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ENERGYAUCTION: DESIGN AND IMPLEMENTATION OF PEER-TO-PEER ENERGY TRADING PLATFORM IN A MICROGRID

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Dedicatoria . . .

A mi familia por haberme inclucado desde temprana edad en lo valórico, sin duda es gran parte de lo que soy hoy como persona. A mis amigos por momentos distendidos y de confianza, a partir de los cuales pude desarrollar nuevas habilidades, emociones y pensamientos. A mis profesores y a la universidad por convertirse un hogar donde pude encontrar desafíos profesionales, pero también espacio para crecer como persona. Especialmente al profesor Mohamed Abdelhamid por estos últimos semestres que hemos compartido, sin duda una de las razones por las que decidí perseguir este postgrado tuvieron que mucho por contar con su apoyo incondicional, en temas de investigación, pero también de crecimiento como persona.

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ABSTRACT

The widespread adoption of distributed energy resources (DERs) has led to the development of various smart grid applications and services. The internet-of-things (IoT) and cloud computing have enabled the efficient management of energy consumption in households. In this context, this thesis presents a peer-to-peer (P2P) energy trading platform for local energy trading among prosumers and consumers in a microgrid. The platform consists of an IoT-Cloud home energy management system (HEMS) for collecting and storing energy consumption data and a blockchain architecture that enables secure and transparent energy trading. The proposed IoT-blockchain architecture is implemented using a private Ethereum blockchain network and a Chainlink oracle network. Smart contracts enable prosumers and consumers to trade energy in an open auction while requesting external energy data from an API through the oracle network for the settlement process. The performance of the platform is evaluated through a testbed scenario using real-world energy data, validating the feasibility of the proposed architecture in enabling local energy trading. This work contributes to the growing body of research on energy management systems by providing a real-world implementation of an IoT-blockchain architecture for local energy trading. The integration of these technologies allows for a more efficient and secure energy trading system that can benefit prosumers, consumers, and utilities in a microgrid. Overall, this work highlights the potential of IoT and blockchain technologies in enabling sustainable and efficient energy management practices.

RESUMEN

En la actualidad, muchos hogares están adoptando recursos energéticos distribuidos (DER), como sistemas fotovoltaicos solares (PV) y sistemas de almacenamiento de energía con baterías (BESS) que permiten a cada hogar generar y consumir energía. Los avances en el Internet de las cosas (IoT) y la computación en la nube abrieron nuevas oportunidades para el desarrollo de diversas aplicaciones y servicios de redes eléctricas inteligentes. La creciente adopción de dispositivos IoT ha permitido el desarrollo de aplicaciones y soluciones para gestionar el consumo de energía de manera eficiente. El comercio de energía local es una nueva forma de gestión del comercio de energía entre productores y consumidores en el sistema de distribución de energía, lo que permite la venta de energía excedente de forma local. Este trabajo presenta una plataforma de comercio de energía P2P que se compone de un sistema de gestión de energía doméstica (HEMS) IoT-Cloud para recopilar y almacenar datos de consumo de energía y de una arquitectura blockchain que permite el comercio de energía local entre hogares inteligentes en una microred. El enfoque principal es la interacción entre redes distribuidas P2P, como blockchain y las redes oráculo. La implementación de la arquitectura propuesta IoT-blockchain consiste en una red blockchain Ethereum privada y una red oráculo de Chainlink. Los contratos inteligentes permiten a los productores y consumidores comerciar energía en una subasta abierta mientras solicitan datos de energía externos de una API a través de la red oráculo para el proceso de liquidación. El aporte principal de este trabajo es la integración de estas tecnologías en una implementación real, lo que permite la validación de la posibilidad de ofertar o demandar energía en una microred. Además, se presenta una descripción detallada de la implementación y los resultados obtenidos. Se espera que este trabajo sirva como base para futuras investigaciones en el campo de la gestión de energía distribuida y el comercio de energía local.

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1 | Introduction

Traditional power grids were designed decades ago to transport electricity from major central power plants to individual homes. Nowadays, there are many changes in the way we produce, manage, and consume electricity as a result of the integration of various technologies such as distributed energy resources (DERs), electric vehicles (EVs), advanced metering infrastructures (AMI), and home energy management systems (HEMS)[1]. Currently, many end-users are transitioning from consumers to prosumers of energy. Energy prosumers can produce and consume energy simultaneously. Energy prosumers and consumers can connect with one another and trade energy locally in a microgrid (MG) through a marketplace during instances of mismatch between supply and demand. [2].

When prosumers have surplus electricity, they can store it with energy storage systems (ESS), export it back to the power grid, or sell it to other energy customers. Direct energy trading among consumers and prosumers is called peer-to-peer (P2P) energy trading [3]. This structure allows surplus energy from small-scale DERs to be exchanged locally in a microgrid, benefiting all parties involved, including consumers, prosumers, and the distribution system operator (DSO). Peer-to-peer energy trading improves the benefits of all consumers and prosumers by facilitating a local energy balance [4].

The technology to enable smart grid applications, such as energy trading within a microgrid, relies heavily on the use of the internet-of-things (IoT). IoT technology can be used for monitoring and controlling various devices such as sensors, actuators, and metering devices [5, 6, 7, 8]. Such integrations are found in HEMS, which facilitates users' operation and management of household appliances and DER, as well as participation in P2P energy trading. To enable a microgrid application such as trading within a microgrid, it is necessary to collect the energy consumption and/or generation of a house. The usage of this data serves as a key element to enable the implementation of various applications, such as energy trading [9, 10]. In general, four layers compose the P2P energy trading market: power grid layer, information and communication technology (ICT) layer, control layer, and business layer [11]. There have been several projects up to date that have been carried out as energy trading pilots. Among these projects: Piclo in the United Kindom, Tranactive Gride and Brooklyn Microgrid in the US, Peer Energy Cloud in Germany, and Powerledger in Australia [12, 13].

Blockchain technology has been gaining attention in non-cryptocurrency related research, such as the integration of heterogeneous IoT systems with the energy market, with features such as data privacy, cybersecurity, and reliability [14]. Research conducted by PricewaterhouseCoopers (PWC) and Deloitte, has commented on the impact of blockchain technology for enabling the backbone of the transactive energy infrastructure for supply and demand applications [15, 16].

This combination of IoT technology and blockchain technology has been covered in [17], where digitalization and decentralization are stated as the key enablers for a transactive energy internet (EI). To provide a visual representation of the interaction between micro-grids, distributed peer-to-peer networks, and cloud-based services, a schematic diagram is presented in Figure 1.1. This diagram illustrates the main components of the study, including the relationships and interactions between these entities. The microgrid is a modern and innovative energy system that involves various parties, including electric vehicles (EV), photovoltaic systems (PV), energy storage systems (ESS), prosumers, consumers, and utilities, which interact by exchanging both energy and data. In this context, cloud-based services, such as the application programming interface (API), provide access to valuable energy consumption and generation data. Additionally, distributed peer-to-peer networks, such as blockchain networks, can store energy transactions through a distributed ledger. Another P2P network, Oracle Networks, serves as a gateway to retrieve data from cloud-based services, such as using available APIs, and route it to blockchain-based services. Figure 1.1 serves as a guideline for the particular technologies and related research fields that are covered in this thesis. This thesis presents a novel P2P energy trading platform composed of IoT and blockchain in the context of microgrids.

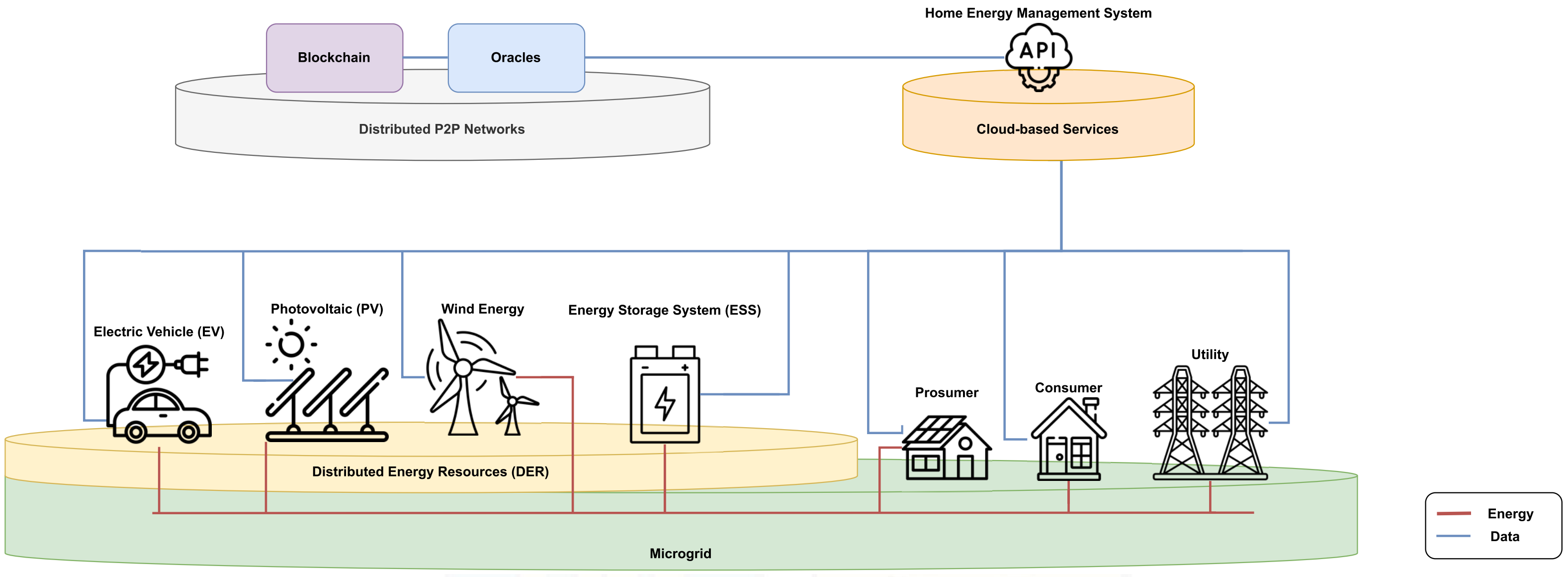

Figure 1.1: Schematic diagram of microgrid with distributed P2P networks and cloud-based services interaction.

1.1 Hypothesis

The hypothesis of this research aims to develop and implement a peer-to-peer energy trading platform in a microgrid. Such local P2P energy trading system should consider two key elements: an IoT cloud-based system and a blockchain network. The IoT cloud-based system is required to enable the collection and management of smart meter energy data. The blockchain component ensures immutability within the distributed ledger, which sets the ground for smart contracts to handle the energy trading logic. Using these elements, a P2P energy trading platform in a microgrid can be accomplished, enabling them to trade in a trusted P2P scheme driven by smart meter data. The proposed local energy trading system can be analyzed from three different perspectives:

- *Energy Data Acquisition:* The energy data acquisition from DER and smart meters is part of the IoT HEMS architecture, it represents the digitalization element in energy trading, from which energy data is used to enable energy trading applications. Such architecture may enable other applications which present a system scalability benefit for future applications.

- *Energy Trading Infrastructure:* The energy trading infrastructure is enabled by blockchain technology, as part of the decentralization element of energy trading. It enables the business logic for energy trading applications, the decentralized network from where users transact in a decentralized manner, and external networks from where off-chain data is brought. Additional components may be built to improve the energy trading system, such as demand response mechanisms.

- *Energy Trading Market Model:* A proper model definition for allowing consumers and prosumers to trade in a microgrid. The model should consider elements such as value proposition, the number of participants, and operation conditions.

1.2 Objectives

- Design and implementation of peer-to-peer energy trading platform using IoT cloud-based blockchain systems for trading surplus energy in a microgrid.

Specific Objectives:

1. Develop an IoT cloud-based architecture to collect and store peer-to-peer energy trading data from smart meters.
2. Develop a blockchain infrastructure that handles the auction business logic on smart contracts and stores energy transactions in a distributed ledger.
3. Implement the energy trading platform in a laboratory environment to trade energy among two participants in a microgrid.

1.3 Methodology

The methodology to meet the objectives stated above consists of the following steps:

1. Study related work and solutions reported in the state-of-the-art regarding energy trading systems, IoT, cloud-based systems, blockchain, smart contracts, and oracles.
2. Define components and entities for the IoT cloud-based infrastructure by providing an architecture following the required layers.
3. Deploy cloud-based and blockchain infrastructures to enable peer-to-peer energy trading services that rely on these dependencies.
4. Model entities and define business logic for the energy trading system and implement them in smart contracts.

5. Implement a testbed and a validation scenario in a laboratory environment to analyze the outcome of the proposed system.

For Specific Objective 1: IoT cloud-based architecture for energy monitoring

1. Study state-of-the-art on testbed implementations for energy data acquisition in smart homes.
2. Propose an IoT cloud-based architecture that enables the energy data collection from smart meters.
3. Implement an IoT framework for collecting energy measurements.
4. Deploy required databases and cloud-based services for storing and managing energy data from IoT devices.

For Specific Objectives 2 & 3: Blockchain-based energy trading system

1. Study and compare different blockchain architectures and implementations for energy related applications.
2. Identify the main entities that interact in the peer-to-peer energy trading system.
3. Deploy and configure IoT cloud-based architecture and blockchain architecture into a common system.
4. Design and implement smart contracts for energy trading logic and oracle to manage smart meter data.
5. Define and execute use cases for validating the proposed peer-to-peer energy trading system.
6. Analyze and validate results.

1.4 General Structure of the Document

The present document is divided into six chapters. The first Chapter introduces the research subject, gives an inside into the related work, and presents the general and specific objectives, the hypothesis, and the methodology to follow. On the other hand, in Chapter 2, the fundamentals of energy trading and its enabling technologies such as IoT and blockchain are presented. These two chapters represent the theoretical background for the development of the thesis. Chapter 3 presents the proposed IoT architecture and the developed HEMS system for energy data collection and storage in an IoT-Cloud System. In Chapter 4 the blockchain network orchestration and sub-components are presented and discussed. To sum up, Chapter 5 presents the conclusions and future work.

2 | Related Work

The concept of energy internet (EI) uses internet technology to achieve coordinated control of a large number of DER, ESS, and loads on the basis of compatibility with traditional power systems. EI presents a virtuous relationship among various entities, such as energy producers and end consumers. When these entities trade with one another, they are defined as a local energy market (LEM), which aims to incentive energy exchange between them in a competitive market, balancing supply and demand locally [18]. The two key enablers for energy trading in a LEM are digitalization and decentralization, which envision a digital energy world with decentralized smart things to maximize producer and consumer interaction, optimize the balancing of supply and demand, and minimize the carbon footprint [17]. In this chapter, digitalization, decentralization, and energy market design will be presented in sections, 2.1, 2.2, and 2.3 respectively.

2.1 Digitalization: IoT and Home Energy Management Systems

In an effort to introduce greater intelligence and reinforce automation within prevailing energy systems, innovative digital devices and sophisticated smart technologies are being deliberately created and implemented across numerous fields. Digital technologies have become omnipresent on a global scale. The digital revolution foresees a transformative epoch in the realm of energy, possessing immense potential to dissolve barriers among energy sectors, enhance adaptability, and promote comprehensive integration throughout the entire infrastructure [19].

IoT is serving as the foundational framework for digital energy systems, facilitates the seamless integration of diverse hardware and software, networks and platforms, as well as services and applications. The IoT architecture, which effectively establishes a closed-loop structure from things-based perception to energy-based automation, is capable of precisely delivering data and energy flows to the right locations, at the right times, and with minimal costs, thanks to its inherent capabilities. This digitalization process acts as a key enabler for energy trading, fostering efficient resource allocation and streamlined operations in modern energy systems [17].

The use of IoT will allow any smart device, also known as the “things” to interact with one or several sensors and other devices in the network, forming a wireless sensor network (WSN). This WSN can rely on a gateway for internet connection, allowing the implementation of different applications based on the collected data [20].

Home energy management systems (HEMS) aim to improve efficiency by providing control of smart home appliances, and this is feasible due to the use of the internet-of-things (IoT) [21]. HEMS rely on smart sensors, appliances, and advanced metering infrastructure (AMI) to achieve continuous monitoring. Authors in [20] presented a survey on the concepts, technical background, architectures, and infrastructures, among other challenges and issues regarding HEMS. The HEMS follow some baseline features, such as monitoring of the main load of the property, individual loads of appliances, and control of appliances. Regarding the components that comprise a HEMS, such a system consists of sensing and measuring devices, smart appliances, a user interface, and a central platform [22].

2.1.1 IoT and HEMS Architectures

In the literature, many multi-layer architectures were defined to construct the IoT-enabled HEMS. Detail information could be found in [17, 20, 23, 24]. The five-layer architecture is commonly the one that presents a granular overview of each core element. Starting from the bottom and moving upward, the layers found are presented in Figure 2.1.

The physical things layer is the first layer, consisting of energy devices on both the supply and demand sides. This layer is where energy transactions actually occur. Data is gathered from both sides, forming a data flow that is sent to the upper layer. After processing, computing, and managing the data in each subsequent layer, control signals are produced and returned to the first layer for distributed automation.

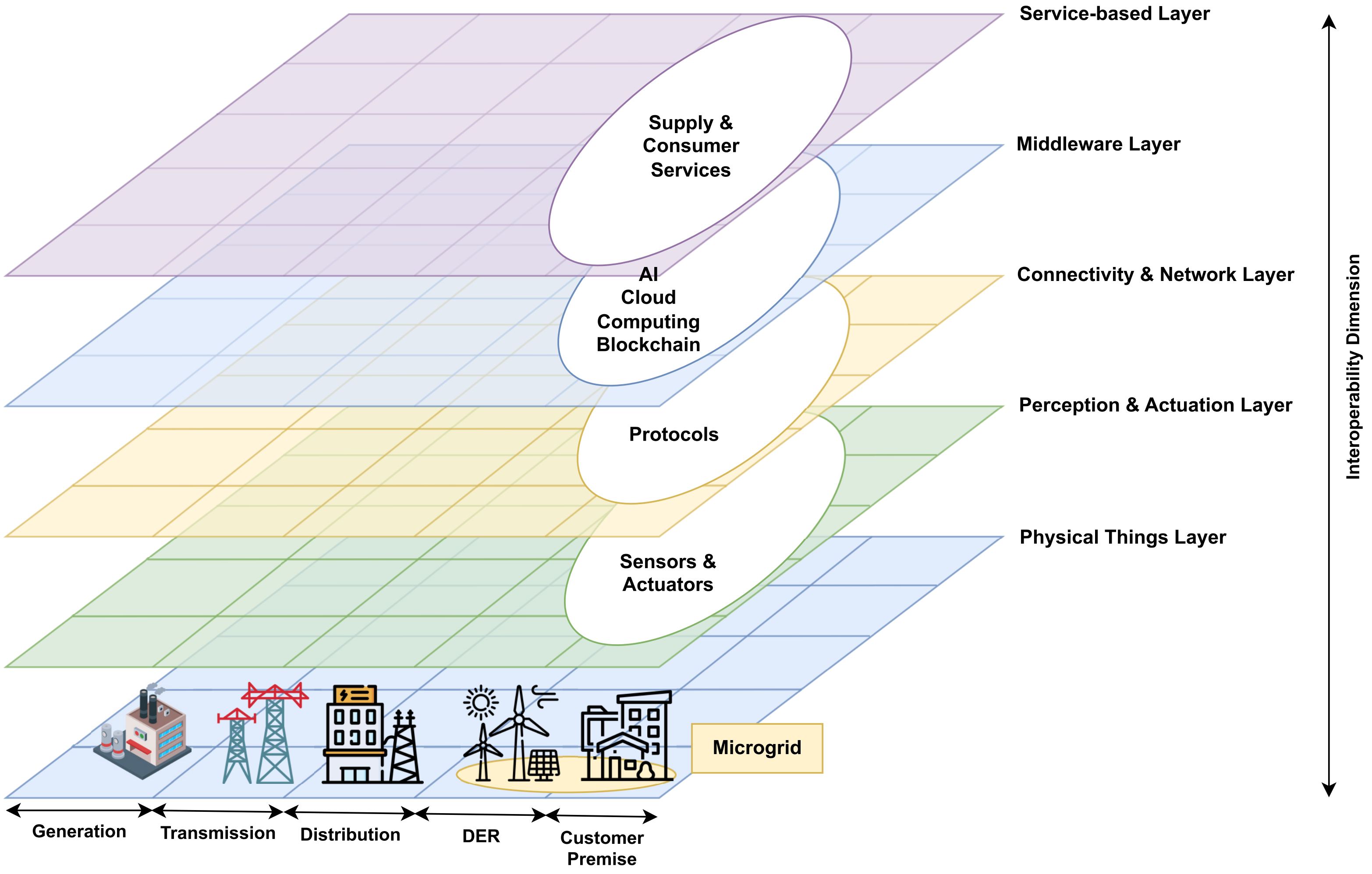

Figure 2.1: IoT-enabled architecture

The perception and actuation layer is the second layer, responsible for the comprehensive sensing of energy supply and demand through sensors across various energy sectors, as well as precise control by actuators.

The connectivity and network layer is the third layer, which ensures the integration and communication of different networks, such as wired field networks (e.g., IEEE 802.3 family, power line communication, and serial communication RS-232/485), wireless field networks (e.g., IEEE 802.11 family, IEEE 802.15 family), mobile field networks (e.g., GSM-based 2G, CDMA-based 3G, LTE-based 4G, and NR-based 5G), and low-power networks (e.g., NarrowBand IoT, LoRa, and Sigfox).

The middleware layer is the fourth layer, which serves as the intermediary bridge that facilitates interaction between IoT devices and cross-domain applications. This layer has high requirements, such as architecture abstraction, function management, programming design, and implementation. Typical solutions include VM-based (MagnetOS, TinyVM), database-based (SINA, TinyDB), service-based (LinkSmart, SenseWrap), application-specific (FIWARE, AutoSec), and fog node-based (EMCP, eclipse kura). The middleware layer not only simplifies the complexities of the lower layers but also offers data services for the upper layers, enabling them to achieve their functional goals with ease. As such, the middleware layer presents the greatest design challenge, being application-independent and primarily focused on data. It must take into account functional requirements like data management, storage, and processing (big data analysis, real-time data analysis, deep data analysis with AI), as well as non-functional requirements like scalability, security, availability, reliability, real-time capabilities, privacy, and more. When these data-centric services are integrated with IoT in the middleware layer, they can be referred to as Big Data-of-Things, Cloud-of-Things, and AI-of-Things.

The service-based layer is the fifth layer, which encompasses energy-aware services or applications from both supply and demand sides. This layer allows for extensive communication between both sides at the cloud level and achieves interoperability of cross-domain applications. In this layer, energy is not just a commodity; it is also enhanced, customized, and made more intelligent to better meet the diverse and dynamic needs of various stakeholders in the Energy Internet. Examples include improving energy efficiency, increasing the penetration of renewables, optimizing energy management, automating demand response, and balancing supply and demand in a more flexible manner.

2.1.2 Surveys and Pilots

Authors in [25] analyzed several IoT applications for smart grids, such as smart homes, smart metering, and energy management, among others. Challenges, issues, and future research regarding the use of IoT to enable Energy Internet (EI) applications were also discussed. A smart home incorporates various IoT-based smart technologies with the goal of providing security, convenience, comfort, energy efficiency, and entertainment which results in improving the quality of life within a residence. Ambient assisted living service, smart energy management technology service, and security are the predominant technology services associated with smart homes [26].

In [27], the authors presented an overview of IoT-enabled energy systems. Some of the outlined challenges include mapping every object into a unique virtual object which can be addressed with standard communication protocols. The authors also stated that given the variety of design decisions made by the system designers, there are different architectures to enable an IoT-based energy system, which implies that there is no unified architecture. In [28], the authors presented a smart load node (SLN) for enabling non-smart home appliances to operate efficiently in a smart grid paradigm. SLN is an innovative solution given that it does not require any modifications in the electrical wiring of a house, nor any modification on the appliances. SLN integrates within a HAN with other devices, such as smart meters and a load management unit (LMU), which enable various smart grid applications within a house, such as scheduling loads in a demand–response (DR) scheme. Authors in [20] presented a novel methodology including the concept of green building in order to reduce energy consumption. A key element stated by the authors is not only regarding the energy efficiency for appliances and at home but also to create awareness among residents on power conservation.

Authors in [21] presented a survey on HEMS which provides an aggregated and unified perspective on residential buildings. An overview of the literature on commonly managed household appliances was also presented.

Authors in [29] described the building operation data, which includes electricity consumption and environmental measurements. The work provided information regarding the architecture of the system, which utilizes EMU, smart meters, and sensors for collecting the data. The data include one-minute interval measurements from 1 July 2018 to 31 December 2019 which are provided to support a variety of data-driven applications.

The authors in [30] , introduced Plug-Mate, an IoT-based occupancy-driven plug load management system. Plug-Mate was able to deliver occupancy information, plug load type, and plug load usage preference. The solution was tested during a 5-month study in a university office with 10 participants. Results showed about 51.7% in the overall energy saving improvement among different plug loads and about 7.5% reduction in the building overall energy consumption.

Due to the services provided by public clouds, there has been an increasing interest in developing data-driven applications. Some of the data-driven applications that can be implemented in the context of a smart home are alarms on irregular load scenarios and scheduling the use of appliances in case of dynamic tariff systems. In [31], the authors presented a comparison between three cloud platforms: Amazon, Google, and Microsoft.

MQTT messaging was used by IoT devices to send information to the cloud platforms, where a performance evaluation was carried out, not to benchmark the maximum message throughput, but rather to measure the service time of the provided message broker. Cost comparison and description of available tiers were also discussed.

Authors in [32] developed a demand response (DR) application on a HEMS in order to reduce utility operational costs and the consumer energy bill price. The proposed infrastructure by the authors is based on an edge–fog–cloud computing architecture, which allows for monitoring and control of residential loads. The testbed was carried out using Raspberry Pi as the HEMS and NodeMCU ESP8266 as smart plugs for energy-related measurements and controlling tasks. Results showed that the proposed system was able to schedule loads and reduce the energy bill when compared to the scenario without the DR algorithm. The proposed testbed scenario considered a dynamic tariff system. Another energy management system (EMS) was proposed by authors in [33], where a system was implemented at the IoT Microgrid Laboratory at Aalborg University. The IoT-based EMS showed the feasibility of using IoT devices to regulate consumption. Features, such as energy management using load priority, were presented in the results.

Authors in [34] presented a cloud-based platform that collects electricity consumption, indoor climate, and occupancy data in real-time using sensors. The energy monitoring platform was implemented in a smart villa. The architecture showed the devices' interaction over a star topology. The system utilizes ThinkEE, a cloud platform for connecting IoT devices. It also provided a web interface for data display and an energy management system for energy control. In [35], the authors released I-BLEND, a 52-month electrical energy dataset at a one-minute sampling rate from commercial and residential buildings of an academic institute campus. The data collection of the system was carried out using a Raspberry Pi to collect measurements from smart meters, while also using the cloud for data storage and processing.

Although previous research provided information on how to implement IoT-based HEMS and how to apply data-driven algorithms, such as demand response and load schedule, most of the solutions were implemented in a laboratory environment that does not represent the actual condition of a smart home. This work aims to fill the knowledge gap by providing a detailed description of the technical implementation of how to design and implement a HEMS that can be used for different applications. Two architectures are considered for local/cloud implementation using available IoT devices while deploying the system on a public cloud. Table 2.1 shows the comparison among previous research work.

Table 2.1: Comparison among previous research work for EMS.

REF.	YEAR	TYPE	DESCRIPTION
[21]	2020	Survey	A survey on home energy management including main goals for operation and target strategies
[22]	2021	Survey	Comprehensive study of IoT business applications and smart energy systems
[36]	2018	Technical/ Simulation	P2P energy trading was designed and simulated for energy trading among prosumers and consumers in a microgrid
[37]	2014	Technical/ Simulation	Energy trading among prosumers in a microgrid to increase the utilization of renewable energy
[25]	2019	Survey	Comprehensive survey on IoT applications for smart grid and smart environments
[26]	2021	Review	Literature review on smart home adoption including motivations, barriers, and risks
[27]	2018	Review	Review on IoT-based energy system with respect to features, specifications, communication infrastructures, and privacy
[28]	2019	Technical/ Implementation	Design and implementation of a low-cost smart load node for monitoring and control non-smart residential load
[20]	2022	Review	Comprehensive review for home energy management system with respect to concepts, architecture infrastructure, and challenges
[31]	2020	Technical/ Simulation	Performance analysis among three different Cloud-IoT platforms services for Amazon web service, Microsoft Azure, and Google Cloud
[32]	2021	Technical/ Implementation	IoT-based infrastructure on edge–fog–cloud architecture to monitor and control residential loads to support demand response
[33]	2019	Technical/ Implementation	IoT-based infrastructure for EMS. The system has been tested in a pilothouse named IoT Microgrid Living Lab, Denmark
[34]	2019	Technical/ Implementation	Energy monitoring platform to collect real-time electricity consumption data in a smart villa, Doha Qatar
[29]	2020	Technical/ Implementation	Detailed building operation data (electricity consumption and indoor environment) of seven-story building in Bangkok, Thailand
[35]	2019	Technical/ Implementation	Electrical energy dataset (52 months) from commercial and residential building at one minute sampling rate, India
[30]	2022	Technical/ Implementation	IoT-based plug load management system capable of providing occupancy and energy consumption information for smart building, Singapore
This work	2023	Technical/ Implementation	Design and implementation of two HEMS architectures (local vs. cloud) in a real household environment located in Valparaiso, Chile

2.2 Decentralization: Blockchain Technology

The accelerated growth of renewable energy resources and the rising adoption of distributed power generation are transforming the energy sector. Peer-to-peer (P2P) energy trading has surfaced as an innovative solution, empowering prosumers and consumers to engage in energy trading in a more adaptable, efficient, and decentralized manner [37, 36]. Blockchain technology, characterized by decentralization, transparency, and immutability, offers an ideal foundation for building P2P energy trading platforms [38].

Blockchain technology facilitates a secure and reliable environment for executing the business logic and allowing participants in energy trading to interact. It creates transparent and tamper-proof records of energy transactions, ensuring that both producers and consumers can trust the system without relying on intermediaries [39]. This decentralized trust model, along with the ability to automate processes through smart contracts, has the potential to revolutionize energy trading and distribution [40].

Numerous recent studies and projects have emphasized the potential of blockchain technology in facilitating P2P energy trading. For instance, authors in [41] propose a decentralized framework for coordinating energy supply and demand in a local market using blockchain and smart contracts. These works illustrate that blockchain technology is a natural facilitator for implementing the business logic and bringing energy trading participants together for interaction. As the energy sector continues to progress, the adoption of blockchain-based solutions is expected to rise, laying the foundation for a more decentralized and efficient energy landscape.

General elements in an IoT blockchain-enabled system consider network selection & configuration, consensus mechanism, privacy and network acess, smart contracts, and oracle networks. These atributes are presented in Figure 2.2 and discussed as follows.

2.2.1 Blockchain Network Design

Blockchain Network Selection: Choosing the right blockchain network is essential for the success of an energy trading platform. There are several networks available, each with its unique features and characteristics. Ethereum (ETH), Hyperledger Fabric, Avalanche, and


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