79	COP 570.54	COP 415.79	COP 338.42	COP 291.99	COP 261.04	COP 238.94	COP 222.35	COP 209.46	COP 199.14
Sincelejo	Sucre	COP 1,141.47	COP 629.36	COP 458.66	COP 373.30	COP 322.09	COP 287.95	COP 263.57	COP 245.28	COP 231.05	COP 219.67
Ibagué	Tolima	COP 1,069.21	COP 589.52	COP 429.62	COP 349.67	COP 301.70	COP 269.72	COP 246.88	COP 229.75	COP 216.43	COP 205.77
Cali	Valle del Cauca	COP 1,150.79	COP 634.50	COP 462.40	COP 376.35	COP 324.73	COP 290.31	COP 265.72	COP 247.28	COP 232.94	COP 221.47

ANNEX 2: MONTHLY AVERAGES OF MEAN GLOBAL IRRADIATION RECEIVED ON THE SURFACE FOR THE MAIN CITIES OF THE COUNTRY (Wh/m2 PER DAY)

Code	Station	Municipality	Department	Latitude	Longitude	Elevation (m.a.s.l.)	Entity	Annual Average	Years of Information	Start Date	End Date
0027015070	Apto. Olaya Herrera	Medellín	Antioquía	6.22	-75.58	1490	IDEAM (conv.)	4335.1	10	ene-85	jun-97
0037055010	Apto. Santiago Perez	Arauca	Arauca	7.07	-70.73	128	IDEAM (conv.)	4619.8	4	ene-86	ene-92
0002904512	Las Flores	Barranquilla	Atlántico	11.04	-74.82	2	IDEAM (aut.)	5951.2	6	nov-09	dic-14
0014015020	Apto. Rafael Nuñez	Cartagena	Bolívar	10.43	-75.50	2	IDEAM (conv.)	5552.5	7	feb-90	dic-00
0024035130	UPTC	Tunja	Boyacá	5.55	-73.35	2690	IDEAM (conv.)	4657.4	6	ene-95	dic-01
0026155230	E.M.A.S.	Manizales	Caldas	5.09	-75.51	2207	IDEAM (aut.)	3767.2	10	may-05	dic-14
0044035050	Macagual - Florencia	Florencia	Caqueta	1.50	-75.66	257	IDEAM (aut.)	3617.5	10	jul-05	dic-14
0003521502	Apto. Yopal	Yopal	Casanare	5.32	-72.38	330	IDEAM (aut.)	4835.1	5	nov-09	dic-14
0028035060	Fedearroz	Valledupar	Cesar	10.46	-73.25	184	IDEAM (aut.)	5280.4	10	sep-05	dic-14
	Monteria	Monteria	Córdoba	8.81	-75.85	17	FEDEARROZ	4247.1	4	oct-11	abr-14
0021205791	Apto. Eldorado	Bogotá	Cundinamarca	4.71	-74.15	2541	IDEAM (conv.)	4037.7	23	mar-81	dic-04
	Inirida	Puerto Inirida	Guainia	4.02	-67.67	90	IDEAM (SUTRON)	4021.6	4	feb-97	sep-02
0021115020	Apto. Benito Salas	Neiva	Huila	2.93	-75.28	439	IDEAM (conv.)	4651.5	14	mar-90	ago-03
0015065010	Apto. Almirante Padilla	Riohacha	La Guajira	11.52	-72.92	4	IDEAM (conv.)	5605.8	17	sep-91	mar-14
0000150150	Univ. Tecnológica de Magdalena	Santa Marta	Magdalena	11.22	-74.19	7	IDEAM (aut.)	5405.4	7	ago-07	dic-14
0035035020	Apto. Vanguardia	Villavicencio	Meta	4.15	-73.62	423	IDEAM (conv.)	4750.7	14	ene-90	dic-14
0052055210	Botana	Pasto	Nariño	1.16	-77.28	2820	IDEAM (aut.)	3742.8	10	may-05	abr-03
0016015010	Apto. Camilo Daza	Cúcuta	Norte de Santander	7.92	-72.50	250	IDEAM (conv.)	4443.8	12	sep-89	nov-13
0026125290	Armenia	Armenia	Quindío	4.53	-75.69	1458	IDEAM (aut.)	3933.8	10	dic-05	nov-96
0026135040	Apto. Matecaña	Pereira	Risaralda	4.80	-75.73	1342	IDEAM (conv.)	4210.9	7	oct-90	oct-13
0017015010	Apto. Sesquicentenario	San Andrés	San Andrés y Providencia	12.58	-81.70	1	IDEAM (conv.)	4818.3	3	ene-01	dic-14
0025025270	Unisucre (Puerta Roja)	Sincelejo	Sucre	9.20	-75.39	221	IDEAM (aut.)	4368.0	10	may-05	dic-99
0021245040	Apto. Perales	Ibagué	Tolima	4.42	-75.13	928	IDEAM (conv.)	4663.2	9	nov-89	dic-14
0002605507	Univalle	Cali	Valle del Cauca	3.38	-76.53	992	IDEAM (aut.)	4332.6	9	nov-06	dic-14