Cleaner Engineering and Technology 21 (2024) 100783

Contents lists available at ScienceDirect

Cleaner Engineering and Technology

journal homepage: www.sciencedirect.com/journal/cleaner-engineering-and-technology

Analysis of IoT technologies suitable for remote areas in Colombia: Conceptual design of an IoT system for monitoring and managing distributed energy systems

Ramón Fernando Colmenares-Quintero [a,*], Marieth Baquero-Almazo [a], Damian Kasperczyk [b], Kim E. Stansfield [c], Juan Carlos Colmenares-Quintero [a,d]

[a] Engineering Research Institute, Universidad Cooperativa de Colombia, Medellín, Colombia
[b] Ekoinwentyka Ltd., Ruda Śląska, Poland
[c] VOCATE Ltd., Worcester, UK
[d] Institute of Physical Chemistry, Polish Academy of Sciences, Warsaw, Poland

ARTICLE INFO

Keywords:
Internet of Thing
Remote monitoring
Non-interconnected zone (NIZ)
Smart networks
Smart energy systems
Sustainable development goals (SDGs)

ABSTRACT

This study presents a conceptual design of an Internet of Things (IoT) communication system for monitoring power generation systems in Colombian Non-Interconnected Zones (NIZs), which lack IoT connectivity due to complex geographical factors. The proposed system aims to ensure the proper operation and energy efficiency of off-grid systems while tracking the variables that influence their performance.

The methods used in this study include identifying the needs of such a system, identifying requirements, obtaining technical specifications, and developing a conceptual design. The study also analyses and compares various technologies, including Wi-Fi, Bluetooth, LoRa and ZigBee, to determine which ones are best suited for IoT system design.

The conceptual design of the proposed IoT monitoring system considers the geographical, communication and coverage characteristics of the NIZs and the technical characteristics of the energy projects to provide a complete functional system that can connect approximately 2 million people located in these isolated and vulnerable zones. Finally, the defined system can serve as a precedent for building prototypes in various NIZs, and research on IoT technologies suitable for NIZs can help us seek the technologies that are most suitable for these areas. Depending on the application and conditions of the energy project, the most appropriate technology can be determined on a case-by-case basis.

1. Introduction

Colombia's Non-Interconnected Zones (NIZs) cover 53% of the national territory. To date, there are 1762 non-interconnected localities in the territory, where there are 403,000 homes, approximately 2 million people in NIZs (IPSE, 2023). These areas grapple with significant social, economic, and environmental challenges owing to their limited and undignified access to electricity.

Recognizing electricity's pivotal role in daily, production, and economic activities (Barnes, 2019), the prevalent use of polluting diesel energy and, to a lesser extent, non-conventional renewable energy sources (NCRE) in these areas has proven unsustainable. As highlighted by (Dávila Rueda, 2022) renewable energy projects in NIZs often operate for less than one year and one of the most relevant causes of this is the lack of relationship of the habitants with these projects and the poor maintenance and management skills of these projects once they are installed. In this way, renewable energy solutions provided to NIZs are prone to damage, maintenance, lack of efficiency and quality, among others, which if not handled promptly can result in days without service or total damage to the solution.

An alternative for the management and monitoring of these isolated solutions is the use of the Internet of Things, concepts such as smart cities, smart transport, smart grids, and smart systems have emerged. In the energy sector, great advances have been developed through the IoT that makes it possible to manage and monitor certain electrical variables, as well as to improve energy efficiency or optimise energy expenditure and production. And relating to other technologies such as

* Corresponding author.
E-mail address: ramon.colmenaresq@campusucc.edu.co (R.F. Colmenares-Quintero).

https://doi.org/10.1016/j.clet.2024.100783
Received 22 November 2023; Received in revised form 2 May 2024; Accepted 16 July 2024
Available online 18 July 2024

Nomenclature

Acronyms

IoT	Internet of Things
NIZs	Non-Interconnected Zones
SDGs	Sustainable Development Goals
IPSE	Institute for the Planning and Promotion of Energy Solutions
NCRE	Non-Conventional Renewable Energy Sources
UHF	Ultra High Frequency
WPAN	Wireless Personal Area Network
WLAN	Wireless Local Area Network
LPWAN	Low Power Wide Area Network
GSM	Global System for Mobile Communications
Wi-Fi	Wireless Fidelity
LoRa	Long Range
LoRaWAN	Long Range Wide Area Network

Artificial Intelligence, Neural Networks and Big Data, makes possible a deeper management of energies, generating alerts and predictions of diverse types (Abbas et al., 2020; Paul and Hati, 2023; Said et al., 2020).

At a general level, energy monitoring and management is important, but at the NIZs level it is vital. These isolated and vulnerable areas see their daily activities intricately tied to the presence or absence of electricity. The identification of system failures and obtaining necessary repairs or replacements involves a prolonged and costly process, often spanning years (IPSE, 2022).

In this sense, the complex process can be avoided if initially there is a good relationship of the inhabitants with the solution and a good management and monitoring of the energy project remotely connected with experts, this monitoring would allow predicting moments of failure, generating alerts and reports and identifying production patterns that would extend the lifetime of the energy generation system and its components and allow for greater efficiency or optimisation.

This research contributes to this discourse by conducting an analysis and comparison of applicable technologies in isolated and vulnerable territories. The focus is on intelligent energy monitoring systems tethered to a high-level Monitoring Centre, with the goal of realizing environmental, social, and economic justice through the application of IoT technologies.

This paper is organised as follows: Section 2 presents a theoretical review of the specific topics to be addressed in the paper and includes a review of similar works that deal with IoT systems in the energy sector or variable measurement. Section 3 presents the methodology implemented for the development of the IoT system. Section 4 presents the results, followed by the discussion in section 5, both sections present the findings of the study. Finally, section 6 includes the conclusions of the study and proposed future work.

2. Background

The Internet of Things (IoT) is a concept that revolves around the massive digital interconnection between objects and the Internet to share, store and process data (Alansari et al., 2018). In fact, the IoT is advanced technology that allows users and systems to be always connected to an infinite number of devices from any point (Shafique et al., 2020).

In this way, there are different technologies that enable communication between objects, differing in terms of power consumption, data transfer capacity, range, protocol, topologies, and applications. Determining the superiority of one technology over another is inherently challenging, given the variability in location, application, context, and other influencing factors. The assessment of the most appropriate technology becomes imperative under these diverse considerations. For this research, several wireless technologies were studied, such as: Wi-Fi, Bluetooth, GSM, 4G, ZigBee, LoRa, Z-wave, etc. From this preliminary search, four technologies were chosen (Wi-Fi, Bluetooth, Zigbee and LoRa) which, given their characteristics, common applications and considering the telecommunication context in the Non-Interconnected Zones, could be the most useful and functional for the IoT smart system that is to be proposed:

2.1. Wi-Fi

Is the most widely used wireless technology worldwide for various IoT applications, Wi-Fi allows data and information to be transmitted via radio waves, commonly operating at 2.4 GHz and 5.0 GHz frequencies that allow information to be transmitted at different distances and speeds (Khalili et al., 2020; Pahlavan and Krishnamurthy, 2021).

2.2. Bluetooth

Bluetooth is an unlicensed standard wireless communication technology conceived as a replacement for the data cable. It is used to exchange information between fixed and mobile devices at short distances using UHF radio waves in the 2.4 GHz ISM-free frequency band (Zeadally et al., 2019). This technology is used by low-power consumption applications in Wireless Personal Area Networks (WPAN), for connecting devices with cell phones and computers. The maximum range of a Bluetooth device is highly dependent on the deployment environment and transmission power. In 2016, the new Bluetooth 5.0 version was released, focusing on IoT applications. Its range was increased to reach up to 240 m outdoors with the line-of-sight, plus the data transmission rate was doubled to reach up to 50 Mbps while still maintaining low-energy consumption (Yin et al., 2019).

2.3. Zigbee

Zigbee is a wireless technology developed as an open global standard that defines and bundles a set of energy-efficient radio frequency protocols to address the specific needs of low-cost IoT networks. The ZigBee standard operates on the IEEE 802.15.4 physical radio specifications for unlicensed bands including 2.4 GHz, 900 MHz, and 868 MHz It was designed to provide a wireless data solution with a safe and reliable network architecture (Osorio et al., 2019).

2.4. LoRa

LoRa is a radio frequency wireless technology in the unlicensed Sub-GHz 915 MHz band for America (Raychowdhury and Pramanik, 2020). This technology uses a type of modulation called Chirp Spread Spectrum, which is a wideband frequency-modulated sinusoidal signal that increases or decreases with time to encode information and establish long-distance communication (several kilometres) (Borrero, 2018; Zourmand et al., 2019). The LoRaWAN protocol includes gateway devices that receive and send information to the nodes or end devices, which, in turn, send and receive information to and from the gateway.

In this perspective, it is worth noting that there is not much information and dimensioning of the challenges related to the sensing of electrical and environmental variables or monitoring of sustainable generation systems through IoT technologies in the context of Colombia's Non-Interconnected Zones. However, it is possible to find some studies where IoT technologies are applied for monitoring, management or sensing of power generation systems in other parts of the world. On one side, there is the work carried out by (Behera and Gupta, 2019) where they propose a smart measurement system that addresses power cut issues in rural areas plagued by generation problems. Their system employs smart meters embedded on the Internet of Things to monitor and communicate electrical use in real-time, providing consumers with the flexibility to manage their demand and obtain real-time pricing information. However, while this approach offers promising advantages, it is crucial to critically assess its effectiveness. Notably, the reliance on three technologies: Wi-Fi, Bluetooth, and ZigBee for sensors-to-processor and energy manager connectivity introduces potential complexities and challenges. The strengths of the study lie in its emphasis on real-time monitoring and consumer empowerment, yet the potential weaknesses related to technological dependencies warrant careful consideration and further examination.

On the other hand, (Nur-A-Alam et al., 2021) present an innovative smart automation system to measure temperature, humidity and detect fire using IoT technologies such as LoRa obtain as a result a satisfactory performance and communication of the system up to 12 km away. Despite the commendable achievements in environmental data accuracy, fire detection, and switching functionality control at long range, it is imperative to critically examine certain aspects. The reliance on Wi-Fi connectivity at the sender end may introduce potential limitations in terms of power consumption and scalability, and the system's performance under varying environmental conditions can be studied.

Finally, it also highlights the significant contribution made by (Liu et al., 2019) in which the design of an IoT system that can operate via Wi-Fi for electrical energy management and to study energy efficiency is proposed. The work highlights the potential of their IoT-based energy management system, but further exploration could delve into the scalability, adaptability, and potential limitations of the deep reinforcement learning approach.

On the other hand, in the field of IoT systems, it is essential to address the cybersecurity component as a priority. This factor is of critical importance to prevent potential attacks that could compromise both the integrity and quality of the system, as well as the data collected. Given the growing presence of these intelligent systems nowadays, it is imperative to dedicate an exhaustive study to this aspect and implement the necessary measures to guarantee the security of the information and the functionality of the system (Colmenares-Quintero et al., 2023; Doss et al., 2022).

3. Materials and methods

The analysis of internet of things technologies that can be used for NIZs and consequently the definition of the conceptual design of an IoT system entailed a series of phases that are explained below and expanded in Results section.

3.1. Needs identification

For this stage it is important to understand the context of the NIZs in the different dimensions: social, environmental and economic, to be able to answer and analyse questions, based on previous work (Colmenares-Quintero, Valderrama-Riveros et al., 2021b; Colmenares-Quintero et al., 2022), such as: what do the inhabitants of the NIZs need, how can the situations of vulnerability and lack of access to electricity be improved, how does the improvement of their electricity needs contribute to the development of economic and social activities of these populations, and what are the problems present in the monitoring or tracking of the renewable energy solutions that are normally implemented in the NIZs. A prevalent issue identified in the NIZs is the absence of effective management, monitoring or tracking systems for electricity generation in renewable energy projects. This deficiency results in the inability to assess the functionality of these projects in real time. The consequential lack of electricity significantly impedes the routine operations within the economic and social sectors of these isolated territories.

3.2. Setting up the requirements

From recognizing the pressing need, the subsequent phase involves delineating requirements. In the engineering context, it has been articulated that there is a demand to enhance the management of renewable energies within NIZs. Consequently, our proposal involves the design of IoT solution aimed at establishing connectivity between NIZs, particularly their renewable energy projects, and central hubs. This connectivity facilitates real-time monitoring of the status and functionality of these projects from locations where comprehensive assessments can be conducted.

3.3. Setting up the technical specifications

At this stage, the necessity becomes evident for the implementation of an IoT-driven smart system. Such a system would enable the real-time monitoring of the electrical and environmental variables pertinent to the renewable energy project. In the same way, the geographical conditions of the locations and related aspects were studied to identify which communication technologies have coverage or applicability in the majority of the NIZs, given that this is a very relevant factor for implementing systems or solutions that connect isolated territories with the rest of the country via the internet, for which the experience of work related to Non-Interconnected Zones was also taken into account, such as that carried out by (Benavides-Castillo et al., 2021; Colmenares-Quintero, Latorre-Noguera et al., 2021a).

3.4. Conceptual design

This phase requires a technical comparison of the different IoT technologies for the subsequent definition of the conceptual design of the IoT smart system based on connection diagrams, internet of things architecture and components of the proposed system, at this stage it is possible to pre-assess the fulfilment of the requirements or functionality of the design.

It is important to highlight that this represents the initial methodology for exploring the problem from both social and engineering perspectives and for constructing an initial conceptual design. This design will subsequently undergo implementation for validation and assessment. Furthermore, the study and analysis carried out for the comparison of the different communication technologies applicable to NIZs (i.e. Wi-Fi, ZigBee, Bluetooth and LoRa) and the conceptual design itself provide a tool for implementing intelligent systems with similar communication strategies in these areas, taking into account their geographical limitations, and knowing that according to experience and similar work in other parts of the world, this type of intelligent systems, whether for the energy sector, agriculture, health, etc., offer great advantages to the territories, their economy and social development.

4. Results

4.1. Comparison of IoT technologies

A fundamental part of the IoT system is the technology through which the communication is going to take place, as it was previously expressed, from different existing technologies, Wi-Fi, Bluetooth, ZigBee and LoRa were studied mainly for having good technical and operational characteristics that would have a better performance in the NIZs than other technologies, such as telephone coverage: GSM, 2G, 3G, 4G and 5G, which in isolated areas or NIZs is usually very low or non-existent (nPerf, 2023).

Table 1 shows the comparison of the selected technologies, where the technical and operational comparisons of each technology can be observed. For this research and for the subsequent conceptual design, considering Table 1, the LoRa technology will be used since it shows characteristics of consumption, range, and appropriate messages size according to the challenges involved in implementing IoT systems in isolated territories. However, it does not exclude the possibility of implementing IoT systems for NIZs with any of the other three

Table 1
Comparison of wireless technologies for IoT applications.

Low-Power Wireless Technologies for IoT Device Networks				
Technology	Wi-Fi 6	Bluetooth 5	Zigbee	LoRa
Network Type	WLAN	WPAN	WPAN	LPWAN
Name	Wireless Local Area Network	Wireless Personal Area Network	Wireless Personal Area Network	Low-Power Wide-Area Wireless Network
Standard	IEEE 802.11ax	IEEE 802.15	IEEE 802.15.4	LoRa Alliance (North America)
Frequency	2.4 GHz or 5 GHz	2.4 GHz	2.4 GHz	902–928 MHz, range allowed for America
Range	Up to 250 m (line-of-sight)	Up to 200 m (line-of-sight)	Up to 300 m (line-of-sight)	Up to 20 km
Transfer Speed	Up to 9.6Gbps	up to 2 Mbps	up to 250 kbps	up to 21.9 kbps
Number of Channels	20, 40, 80, 160 (80 × 80) MHz	40 (2 MHz width)	16 (2 MHz width)	64 (125 kHz width)
Network Size/Number of Nodes	Wi-Fi 6 enables eight devices. and up to 255 devices per router	8 active devices per Piconet, Maximum 10 Piconet	up to 65.000 240 devices per subnet	Many (not specified)
Transmission Power	5–20 W	Up to 100 mW (it depends on the type)	Up to 100 mW	1 W maximum
Maximum Current Consumption	Up to 5 A	Lower than 15 mA	Lower than 30 mA	up to 125 mA, it depends on Rx/Tx power
Licensed	No	No	No	No
Messages Size	1500 bytes	255 bytes	102 bytes	255 bytes
Security/Encryption	Protected Access 3 (WPA3)	AES-128 in CCM mode	AES-128 at both network layer and application layer	AES-128 at both Network and Application layers
Topology	Point-to-multipoint Access point Peer-to-peer	Piconet (Star) Scatternet	Star Tree Self-Forming and Self-Healing Mesh	Star

technologies. LoRa is taken as an example of the most extreme communication case, where the renewable energy project is isolated many kilometres (maximum 20 km) from the nearest internet point.

It is important to note that to choose the LoRa technology over the other technologies exposed for the conceptual design of the smart system, in addition to the specifications in Table 1, a simulation was performed in Python where an IoT network is simulated, the objective of the simulation was to send a signal from a smart measuring system to an IoT gateway using each of the technologies studied. In this way it could be established which of the technologies would have a better performance considering the conditions of the NIZs.

The simulation had as inputs: frequency, signal power, distance between the transmitter and receiver, sensitivity values, among other factors, its process was by means of equations that simulate the behaviour of the signals, to finally calculate the signal loss with respect to the distance, in the same way the current and energy consumption is considered with respect to the size of the data packet or signal sent. The respective characteristics for each technology were evaluated and the optimum free space conditions for signal transmission were established. This resulted in the graph in Fig. 1, which shows that the signal with the best performance is LoRa, since it is strong enough to be detected by the receiver over a long distance, unlike the other signals, which have a high loss and are no longer detected by the receiver.

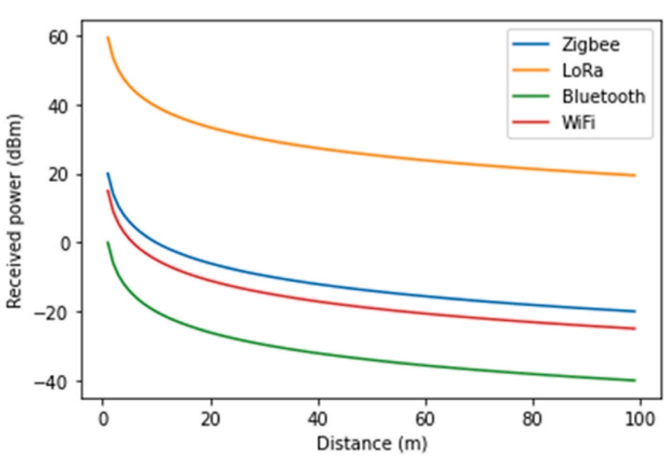

Fig. 1. Signal loss curve for communication technologies.

4.2. Conceptual design of the IoT smart system

In general terms, the IoT system architecture is designed based on 4 main stages:

Physical stage. This is the stage where the electrical and environmental variables are sensed directly from the renewable energy project to be managed by the sensors.

Connection stage. The data collected by the sensors is processed by the microcontroller from analogue to digital. After processing this data, it must be transmitted from the project site, where the measurement is taken, to the nearest internet point. At this stage, IoT communication technology is used, in this practical case the technology used is LoRa, given that it has a range of up to 20 km, so that even if the measurement site is far from the internet point, there will be no problem in communication.

Storage stage. When data is transferred from the microcontroller (in the measurement area) to the nearest internet point, this data is stored in a cloud database so can be accessed from anywhere with internet access.

Implementation stage. This last stage is related to the visualisation and processing of this data stored in the cloud. It is possible to design visualisation interfaces (generate graphs and tables of the behaviour of variables) and obtain information from these data to help with energy management in NIZs, decision making and overall monitoring of the functionality and efficiency of the renewable electricity system. Additionally, from this final data and information, optimisation algorithms can be implemented to improve system performance and include additional functions (Paul, 2022; Paul et al., 2022).

Fig. 2 shows the complete conceptual design where each of the stages and their connections are related.

It should be noted that the architecture in Fig. 2 presents a variation with respect to traditional architectures because NIZs have great connectivity challenges, so in the communication stage it uses a LoRa transmitter module to transmit the data from the energy project normally located at a long distance from the nearest internet point of "Vive Digital" where the LoRa receiver module is located. In this way, the data is received from the LoRa transceiver to the Wi-Fi with connection to the cloud.

On the other hand, the innovative factor of the intelligent system lies in the direct connection with the Monitoring Centre in the city of

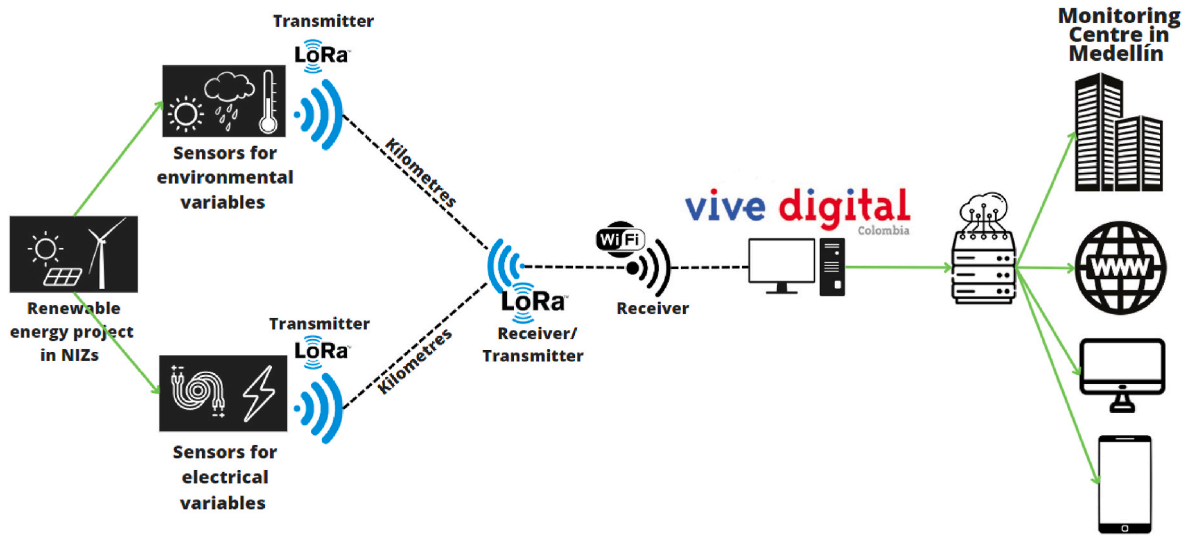

Fig. 2. Conceptual design of the IoT architecture.

Medellin, Colombia, where beyond monitoring the actual status of energy projects, different algorithms for data analytics, optimisation, business intelligence, fault prediction and artificial intelligence will be implemented to provide a high level of functionality to the measurement system. In the same way, the innovation of this intelligent system is precisely its application in isolated and vulnerable territories in Colombia, highlighting the fact that there are currently no similar systems operating in these areas where its use would bring great advantages for the communities.

5. Discussion

Understanding the status of environmental variables is important, as it enables the monitoring of conditions influencing the generation system. These variables, encompassing temperature, radiation, humidity, wind, and the presence or absence of rain, among others, play a pivotal role in determining energy production and system performance (Pawar et al., 2020). Although environmental variables cannot be controlled in the process of electricity generation through renewable energies, they can be monitored to observe how they affect or benefit the system, what adjustments can be made to the system to have a better behaviour according to the real operating conditions and even these data are primary input to obtain intelligent algorithms for optimisation and energy efficiency and the study of these data with deeper data science analysis can result in new relationships of environmental variables with electricity generation for better performance and longer life of the system components.

On the other hand, understanding electrical variables such as voltage, current and power is highly significant. These variables represent the generated output and the objective of the system. They facilitate the tracking of energy production, provide traceability for system performance, and, similarly to environmental variables, their monitoring supports the development of optimisation, efficiency, and prediction models (O'Dwyer et al., 2019).

Having the monitoring of these two types of variables will facilitate the total connection with the system without the need to be on site, will allow the knowledge of its proper functioning all the time and even generate alerts for its timely maintenance.

LoRa technology for the specific case, on which the conceptual design was inspired (which can however be adapted for use in other NIZs), of the Wayuu indigenous community in La Paz in Manaure La Guajira brings great advantages given that they are a community with little technical knowledge of maintenance of power generation systems. Their location is difficult to access and many of their activities depend on electricity, access to decent education and drinking water treatment through desalination are just a few examples of the impact and importance of electricity for this community located in a desert area. The presence of an effective monitoring system with robust communication technology not only enables system connectivity nationwide but also extends the associated benefits to a vulnerable community that depends on the optimal performance of its generation system. From a technical stand, other communication technologies are not contemplated, as points with internet access are scarce and distant from the power generation system. Additionally, telephone coverage is often limited, and in some instances, non-existent. LoRa technology allows connecting the intelligent system up to 20 km with the internet point to transmit data in a timely, automatic, and lossless way.

Incorporating cloud-based data storage, a pivotal component of IoT systems, not only facilitates real-time and remote monitoring but also enables universal access to data. This accessibility, available from any location worldwide and instantly upon sensors reading, empowers experts to develop optimisation algorithms, enhance energy efficiency, conduct data analysis, or implement artificial intelligence algorithms for tasks such as generating alerts and predict failures.

The biggest challenge in the entire process of interconnecting and linking NIZs projects with monitoring centres is constant communication for data transmission, a problem that is solved by the application of IoT technologies. However, the application of these technologies is conditional on the characteristics of the projects and their locations. Identifying the specific characteristics and communication challenges enable the tailored selection of technologies for each project and location. This, in turn, facilitates the integration of IoT technologies and smart systems, bringing forth significant advantages, conveniences, and benefits to these frequently forgotten areas.

This study presents an innovative conceptual design of an IoT communication system to monitor power generation systems in Colombia's Non-Interconnected Zones (NIZ). However, its relevance is not limited to Colombia, but extends to other developing regions with similar challenges. In places like Africa, where NIZs are common and connectivity is scarce due to geographic and financial factors, the proposed design can offer a practical and scalable solution to improve energy efficiency and ensure a stable power supply.

This approach is particularly important given that IoT architectures for NIZs are underrepresented in the state of the art. By filling this gap, this work not only opens up new technological possibilities, but also has profound implications at the social and economic level in the impacted communities, the implementation of this system could not only improve the quality of life of these communities in the NIZ by facilitating important services such as health and education, but could also serve as a model and precedent for future projects, thus contributing to the sustainable development of these marginalized areas.

On the other hand, the implications of this type of technology for the industry are many, as this design could drive technological advances in the monitoring and management of power generation systems in remote and hard-to-reach environments. This innovative approach not only opens up new opportunities for companies and technology providers in the renewable energy sector, but could also foster investment in IoT-related infrastructure and services in underserved regions. In addition, by offering a solution tailored to the specific needs of these areas, the proposal could generate a new potential market for IoT-related products and services, thus expanding business and collaboration opportunities in the industry.

6. Conclusions and future work

It is not common to study the topic of IoT technologies in NIZs, as these places often pose significant challenges, from the initial characterization and community approach to the technical difficulties involved given their location. The first step in talking about truly smart areas is to start conducting these methodological, analytical, and exploratory studies on the state of these technologies, their applicability and, importantly, identifying the limitations and opportunities of these locations. An example of a limitation in applying IoT technology in NIZs is the often-insufficient phone signal coverage. However, this presents an opportunity to explore alternative technologies like LoRa, which performs exceptionally well in open spaces without interference, such as expansive landscapes or areas without dense structures.

Furthermore, what is defined in this document will serve as a precedent for building prototypes in several unconnected areas. In general, the research on IoT technologies suitable for NIZs will enable the pursuit of technologies that are most suitable for these areas, depending on the application and conditions of the project, we will understand which technology is best on a case-by-case basis.

Designing solutions that are fully adapted to NIZs is necessary for real progress, development, and achievement of Sustainable Development Goals in rural, vulnerable, or isolated areas of the country. It is important to close the technology gap between these regions and the cities (Prieto-Egido et al., 2022). Smart systems are a way of connecting the regions and their needs with the rest of the country, thereby promoting the development of their economic and social activities, which are essential for the progress and improvement of the living conditions of these populations.

Furthermore, this exploration goes beyond academia, driven by a commitment to equity and progress. Non-Interconnected Zones (NIZs), often marginalized, warrant attention not just as study subjects but as integral part of the nation. This study calls for bridging technological divides, aiming to ensure that the benefits of innovation reach every corner of the diverse landscape. By outlining NIZs' unique challenges and opportunities, this research is a crucial for the sustainable development. It highlights IoT technologies' transformative potential in empowering marginalized regions, paving the way for inclusive progress.

The proposed future work involves the construction and implementation of a prototype based on the conceptual design. Subsequently, a comprehensive study of the data generated by the system will be undertaken. This data, coupled with advanced data analysis and artificial intelligence techniques, will empower the prediction of events within the energy system and the informed decision-making process in NIZs.

These forward-looking initiatives align with the overarching goal of not only addressing the challenges highlighted in this study but also contributing to the advancement of sustainable and intelligent solutions tailored for the unique context of NIZs.

Funding

This work was supported by the Universidad Cooperativa de Colombia, project title: "Prototipo Para Monitoreo De Sistemas Energéticos En Zonas No Interconectadas", Project reference # INV3309 (TTC03) and project title: "Desarrollo De Una Herramienta Computacional Para La Selección De Sistemas Energéticos Optimizados A Nivel Del Costo Nivelado De Energía (LCoE) Para Zonas No Interconectadas De Colombia", Project reference # INV3300.

CRediT authorship contribution statement

Ramón Fernando Colmenares-Quintero: Writing – review & editing, Validation, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Marieth Baquero-Almazo:** Writing – original draft, Visualization, Methodology, Investigation, Formal analysis. **Damian Kasperczyk:** Validation, Methodology, Conceptualization. **Kim E. Stansfield:** Writing – review & editing, Validation. **Juan Carlos Colmenares-Quintero:** Visualization, Validation, Resources.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

References

Abbas, S., Khan, M.A., Falcon-Morales, L.E., Rehman, A., Saeed, Y., Zareei, M., Zeb, A., Mohamed, E.M., 2020. Modeling, simulation and optimization of power plant energy sustainability for IoT enabled smart cities empowered with deep extreme learning machine. IEEE Access 8, 39982–39997. https://doi.org/10.1109/ACCESS.2020.2976452.

Alansari, Z., Anuar, N.B., Kamsin, A., Soomro, S., Belgaum, M.R., Miraz, M.H., Alshaer, J., 2018. In: Miraz, M.H., Excell, P., Ware, A., Soomro, S., Ali, M. (Eds.), Challenges of Internet of Things and Big Data Integration, Emerging Technologies in Computing. Springer International Publishing, pp. 47–55. https://doi.org/10.1007/978-3-319-95450-9_4.

Barnes, D.F., 2019. Electric power for rural growth: how electricity affects rural life. In: Developing Countries. Routledge. https://doi.org/10.4324/9780429042096.

Behera, S., Gupta, M., 2019. Implementation of IOT for energy management. Test Eng. Manag. 81 (11–12), 4856–4860.

Benavides-Castillo, J.M., Carmona-Parra, J.A., Rojas, N., Stansfield, K.E., Colmenares-Quintero, J.C., Colmenares-Quintero, R.F., 2021. Framework to design water-energy solutions based on community perceptions: case study from a Caribbean coast community in Colombia. Cogent Eng. 8 (1), 1905232 https://doi.org/10.1080/23311916.2021.1905232.

Borrero, J.D., 2018. Aplicación de la tecnología LoRaWAN en la agricultura. https://doi.org/10.13140/RG.2.2.24492.77443.

Colmenares-Quintero, R.F., Latorre-Noguera, L.F., Rojas, N., Kolmsee, K., Stansfield, K. E., Colmenares-Quintero, J.C., 2021a. Computational framework for the selection of energy solutions in indigenous communities in Colombia: Kanalitojo case study. Cogent Eng. 8 (1), 1926406 https://doi.org/10.1080/23311916.2021.1926406.

Colmenares-Quintero, R.F., Maestre-Gongora, G., Baquero-Almazo, M., Stansfield, K.E., Colmenares-Quintero, J.C., 2022. Data analysis of electricity service in Colombia's non-interconnected zones through different clustering techniques. Energies 15 (20). https://doi.org/10.3390/en15207644. Article 20.

Colmenares-Quintero, R.F., Maestre-Gongora, G., Valderrama-Riveros, O.C., Baquero-Almazo, M., Stansfield, K.E., 2023. A data-driven architecture for smart renewable energy microgrids in non-interconnected zones: a Colombian case study. Energies 16 (23). https://doi.org/10.3390/en16237900. Article 23.

Colmenares-Quintero, R.F., Valderrama-Riveros, O.C., Macho-Hernantes, F., Stansfield, K.E., Colmenares-Quintero, J.C., 2021b. Renewable energy smart sensing system monitoring for off-grid vulnerable community in Colombia. Cogent Eng. 8 (1), 1936372 https://doi.org/10.1080/23311916.2021.1936372.

Dávila Rueda, E.A., 2022. Factores que afectan la supervivencia de los proyectos de energía eléctrica en las zonas no interconectadas: Lecciones para Colombia de la experiencia internacional [Trabajo de grado - Maestría, Universidad Nacional de Colombia]. https://repositorio.unal.edu.co/handle/unal/81275.

Doss, A.N., Shah, D., Smaisim, G.F., Olha, M., Jaiswal, S., 2022. A Comprehensive Analysis of Internet of Things (IOT) in Enhancing Data Security for Better System

Integrity—A Critical Analysis on the Security Attacks and Relevant Countermeasures. In: 2022 2nd International Conference on Advance Computing and Innovative Technologies in Engineering (ICACITE), pp. 165–167. https://doi.org/10.1109/ICACITE53722.2022.9823817.

IPSE, 2022. ABC Estructuración de proyectos. Instituto de Planificación y Promoción de Soluciones Energéticas para las Zonas No Interconectadas - IPSE, p. 12. https://ipse.gov.co/documentos_guia_estructuracion_proyectos/documentos/ABCEstructuraci%C3%B3ndeProyectos.pdf.

IPSE, 2023. Caracterización Energética de las ZNI – IPSE-CNM. https://ipse.gov.co/cnm/caracterizacion-de-las-zni/.

Khalili, A., Soliman, A., Asaduzzaman, M., Griffiths, A., 2020. Wi-fi sensing: applications and challenges. J. Eng. 2020 (3), 87–97. https://doi.org/10.1049/joe.2019.0790.

Liu, Y., Yang, C., Jiang, L., Xie, S., Zhang, Y., 2019. Intelligent edge computing for IoT-based energy management in smart cities. IEEE Network 33 (2), 111–117.

nPerf, 2023. Mapa de cobertura Colombia [Map]. https://www.nperf.com/es/map/CO/-/-/signal/?ll=4.634800397439164&lg=-74.3&zoom=5.

Nur-A-Alam, Ahsan, M., Based, M.A., Haider, J., Rodrigues, E.M.G., 2021. Smart monitoring and controlling of appliances using LoRa based IoT system. Designs 5 (1). https://doi.org/10.3390/designs5010017. Article 1.

O'Dwyer, E., Pan, I., Acha, S., Shah, N., 2019. Smart energy systems for sustainable smart cities: current developments, trends and future directions. Appl. Energy 237, 581–597. https://doi.org/10.1016/j.apenergy.2019.01.024.

Osorio, A.E., Sánchez, E.A.G., García, G.F., Machuca, S.F.H., Lozano, P.S.L., 2019. Evaluation of wireless network based on ZigBee technology using XBee modules. In: 2019 IEEE International Conference on Engineering Veracruz (ICEV), vol. I, pp. 1–6. https://doi.org/10.1109/ICEV.2019.8920468.

Pahlavan, K., Krishnamurthy, P., 2021. Evolution and impact of wi-fi technology and applications: a historical perspective. Int. J. Wireless Inf. Network 28 (1), 3–19. https://doi.org/10.1007/s10776-020-00501-8.

Paul, K., 2022. Multi-objective risk-based optimal power system operation with renewable energy resources and battery energy storage system: a novel Hybrid Modified Grey Wolf Optimization–Sine Cosine Algorithm approach. Trans. Inst. Meas. Control, 01423312221079962. https://doi.org/10.1177/01423312221079962.

Paul, K., Hati, D., 2023. A novel hybrid Harris hawk optimization and sine cosine algorithm based home energy management system for residential buildings. Build. Serv. Eng. Res. Tecnol. 44 (4), 459–480. https://doi.org/10.1177/01436244231170387.

Paul, K., Shekher, V., Kumar, N., Kumar, V., Kumar, M., 2022. Influence of wind energy source on congestion management in power system transmission network: a novel modified whale optimization approach. Proc. Integr. Opt. Sustain. 6 (4), 943–959. https://doi.org/10.1007/s41660-022-00271-1.

Pawar, P., TarunKumar, M., Vittal, K.P., 2020. An IoT based Intelligent Smart Energy Management System with accurate forecasting and load strategy for renewable generation. Measurement 152, 107187. https://doi.org/10.1016/j.measurement.2019.107187.

Prieto-Egido, I., Sanchez-Chaparro, T., Urquijo-Reguera, J., 2022. Impacts of information and communication technologies on the SDGs: the case of Mayu Telecomunicaciones in rural areas of Peru. Inf. Technol. Dev. 0 (0), 1–25. https://doi.org/10.1080/02681102.2022.2073581.

Raychowdhury, A., Pramanik, A., 2020. In: Thampi, S.M., Trajkovic, L., Mitra, S., Nagabhushan, P., El-Alfy, E.-S.M., Bojkovic, Z., Mishra, D. (Eds.), Survey on LoRa Technology: Solution for Internet of Things, Intelligent Systems, Technologies and Applications. Springer, pp. 259–271. https://doi.org/10.1007/978-981-15-3914-5_20.

Said, O., Al-Makhadmeh, Z., Tolba, A., 2020. EMS: an energy management scheme for green IoT environments. IEEE Access 8, 44983–44998. https://doi.org/10.1109/ACCESS.2020.2976641.

Shafique, K., Khawaja, B.A., Sabir, F., Qazi, S., Mustaqim, M., 2020. Internet of things (IoT) for next-generation smart systems: a review of current challenges, future trends and prospects for emerging 5G-IoT scenarios. IEEE Access 8, 23022–23040. https://doi.org/10.1109/ACCESS.2020.2970118.

Yin, J., Yang, Z., Cao, H., Liu, T., Zhou, Z., Wu, C., 2019. A survey on Bluetooth 5.0 and mesh: new milestones of IoT. ACM Trans. Sens. Netw. 15 (3), 1–29. https://doi.org/10.1145/3317687.

Zeadally, S., Siddiqui, F., Baig, Z., 2019. 25 Years of Bluetooth technology. Future Internet 11 (9). https://doi.org/10.3390/fi11090194. Article 9.

Zourmand, A., Kun Hing, A.L., Wai Hung, C., AbdulRehman, M., 2019. Internet of Things (IoT) Using LoRa Technology. In: 2019 IEEE International Conference on Automatic Control and Intelligent Systems (I2CACIS), pp. 324–330. https://doi.org/10.1109/I2CACIS.2019.8825008.