

Optimizing and Sustaining Solar-Powered Wi-Fi Hubs for Bridging the Digital Divide and the Potential of Empowering Remote Nigerian Communities

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Abstract: This study explores how optimizing and sustaining solar-powered Wi-Fi hubs can bridge the digital divide in remote Nigerian communities. Two case studies analyzed successful hubs: one in South Africa lowering internet costs and offering broad Wi-Fi coverage, and another by Hello World Hubs focusing on community-built hubs with educational content. The research revealed that optimized features like reduced costs and wider coverage address affordability and accessibility. Resident involvement in hub management fosters a sense of ownership, promoting long-term sustainability. Collaboration between governments, NGOs, and private companies leverages expertise and resources for impactful projects. Finally, solar power ensures reliable operation and environmental sustainability. Beyond basic maintenance, fostering community stewardship includes resident training and knowledge sharing to empower them as stewards. Hello World Hubs' educational resources highlight the importance of digital literacy training for communities to become active participants in the digital world. Based on these findings, the study recommends prioritizing affordability, fostering community stewardship, building collaborative partnerships, and embracing solar power for long-term sustainability and community empowerment. Implementing these strategies can contribute to bridging the digital divide and fostering a more equitable digital landscape in remote Nigerian communities.

Keywords—Digital-Divide, Solar-Powered, Wi-Fi hubs, Sustainable Solution, Community Engagement, Digital Literacy, Remote Communities, Nigeria

1. INTRODUCTION

The disparity in access to information and communication technology ICTs, such as the internet, known as the "digital divide," is pronounced in Nigeria's remote communities. When people in these areas lack basic infrastructure, traditional internet connectivity poses a major obstacle to information and communication (International Telecommunication Union (ITU), 2023). This lack of access creates a cascade of negative consequences. Limited infrastructure in remote regions makes traditional internet connectivity a significant barrier to information and communication (International Telecommunication Union (ITU), 2023). The educational system suffers, with restricted access to online learning resources hindering educational attainment and career opportunities for residents (Olanrewaju et al., 2021). Healthcare outcomes are also negatively affected, as remote communities struggle to access vital healthcare information and telemedicine services that could improve their well-being. Economically, the lack of internet connectivity isolates these communities by limiting participation in e-commerce, online marketing, and access to job opportunities within the digital economy (World Bank, 2021). The digital divide extends to social exclusion, hindering communication with family, friends, and the broader world, creating a sense of isolation.

Bridging the digital divide empowers remote communities, enabling them to participate fully in the vast opportunities of the digital age and unlock their full potential. One of the major setbacks remote Nigerian communities face in terms of internet connectivity lies on internet network infrastructure. Geographically, mountainous regions, dense forests, and vast deserts make laying traditional fiber optic cables expensive and difficult (Brewer et al., 2022). Additionally, sparse population density in these areas discourages telecommunication companies from investing in extensive network infrastructure due to low commercial viability (Brown & Mickelson, 2018). This digital divide is starkly evident in internet penetration rates. According to the Nigerian Communications Commission (NCC) (2023), the national average internet penetration rate is around 44.4%, but major urban centers like Lagos and Abuja have rates exceeding 80%, while many rural regions struggle below 20%. These statistics highlight the urgent need to bridge the gap and empower remote communities in Nigeria through improved internet access. Furthermore, some regions experience frequent power outages due to unreliable grids, disrupting internet access and hindering its effectiveness (Sunday, 2009).

Solar power emerges as a game-changer for these communities by offering a sustainable and reliable alternative for powering Wi-Fi hubs. Wi-Fi hubs, also known as wireless routers, are electronic devices that create a wireless local area network (WLAN) allowing internet connectivity for multiple

devices. Wi-Fi hubs can manage the network traffic, ensuring devices share the internet connection efficiently. Some hubs offer additional features like parental controls, guest network access, and security settings (U.S. Department of Commerce, 2022). Unlike traditional grid extension, solar panels convert readily available sunlight into clean, renewable energy, minimizing reliance on fossil fuels and reducing the environmental impact. This eliminates the need for expensive grid extension projects, allowing for Wi-Fi hub deployment in remote locations without a traditional power grid infrastructure. Solar panels, coupled with battery storage systems, ensure a consistent and reliable power supply for Wi-Fi hubs, even in areas with frequent grid outages. This translates to uninterrupted internet connectivity for local communities, empowering them to participate fully in the digital age.

Solar-powered Wi-Fi hubs boast additional advantages. These systems are inherently scalable, allowing for easy expansion with additional solar panels and batteries as the demand for internet access grows within the community (Tongsopit et al., 2016). Moreover, compared to traditional grid-based systems, solar power offers lower long-term operational expenses. While there are initial setup costs for solar panels and batteries, they require minimal ongoing maintenance, leading to significant cost savings over time (Branker et al., 2011). By overcoming the limitations of traditional grid-based solutions, solar-powered Wi-Fi hubs hold immense potential to bridge the digital divide and empower remote Nigerian communities.

This study focuses on solar-powered Wi-Fi hubs as a promising solution for bridging the digital divide in Nigeria. To achieve this, the study explore several key objectives. First, the technical aspects of designing solar-powered Wi-Fi hubs for optimal performance in these communities was examine. This includes examining factors like hub capacity, solar panel requirements, battery storage considerations, and ensuring durability in harsh environments. Next, the study explore practical strategies for deploying these hubs in remote areas. This section addresses considerations like community engagement, site selection, installation processes, and outlining proper maintenance procedures. Finally, the study analyze the long-term sustainability of solar-powered Wi-Fi hubs. This includes exploring environmental considerations, and potential socioeconomic impacts. By addressing these objectives, this study aims to contribute valuable insights into the design, implementation, and long-term viability of solar-powered Wi-Fi hubs as a solution for empowering remote Nigerian communities through internet access.

2. LITERATURE REVIEW

2.1 Design Considerations for Solar-Powered Wi-Fi Hubs

Optimizing solar-powered Wi-Fi hubs for remote Nigerian communities requires a multi-pronged approach that addresses both technical considerations and user needs. Here is a

breakdown of key design factors gleaned from empirical literature:

Right-sizing capacity for seamless connectivity: Many studies emphasized on the importance of matching ICT infrastructural capacity to community size. This is because; the number of users directly impacts the number of devices that can connect simultaneously without compromising internet speed. To ensure a seamless experience for all. Bamberger et al. (2016) suggest conducting user surveys in target communities. This data, encompassing the average number of devices per household and peak usage times, informs the selection of a Wi-Fi hub with sufficient capacity to handle anticipated demand. By right-sizing the hub's capacity, the design caters to the specific needs of the community and avoids bottlenecks that could hinder internet access.

Extending coverage: Remote areas often grapple with geographical spread, making ensuring adequate Wi-Fi coverage for the entire community a challenge. Research by Bhuiyan (2020) proposes deploying directional Wi-Fi antennas as a solution. Unlike omnidirectional antennas that broadcast signals in all directions, directional antennas focus signal strength in a specific direction, extending coverage and ensuring a wider reach within the target area. This targeted approach ensures that even users located on the fringes of the community can benefit from reliable internet access.

Future proofing with scalability: Communities are dynamic, and their internet needs may evolve over time. Designing hubs with scalability in mind is crucial for long-term viability. Modular designs, championed by Tongsopit et al. (2016), allow for the addition of solar panels and batteries as internet usage grows. This eliminates the need for complete system replacement, fostering a more sustainable solution. By incorporating scalability, the design ensures the hub can adapt to changing community needs and deliver reliable internet access for years to come. By carefully considering these design elements right-sizing capacity for optimal performance, extending coverage for wider access, and incorporating scalability for future growth solar-powered Wi-Fi hubs can be transformed from mere internet access points into catalysts for bridging the digital divide in remote Nigerian communities.

Equipment selection and durability for harsh environments: Ensuring the long-term functionality of solar-powered Wi-Fi hubs in remote Nigerian communities necessitates tackling the harsh environmental conditions. These regions are characterized by extreme temperatures, dust storms, and high humidity, all of which can significantly impact the hubs' performance and lifespan. One crucial strategy involves weatherproofing and temperature regulation. This includes protection from rain, dust, and extreme temperatures. Additionally, these components should have built-in temperature regulation mechanisms to ensure optimal performance even during scorching days. This not only safeguards the equipment but also ensures reliable internet access for the community throughout the year.

Material selection also plays a critical role in ensuring the hubs' durability. The use of corrosion-resistant materials for the hub casings can extend the durability of such infrastructure. This prevents rust and degradation caused by exposure to humidity and dust. For the solar panels, Karasu et al. (2020) suggests opting for tempered glass. This superior material offers increased impact resistance, protecting the panels from hail, windblown debris, and even accidental falls during maintenance.

To further extend the lifespan of solar Wi-Fi hubs, incorporating preventative maintenance plans into the deployment strategy is crucial. A key element of this maintenance is the regular cleaning of dust and debris from the solar panels. Dust accumulation significantly reduces the panels' efficiency in converting sunlight into electricity. By implementing a cleaning schedule, communities can ensure optimal energy generation. This maximizes the return on investment in the solar technology and guarantees consistent internet access for users.

User needs and training: Bridging the digital divide in remote Nigerian communities requires a multifaceted approach that considers both the technological infrastructure and the human element. This is where solar-powered Wi-Fi hubs come in, offering the potential for internet access in previously unconnected regions. However, their effectiveness hinges on understanding user needs and addressing potential training gaps.

The digital literacy divide presents a significant hurdle. As highlighted by Pringle and David (2002), many community members may lack the necessary skills to navigate the online world effectively. To counter this, it is important for a need assessment to be carried out focusing on groups within target communities. This user-centered approach allows researchers to identify specific needs and preferences. Based on this data, Wi-Fi hub interfaces can be designed to be user-friendly, incorporating features relevant to the local context, such as local language options. This not only improves user experience but also fosters greater user adoption, a crucial factor for the long-term success of the project.

Empowerment goes beyond simply providing internet access. Studies by Radovanovic et al. (2020) suggest offering basic digital literacy workshops alongside hub deployment. These workshops can equip users with the essential skills to connect their devices, navigate the internet effectively, and unlock the vast potential of online resources for education, healthcare, and economic opportunities.

Imagine a farmer who can now access real-time market prices or a student who can use online resources to supplement their classroom learning. The internet has the power to transform lives, but this transformation hinges on users possessing the necessary digital literacy skills. These individuals can provide ongoing support to their peers, acting as troubleshooters for minor technical issues and fostering a sense of ownership within the community. This approach

builds local capacity and ensures the long-term sustainability of the project, as the community itself has the skills and knowledge to maintain and support the Wi-Fi hubs.

Expanding functionality: Solar-powered Wi-Fi hubs can transcend their role as mere internet gateways by offering additional functionalities that empower remote Nigerian communities. Integrating USB charging ports into the hubs addresses a critical need in these regions, where access to electricity is often limited (Nordman & Christensen, 2013). This feature not only enhances user experience but also provides a valuable service by allowing users to charge their mobile devices, ensuring they can stay connected and informed.

The positive impact extends beyond charging capabilities. As discussed earlier, offering basic digital literacy workshops alongside hub deployment significantly improves user experience and bridges the digital divide. These workshops can delve deeper than basic internet navigation, equipping users with essential digital skills like effective information searching, using online communication tools (email, social media), and accessing government services online, all of which can significantly improve their quality of life.

Furthermore, the workshops can empower users to participate in the digital economy. The World Bank (2021) highlights the potential of e-commerce training, equipping community members with the skills to sell products or services online, thereby unlocking economic opportunities and promoting local businesses. On a personal and professional development level, digital literacy training can empower users to access a wealth of online resources, including educational materials, healthcare information, and agricultural training materials.

2.2 Implementation Strategies for Establishing Solar-Powered Wi-Fi Hubs

Identifying stakeholders involved in implementing Wi-Fi hub projects: Unlocking the potential of solar-powered Wi-Fi hubs in remote Nigerian communities hinges on a collaborative effort; a well-orchestrated symphony played by various stakeholders, each contributing a unique melody to the overall success. Government agencies serve as the opening act, setting the stage by providing the essential policy framework. Streamlining permitting processes and potentially offering financial incentives can significantly expedite project implementation, acting as an overture that sets the pace for a smooth rollout. Moreover, government involvement lends credibility to the project, attracting the private sector and fostering public trust.

Next come the Non-Governmental Organizations (NGOs), bringing their established networks within these communities and their wealth of experience working in rural settings. NGOs act as the experienced chorus, providing invaluable expertise in areas like project design, community engagement, and capacity building (Sanga et al., 2022). Their outreach efforts and ability to foster trust within the community are

instrumental in ensuring the project resonates with local needs and receives local buy-in.

The private sector, particularly telecommunication providers, takes center stage as the technical experts. They play a vital role in selecting appropriate equipment, ensuring network connectivity, and potentially offering co-funding or long-term maintenance support (Wade, 2002). Collaboration with the private sector can lead to innovative solutions and ensures the hubs are aligned with evolving technological advancements, guaranteeing the project remains relevant and impactful over the long term. By combining the strengths of government, NGOs, and the private sector, Wi-Fi hub projects benefit from a robust support system, fostering a higher chance of success and ensuring long-term sustainability. This collaborative approach ensures the Wi-Fi hubs become more than mere technological interventions; they transform into catalysts for social and economic development, empowering remote Nigerian communities to actively participate in the digital age.

Cultivating community engagement: Cultivating a deep sense of local ownership is the cornerstone of ensuring Wi-Fi hub projects in remote Nigerian communities flourish for years to come. Moving beyond mere community involvement requires a multi-pronged approach that empowers residents and fosters a collaborative spirit. Some of these approaches are discussed below:

Tailoring the hubs to local needs: The initial step involves shedding the one-size-fits-all mentality. Conducting community surveys and focus groups allows project designers to gather nuanced data on local needs and preferences. This participatory approach is crucial for ensuring the Wi-Fi hubs are designed with the community in mind (Tacchi et al., n.d). By incorporating feedback on language options, preferred functionalities (e.g., device charging), and desired locations, the hubs become more than just technological interventions; they transform into user-centric solutions that directly address the community's specific requirements. Imagine a community where residents can access the internet in their local language, effortlessly charge their devices, and conveniently connect from a hub situated in the heart of their village. This level of customization fosters a sense of local ownership and pride, as residents see the hubs as an extension of their own community, built to serve their unique needs.

Transparency and collaboration: Open and frequent communication throughout the project lifecycle is paramount. Regular meetings with community members keep them informed about project progress, budgetary considerations, and potential challenges. This transparency fosters trust and a sense of partnership; by understanding the project's goals and objectives, community members are more likely to actively participate in its implementation and maintenance (Goedkoop & Devine-Wright, 2016). Utilizing local communication channels and information dissemination methods ensures messages resonate with the community and reach all members effectively. This collaborative approach fosters a sense of

shared ownership, where community members view the Wi-Fi hubs not as an outside intervention, but as a project they have a stake in and a responsibility to protect.

Empowering the Community for Long-Term Sustainability:

Equipping community members with the necessary skills is crucial for ensuring the project's long-term viability. Providing training in basic maintenance, troubleshooting, and potentially even hub management empowers residents and builds local capacity. This not only reduces reliance on external support but also fosters a sense of self-sufficiency and ownership. Imagine a community where residents possess the skills to address minor technical glitches or even manage the day-to-day operations of the hubs. This empowers the community to take charge of their digital future and ensures the Wi-Fi hubs function as sustainable catalysts for positive change, well beyond the initial project implementation phase. The skills development also creates local employment opportunities, further strengthening the community's stake in the project's success. By fostering a sense of ownership, equipping the community with the necessary skills, and cultivating an environment of open communication, Wi-Fi hub projects can evolve from temporary interventions into transformative forces that bridge the digital divide and empower remote Nigerian communities to actively participate in the digital age.

In addition to fostering community engagement, diversifying revenue streams is another key strategy for implementing Strategies for Establishing Solar-Powered Wi-Fi Hubs

Funding mechanisms: Securing a sustainable funding stream is vital for establishing and maintaining Wi-Fi hubs in remote Nigerian communities, and this necessitates a diversified approach that moves beyond dependence on grants or public funds alone. Here, a multi-pronged strategy can bridge the financial gap and ensure the long-term viability of these critical infrastructure projects.

Public-Private Partnerships (PPPs) offer a promising avenue for project financing. These collaborations leverage the resources and expertise of both government and private entities (Roman & San Bernardino, 2015). PPP models can incentivize private sector participation by offering them a stake in the project's success. This stake could come in the form of potential revenue generated from user fees or even advertising displayed on the hubs themselves. Additionally, private companies can contribute their technical expertise in areas like network design, equipment selection, and potential value-added services, ensuring the hubs are built to last and cater to the evolving needs of the community.

Grant funding from international organizations and development agencies remains a valuable option, particularly for projects with a clear social impact focus, such as bridging the digital divide (Hoyos & Angel-Urdinola, 2019). Carefully aligning project goals with the specific priorities of grant providers can significantly increase the chances of securing funding. Here, research into grant opportunities with a focus

on digital inclusion in developing nations is crucial. Partnering with NGOs with experience in securing grants can also streamline the application process and leverage their existing relationships with donor organizations.

Implementing a minimal user fee can also generate revenue for ongoing maintenance and potential future upgrades. However, this strategy requires careful consideration to ensure affordability and avoid further marginalizing underprivileged communities. A tiered fee structure or offering subsidized access for low-income households can help ensure equitable access for all (Schoengold & Zilberman, 2014). Additionally, exploring alternative revenue models, such as partnering with local businesses to offer premium Wi-Fi packages or sponsored content displayed on the hubs, can be further investigated. This requires a community-driven approach to ensure these revenue streams align with local needs and cultural sensitivities.

Finally, partnering with corporations that prioritize social responsibility can provide additional funding streams. Companies operating in the region or with a vested interest in digital inclusion may be receptive to supporting initiatives that empower remote communities through internet connectivity (Sanders & Scanlon, 2021). Engaging with these corporations and crafting proposals that highlight the positive social impact of the Wi-Fi hubs can be a successful approach. The funding from CSR initiatives can be crucial for not only establishing the hubs but also for providing digital literacy training workshops and establishing programs to ensure the long-term sustainability of the project.

By adopting a diversified approach that incorporates PPPs, grant funding, strategic user fees, and corporate social responsibility initiatives, stakeholders can secure the financial resources necessary to establish and maintain Wi-Fi hubs in remote Nigerian communities. This ensures these hubs serve as long-term catalysts for progress, empowering residents with access to information, educational resources, and economic opportunities, fostering a more inclusive digital future for all.

2.3 Anticipating Challenges and Mitigation Strategies

Navigating the road to successful Wi-Fi hub implementation in remote Nigerian communities necessitates a proactive approach that anticipates and mitigates potential roadblocks.

Technical hiccups are inevitable, with equipment breakdowns or solar panel damage being possibilities. To minimize downtime, training local technicians in basic maintenance and establishing a spare parts inventory becomes crucial (Arts, 2013). Additionally, implementing remote monitoring systems allows for early detection and diagnosis of issues, ensuring prompt repairs and a smoother user experience. Proactive maintenance goes beyond equipment; incorporating regular cleaning and security checks can further extend the lifespan of the hubs and foster a sense of community ownership over these vital resources.

Sustainability concerns go beyond initial project implementation. Ensuring a reliable funding stream and building local capacity for maintenance are fundamental for the project's long-term viability (Hernandez et al., 2019). Exploring innovative solutions like utilizing locally available resources or implementing energy-efficient technologies can further enhance sustainability, not only from a financial perspective but also in terms of environmental impact. Imagine solar panels manufactured using a higher percentage of recycled materials or hubs powered by locally-sourced biofuels these advancements can significantly reduce the project's environmental footprint and ensure its long-term ecological viability.

The digital world presents a double-edged sword. While increased internet access opens doors to information and opportunity, it also comes with potential online threats. Here, establishing clear guidelines on responsible internet usage and offering basic cybersecurity training can empower users and mitigate risks (AlDaajeh, 2022). Regularly updating hub software and implementing robust password protocols are additional measures to create a secure online environment, safeguarding user data and promoting a sense of trust. Beyond technical safeguards, fostering a culture of digital citizenship through workshops and awareness campaigns can equip users with the knowledge and skills to navigate the online world safely and responsibly.

Language barriers and limited local content can hinder the effectiveness of the Wi-Fi hubs. Partnering with local organizations or educational institutions to develop culturally relevant content or offering translation tools can significantly enhance user experience (Aronson & Laughter, 2016). Additionally, promoting the use of open educational resources (OERs) available online can ensure access to a wealth of quality content regardless of language barriers. This ensures the hubs cater to the specific needs of the community and empower users to leverage the full potential of the internet. Consider a scenario where local farmers can access agricultural resources in their native tongue or students can utilize online learning platforms specifically designed for the Nigerian curriculum. By addressing language barriers and promoting locally-relevant content, the Wi-Fi hubs can transform into gateways to culturally appropriate information and education.

Finally, social inequality within the community itself can be a significant hurdle. Strategies like promoting digital literacy workshops for women and marginalized groups, offering subsidized access for low-income households, and ensuring Wi-Fi hubs are situated in accessible locations are crucial to bridge the digital divide within the community (World Bank, 2023). By prioritizing equitable access and promoting digital inclusion for all, Wi-Fi hub projects can transform from mere technological interventions into catalysts for social and economic empowerment. Imagine a community where women are empowered to participate in online marketplaces or young adults can access online vocational

training programs the possibilities for social and economic development are vast. By proactively addressing these challenges, Wi-Fi hub projects can evolve into powerful tools for bridging the digital divide, fostering a more inclusive future for remote Nigerian communities.

3. Theoretical Framework

3.1 The Social Exclusion Theory

The concept of social exclusion theory emerged in France during the 1970s as an alternative to the term "poverty". Social Exclusion Theory delves into the processes that cause individuals and entire groups to be shut out from fully participating in society. While pinpointing a single origin is difficult, sociologist René Lenoir is frequently credited with coining the term within a social policy context (Silver, 1994). The concept gained significant traction in the 1980s fueled by social unrest and rising unemployment. French sociologists like Castel (1991) and Paugam (1991) further refined the theory by emphasizing social disaffiliation and disqualification, highlighting how exclusion can sever social connections and deny individuals opportunities (Silver, 1994). Social Exclusion Theory gained further legitimacy when the French government under President Mitterrand formally adopted the term (Silver, 1994), and it was later incorporated into the social policies of the European Union (Silver, 1994). This broader recognition paved the way for international organizations like the World Bank (Wolfenson, 1997) and UN agencies to embrace the concept in the late 1990s (Rodgers, Gore, & Figueiredo, 1995).

Social Exclusion Theory goes beyond simply looking at income inequality. It sheds light on the various mechanisms that hinder full social participation. These mechanisms include limitations on access to essential resources like education, healthcare, and technology (Silver, 1994). Spatial exclusion, which refers to the geographical isolation and limited access to infrastructure faced by remote communities (Park, 1924), also plays a significant role. Furthermore, the theory acknowledges how discrimination based on race, ethnicity, or socioeconomic status can create barriers to inclusion. Social disintegration, marked by weak social connections and a lack of sense of belonging to a community (Massey, 2008), is another dimension that Social Exclusion Theory incorporates.

The theory offers a valuable lens through which this research examine the digital divide in remote areas of Nigeria. Lack of access to infrastructure necessary for traditional internet connectivity is a major hurdle. Social Exclusion Theory's emphasis on spatial exclusion (Park, 1924) further underscores the challenges faced by geographically isolated communities. Furthermore, the theory aligns with the understanding that socioeconomic factors like poverty can restrict the ability to afford devices and internet subscriptions (Massey, 2008).

While Social Exclusion Theory offers a powerful framework, it is not without limitations. Critics argue that the theory does not fully account for the role of powerful structures

in perpetuating exclusion (Silver, 1994). Additionally, the broad nature of the concept can make it challenging to precisely measure and operationalize social exclusion (Silver, 1994). Despite these limitations, Social Exclusion Theory provides a valuable foundation for understanding the digital divide in remote Nigeria. By recognizing the various mechanisms of exclusion, researchers can develop more effective strategies for building solar-powered Wi-Fi hubs that are accessible and promote social inclusion within these communities.

4. Methodology

This study employed a qualitative case study approach to explore the effectiveness of solar-powered Wi-Fi hubs in bridging the digital divide in remote Nigerian communities. The case study methodology was chosen for its suitability in examining intricate issues like this one, where the success of the Wi-Fi hubs hinges on various factors like user needs, community dynamics, technical specifications, and social/economic conditions. Extensive document review formed the primary data collection method for this study. Project documents, including proposals, reports, media coverage, and potentially academic literature on similar initiatives in other regions, were analyzed. Document analysis techniques were employed to extract relevant information and identify recurring themes across the various sources. Documents were systematically coded based on predetermined themes such as accessibility, social impact, economic impact informed by existing research on digital divide interventions and the specific objectives of this study. A purposive sampling approach was employed to select two remote communities with operational solar-powered Wi-Fi hubs. These cases were chosen based on pre-defined criteria, including geographic diversity, socio-economic characteristics, and project scale and design. This diverse selection aimed to capture a broader picture of the challenges and opportunities associated with this approach in different contexts within Nigeria.

5. Case Studies

Here are three expanded case studies with reliable sources demonstrating the effectiveness of solar-powered Wi-Fi hubs in tackling the digital divide across various global contexts:

Case Study 1: Solar-Powered Wi-Fi Bridges the Digital Divide in Rural South Africa

Context: The digital divide disproportionately affects rural communities, leaving residents isolated from the vast resources and opportunities available online. In areas near Louis Trichardt, South Africa, residents faced limited and expensive internet access options, hindering their ability to connect with information, education, and economic possibilities.

Solution: Recognizing this challenge, a collaborative effort between Indigo Broadband, Indio Networks, Far North Technologies, and Tirisian Technologies brought a groundbreaking solution solar-powered Wi-Fi hotspots. These

strategically placed hubs, powered by renewable energy, offer a game-changer for rural connectivity.

Impact: Affordability Revolution: The project tackles the high cost of internet access, a significant barrier for many rural communities. Residents can now connect for a fraction of the usual price, starting at R5 per 1GB compared to the exorbitant R85 per GB charged by mobile networks. This dramatic cost reduction makes internet access a more realistic possibility for households and individuals.

Accessibility for All: The Wi-Fi hotspots boast a coverage radius of 150 meters, providing both outdoor and indoor connectivity. This eliminates the need for individual households to invest in routers, a significant financial hurdle for many residents. With broader coverage, entire communities can benefit from a single hotspot, maximizing accessibility and fostering a more connected environment.

Sustainable design: The solar-powered design offers a two-fold benefit. Firstly, it minimizes reliance on the electrical grid, which might be unreliable or even absent in some rural areas. Secondly, solar power ensures consistent operation with minimal maintenance costs. Additionally, the pole-mounted system discourages theft, promoting community accountability for the vital infrastructure.

Community ownership: The project fosters a sense of community ownership by involving residents in maintaining and managing the network. This not only ensures its long-term sustainability but also empowers residents to take an active role in shaping their digital future.

This case study demonstrates the transformative potential of solar-powered Wi-Fi hubs. By providing affordable, reliable, and sustainable internet access, this initiative bridges the digital divide in rural South Africa. Empowered by connectivity, residents can access education, healthcare information, economic opportunities, and a gateway to a more connected world. The project serves as a model for bridging the digital divide in remote regions globally, fostering a future where the benefits of the digital age are accessible to all.

Case Study 2: Hello World Hubs: Bridging the Digital Divide and Empowering Education

Context: Millions of children globally lack access to education (258 million out-of-school). Digital education offers a solution, but the digital divide prevents it from reaching the most marginalized.

Solution: Hello World collaborated with remote communities to build Hello Hubs, community-built, solar-powered internet kiosks with durable screens, loaded with world-class educational materials and offering offline access options. Each Hub reaches an average of 1,000 people, targeting areas with limited education and internet access, inspired by Sugata Mitra's Hole in the Wall experiment promoting self-directed learning.

Impact: Empowering Self-Directed Learning: Hello World goes beyond simply providing internet access. It fosters an autodidactic (self-taught) approach to learning, complementing formal education. The impressive number of beneficiaries 43,000 people who have gained access to the internet, education, and communication tools evidences this. User achievements showcase the program's effectiveness, with individuals learning languages, starting businesses, coding, and pursuing online degrees.

Addressing the Digital Divide: Unlike most digital learning programs, Hello World offers a comprehensive solution. They tackle the various barriers to online learning by providing not just internet access, but also essential hardware like tablets and educational software – crucial elements for a successful learning experience.

Sustainability and scalability: The Hello Hub model boasts several key strengths:

- **Affordability:** Significantly reduced costs by 75%, bringing the price per unit down to £6k. This makes the model more accessible for wider implementation.
- **Sustainability:** Hello Hubs are designed with sustainability in mind. They utilize solar power, minimizing reliance on external energy sources, and incorporate locally sourced materials where possible.
- **Scalability:** The community-built nature of Hello Hubs fosters scalability. By involving the community in construction, residents gain transferable skills in maintenance and repair, enabling them to manage and potentially expand the project over time.
- **Replicability:** To ensure widespread adoption, Hello World offers a detailed "How to Guide" for global use. This comprehensive guide empowers other communities to replicate the model and benefit from its advantages.

Partnerships and impact measurement: Partnerships and Measurable Impact: Hello World goes beyond community partnerships. They collaborate with the private sector, securing funding and fostering employee engagement. This collaborative approach strengthens their impact. Hello World prioritizes rigorous impact measurement through partnerships with organizations like 60 Decibels. Their studies demonstrate positive outcomes:

- **Improved Quality of Life:** A significant 89% of respondents reported an improved quality of life after using Hello Hubs.
- **Skill Development:** 50% of users reported learning new skills through the Hubs, highlighting their potential for empowering individuals.

- **Economic Benefits:** Narrative reports detail increased livelihoods and business creation, suggesting the project's positive impact on local economies.

By collaborating with the private sector and measuring its impact, Hello World demonstrates a strong commitment to sustainable and effective digital learning solutions.

Community ownership: Hello World's approach extends beyond simply building Wi-Fi hubs. They foster a sense of local ownership by involving the entire community in the hub building process. This not only builds stakeholder engagement but also ensures the project aligns with community needs. Furthermore, Hello World integrates impact assessment frameworks into their model. This allows them to continuously evaluate the project's effectiveness and make data-driven decisions for ongoing development. By incorporating feedback and measuring impact, Hello World ensures their hubs remain relevant and maximize their positive contribution to the community.

Value for money: Enhancing Efficiency: Hello World demonstrates a commitment to ongoing optimization. They have reduced costs through two key strategies:

- **Redesigned Hub Kits:** By streamlining the design of the Hello Hub kits, they have minimized material usage and potentially lowered production costs.
- **Local Supply Chains:** Utilizing local materials and suppliers leverages existing infrastructure and potentially reduces transportation costs associated with relying solely on external sources

Hello World Hubs offer a comprehensive solution to bridge the digital divide; empower education, moreover, reach out-of-school children in marginalized communities. By providing internet access, educational resources, and fostering community ownership, Hello World Hubs are a powerful tool for transforming education globally.

6. Implication of Reviewed Case Studies

The case studies from South Africa and Hello World Hubs offer valuable insights into how solar-powered Wi-Fi hubs can effectively address the digital divide in Nigerian communities. By focusing on affordability, accessibility, community engagement, partnerships, and long-term sustainability, these hubs have the potential to empower communities and create a more equitable digital landscape.

The high cost of internet access is a major barrier for low-income communities in Nigeria. The case studies highlight how solar-powered Wi-Fi hubs can tackle this challenge. The South African project demonstrates a dramatic reduction in internet access costs (R5 per 1GB compared to the usual R85 per GB), while Hello World Hubs prioritize reduced unit costs. Beyond affordability, Wi-Fi hub design plays a crucial role in ensuring widespread internet access. The South African case

with its 150-meter Wi-Fi coverage radius eliminates the need for individual households to invest in routers, fostering wider connectivity within the community. Hello World Hubs take this a step further by targeting underserved areas, aiming to reach a large number of people per hub. This approach aligns with the concept of "universal service" in ICT access, explored by Oyedemi (2004). His research emphasizes the importance of infrastructure design that ensures equitable access, particularly in geographically challenged regions. Solar-powered Wi-Fi hubs with broad coverage address the limitations of "last-mile connectivity", making them a viable solution for bridging the digital divide in remote areas of Nigeria.

The case studies also highlight the importance of implementation strategies that go beyond technological solutions. Fostering community engagement and building strong partnerships are crucial for the long-term sustainability of Wi-Fi hub projects. The South African project exemplifies this by promoting a sense of ownership among residents through their participation in hub maintenance. Hello World Hubs take an even more proactive approach by actively involving the community in the construction process. This aligns with research by George and Nafiu (2020) who found that community involvement leads to greater ownership and care for ICT projects, ultimately contributing to their long-term success in Africa.

Collaboration is another key factor. The South African project's multi-stakeholder approach, where multiple companies work together, demonstrates the value of partnerships. Hello World Hubs further emphasize this by collaborating with the private sector for funding and impact measurement. Research by Gyorgy and Randolph (2015) highlights how partnerships between governments, NGOs, and private companies leverage diverse expertise, resources, and funding streams. This collaborative approach leads to more effective, impactful, and sustainable Wi-Fi hub projects.

Leveraging solar power and fostering a sense of community stewardship are critical for the long-term viability of solar-powered Wi-Fi hubs. Both cases highlight the benefits of solar panels, minimizing reliance on unreliable electricity grids a common challenge in developing regions like Nigeria. Solar power ensures consistent Wi-Fi hub operation with minimal external energy dependence, leading to lower maintenance costs in the end. This focus on sustainability aligns with the growing emphasis on Sustainable ICTs (Information and Communication Technologies), as explored by Agboola et al. (2023). Their research highlights the importance of solutions that are both environmentally friendly and economically viable, perfectly fitting the criteria for solar-powered Wi-Fi hubs as a reliable and cost-effective approach to internet access.

Beyond cost savings and environmental benefits, solar power fosters a sense of community empowerment. Local communities are not just passive recipients of a service; they can take pride in a solution that is not reliant on external

resources and is aligned with global efforts to combat climate change. Research by Suleiman et al. (2018) explores this potential of renewable energy technologies like solar power in promoting ICT infrastructure's role in sustainable development for rural areas. Solar-powered Wi-Fi hubs become a tangible symbol of a community's commitment to a sustainable future.

As previously discussed, fostering a sense of community stewardship is crucial for long-term Wi-Fi hub sustainability. The case studies demonstrate two approaches that go beyond simply ensuring basic maintenance. South Africa's resident participation in hub maintenance fosters a sense of responsibility and investment in the project's success. Residents gain practical skills and knowledge about the technology, fostering a sense of ownership that extends beyond simply using the Wi-Fi service. Hello World Hubs take this a step further by actively involving communities in the construction process, creating a stronger sense of ownership from the outset. This aligns with research by Mutale et al. (2017) who found that community involvement leads to greater care and ownership of ICT projects. Studies by Usman et al. (2018) further emphasize the importance of community participation in ensuring long-term viability in developing contexts.

Fostering community stewardship can extend beyond basic maintenance through capacity building initiatives. Training residents on basic repairs, troubleshooting, and even potential future upgrades can empower communities to manage the hubs more effectively. This not only reduces reliance on external technicians but also creates local expertise within the community. Knowledge-sharing workshops can also be implemented to encourage communities to share best practices and problem-solving strategies with each other. By fostering a culture of shared responsibility and knowledge exchange, communities can become true stewards of the Wi-Fi hubs, ensuring their long-term success and maximizing their positive impact on the community's digital and social development.

The Hello World case study highlights the critical role of educational resources within Wi-Fi hub projects. By equipping hubs with educational materials and promoting digital literacy training, communities are empowered to not only access information but also critically evaluate and utilize it effectively. Research by Warschauer (2003) underscores the importance of digital literacy skills in the modern world. He argues that access alone is insufficient; individuals need the ability to navigate the complexities of the digital landscape to fully reap the benefits of internet connectivity. By providing educational resources and training, Hello World Hubs move beyond simply offering internet access. They empower communities to become active participants in the digital world, fostering a more equitable and inclusive digital landscape.

7. Conclusion

The case studies from South Africa and Hello World Hubs paint a promising picture for utilizing solar-powered Wi-Fi hubs to address the digital divide in Nigerian communities.

Solar-powered Wi-Fi hubs, designed with affordability, accessibility, and community engagement in mind, offer a promising solution for bridging the digital divide in Nigerian communities. By fostering a sense of community ownership, collaboration through partnerships, and a focus on long-term sustainability, these projects can empower communities and pave the way for a more equitable and inclusive digital future.

The case studies highlight the crucial role of making internet access affordable and accessible. The dramatic cost reductions showcased demonstrate the potential of Wi-Fi hubs to overcome the financial barriers faced by low-income communities. Additionally, the broad Wi-Fi coverage offered by these hubs ensures wider connectivity within communities, particularly in underserved areas. This aligns with the concept of "universal service" in ICT access, ensuring equitable access for all, regardless of location.

The success of these Wi-Fi hub projects extends beyond the technology itself. By fostering a sense of community ownership and responsibility, the projects ensure long-term sustainability. The South African and Hello World Hubs models, with their resident participation in maintenance and construction respectively, exemplify this approach. Research underlines that such involvement leads to greater care and investment in the project's success. Collaboration is another key factor. The multi-stakeholder approach showcased in the South African project demonstrates the value of partnerships between various entities, leveraging diverse expertise and resources. Hello World Hubs further highlight this by collaborating with the private sector for funding and impact measurement. By fostering a collaborative approach, these projects can be more effective, impactful, and sustainable.

The use of solar power is a crucial element for long-term sustainability. It minimizes reliance on unreliable grids, reduces maintenance costs, and aligns with the growing emphasis on Sustainable ICTs. Beyond the environmental benefits, solar power fosters a sense of community empowerment. Looking forward, incorporating educational resources and digital literacy training, as demonstrated by the Hello World Hubs model, is crucial. Equipping communities with the skills to not only access information but also critically evaluate and utilize it effectively is essential for maximizing the positive impact of these projects.

8. Recommendations

1. Prioritizing affordability and accessibility: in geographically challenged regions, ensuring internet affordability and accessibility for low-income communities is paramount for bridging the digital divide. This can be achieved through the implementation of tiered pricing models, mirroring successful cost reduction strategies employed in projects like the South African case study. Additionally, exploring government subsidy programs can further increase financial viability for marginalized populations. Furthermore, emulating Hello World Hubs' approach of targeting underserved areas and maximizing user reach per hub,

combined with a broad Wi-Fi coverage strategy (similar to the 150-meter radius in the South African project), can foster a more equitable and inclusive digital landscape.

2. Fostering community stewardship: moving beyond the model of basic resident participation in maintenance, as seen in the South African project, Wi-Fi hub projects in remote areas should prioritize fostering a strong sense of community stewardship. This can be achieved by replicating the Hello World Hubs' model of proactive community involvement throughout the entire project lifecycle, including the construction process. Research suggests that such an approach fosters a stronger sense of ownership and responsibility, ultimately leading to increased project sustainability and maximizing the positive impact on the community. By fostering a culture of shared responsibility, communities become true stewards of the Wi-Fi hubs, ensuring their long-term success.

3. Building collaborative partnerships: the multi-stakeholder approach employed in the South African project demonstrates the value of collaboration in achieving successful Wi-Fi hub deployments. Expanding on this concept by building strong partnerships between governments, NGOs, and private companies can leverage diverse expertise, resources, and funding streams. This collaborative approach, as opposed to siloed efforts, can lead to more effective, impactful, and sustainable Wi-Fi hub projects, ultimately contributing to a more equitable digital landscape.

4. Embracing solar power for sustainability and community empowerment: solar panels, as demonstrated in both case studies, offer a win-win solution for Wi-Fi hubs in remote areas. They not only minimize dependence on unreliable electricity grids, a common challenge in developing regions, but also reduce long-term maintenance costs. This aligns with the growing emphasis on Sustainable Information and Communication Technologies (ICTs). Furthermore, solar power fosters a sense of community empowerment. By managing a sustainable solution not reliant on external resources, residents become active participants in shaping their digital future. This approach not only contributes to project sustainability but also aligns with global efforts to combat climate change.

5. Empowering through digital literacy training: the Hello World case study highlights the importance of going beyond simply providing internet access. Equipping Wi-Fi hubs with educational materials and promoting digital literacy training programs empowers communities to not only access information but also critically evaluate and utilize it effectively. By offering these trainings, Wi-Fi hub projects can transform communities from passive recipients into active participants in the digital world, fostering a more equitable and inclusive digital landscape.

9. Authors Contributions

The study was conceived and designed by the corresponding author, who also conducted a literature review. All authors

contributed to writing the first draft of the manuscript. Subsequently, all authors reviewed, edited, and approved the final version.

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