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Speciality: Economics/Policies/Infrastructures and Green Hydrogen Technology

Topic:

Techno-Economic Analysis of Hybrid Renewable Energy Systems for Off-Grid Power Supply and Hydrogen Production: A case study of the Yalgo community, Burkina Faso

Presented, 16th September 2025 by:

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Dedication

This thesis is dedicated to my family,

And mentors Assane, Richa, and Maria.

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Acronyms and Abbreviations

AC	:	Alternative Current
ATP	:	Ability To Pay
BAT	:	Battery
CAPEX	:	Capital Expenditure
CO2	:	Carbone dioxyde
CRF	:	Cost Recovery Factor
DC	:	Direct Courant
DG	:	Diesel Generator
EG	:	Energy Generator
FED	:	Future Electricity Demand
GSP	:	Graduate School Programme
HOMER	:	Hybrid Optimisation Model for Energy Resources
HRES	:	Hybrid Renewable Energy Sources
IEA	:	International Energy Agency
IRENA	:	International Renewable Energy Agency
LCOE	:	Levelised Cost of Energy
LCOH	:	Levelised Cost of Hydrogen
NPC	:	Net Present Cost
OPEX	:	Operational Expenditure
PANER	:	Plan d'Action National des Energies Renouvelables
PED	:	Present Electricity Demand
PM	:	Profit Margin
PV	:	Photovoltaic
RE	:	Renewable Energy
RES	:	Renewable Energy Sources
RES	:	Renewable Energy Sources
SONABEL	:	Société National Burkinabè d'Electricity
STC	:	Standard Test Condition
USD	:	United States Dollars
WASCAL	:	West African Science Service Centre for Climate and Adapted Land Use
WT	:	Wind Turbines
WTP	:	Willigness To Pay

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Abstract

In Burkina Faso, ensuring access to modern, reliable, and affordable energy remains a major challenge, particularly in rural areas, where, as of 2022, the electrification rate stood at just 5.49% compared to 86.96% in urban areas according to the Rural Electrification Strategy (2024). This study proposes a hybrid renewable energy system (HRES) tailored to the off-grid community of Yalgo in northern Burkina. A techno-economic evaluation and affordability assessment are carried out for a demand of 1762.05 kWh/day, estimated through a door-to-door survey, while also considering green hydrogen production. Four technical scenarios are optimised using HOMER software and compared in respect of the net present cost (NPC), levelized cost of energy (LCOE), electricity unmet demand (UD), and excess energy produced (EEP). The first three scenarios include wind-battery, PV-battery, and Wind-PV & battery. The wind-PV & battery configuration proves more attractive, delivering an LCOE of 0.28 USD/kWh, with UD of less than 1% and about 40% EEP. Building on this result, an electrolyser is integrated into the optimal configuration, making the fourth scenario (Wind/PV/Battery/Electrolyser) suitable for evaluating hydrogen co-production. Hydrogen is generated primarily from surplus electricity and, in turn, lowers EEP to 9.25 % while maintaining 100% coverage of the community's electricity demand. Although the LCOE rises to 0.8 USD/kWh, the system remains competitive for remote contexts. Beyond acting as a flexible energy carrier, green hydrogen opens opportunities for power regeneration, local mobility, agro-processing, and clean-cooking applications, thereby adding value that would otherwise be lost. Finally, three tariff-design scenarios, are analysed to identify structures that keep community expenditure below common affordability thresholds and address energy justice concerns. The novelty of this work lies in combining detailed techno-economic optimisation with scenario-based tariff analysis to deliver a 100% renewable energy, hydrogen-enhanced electrification solution explicitly benchmarked against rural income levels. This integrated framework and its results provide new evidence for designing equitable, sustainable energy systems, offering policymakers and rural electrification stakeholders a replicable blueprint for Africa's green hydrogen future.

Keywords: **Electricity access, Hybrid Renewable Energy systems, Hydrogen, Affordability, Tariff design**

Resumé

Au Burkina Faso, garantir l'accès à une énergie moderne, fiable et abordable reste un défi majeur, en particulier dans les zones rurales où, selon la Stratégie d'électrification rurale (2024), le taux d'électrification n'était que de 5,49 % en 2022, contre 86,96 % dans les zones urbaines. Cette étude propose un système hybride d'énergie renouvelable adapté à la communauté hors réseau de Yalgo, dans le nord du Burkina. Une évaluation technico-économique et une analyse de l'accessibilité financière sont réalisées pour une demande de 1 762,05 kWh/jr, estimée à partir d'une enquête porte-à-porte, tout en tenant compte de la production d'hydrogène vert. Quatre scénarios techniques sont optimisés à l'aide du logiciel HOMER et comparés en termes de coût net actuel (NPC), coût de production d’électricité, de demande d'électricité non satisfaite (UD) et d'excédent d'énergie produite (EEP). Les trois premiers scénarios comprennent l'éolien/batterie, le photovoltaïque/batterie et l'éolien/photovoltaïque/batterie. La configuration éolien/PV/batterie s'avère plus intéressante, avec un LCOE de 0,28 USD/kWh, une UD inférieure à 1 % et un EEP d'environ 40 %. Sur la base de ce résultat, un électrolyseur est intégré à la configuration optimale, ce qui donne le quatrième scénario (éolien/PV/batterie/électrolyseur) pour évaluer la coproduction d'hydrogène. L'hydrogène est principalement produit à partir de l'électricité excédentaire, ce qui réduit l'EEP à 9.25 % tout en maintenant une couverture de 100 % de la demande en électricité de la communauté. Bien que le LCOE augmente a 0.8 USD/kWh, le système reste compétitif pour les contextes isolés. Au-delà de son rôle de vecteur d'énergie flexible, l'hydrogène vert ouvre des possibilités en matière de régénération d'électricité, de mobilité locale, de transformation agricole et d'applications de cuisson propre, ajoutant ainsi une valeur. Enfin, cinq (03) scénarios de tarification sont analysés, afin d'identifier les structures qui maintiennent les dépenses de la communauté en dessous des seuils d'accessibilité courants et répondent aux préoccupations en matière de justice énergétique. La nouveauté de ce travail réside dans la combinaison d'une optimisation technico-économique détaillée et d'une analyse tarifaire basée sur des scénarios afin de fournir une solution d'électrification 100 % renouvelable et améliorée par l'hydrogène, explicitement comparée aux niveaux de revenus ruraux. Ce cadre intégré et ses résultats fournissent de nouvelles preuves pour la conception de systèmes énergétiques équitables, offrant aux décideurs politiques et aux acteurs de l'électrification rurale un modèle reproductible pour l'avenir de l'hydrogène vert en Afrique.

Mots clés **: Accès à l'électricité, Systèmes hybrides d'énergie renouvelable, Hydrogène, Accessibilité financière, Conception tarifaire.**

Introduction

- Background

Access to modern, reliable, and affordable energy remains one of the challenges in most of the Sub-Saharan African (SSA) countries, where over 600 million people still live without electricity and rely heavily on traditional biomass such as wood and charcoal for cooking (World Bank, 2024). Only 18% of the SSA population uses clean cooking fuels, while fossil fuel-based electricity systems persist, despite their high cost, environmental impact, and misalignment with global climate goals (Wright et al., 2020). As the world strives to limit global warming to 1.5°C by 2030 (Méjean et al., 2019), a transition toward renewable energy systems becomes important, particularly for rural communities.

However, renewable energy sources such as solar and wind, though abundant, are intermittent by nature. This intermittency poses a technical challenge in continuously meeting electricity demand, particularly in isolated and off-grid contexts. Several researchers, including Boly et al., (2021), have highlighted the limitations of standalone systems and recommend combining multiple energy sources to improve supply reliability and system resilience.

In Burkina Faso, the electricity access situation reflects the broader regional trend. As of 2022, according to the "Strategie Nationale d'Electrification Rural" (2024), the country's electricity access rate stood at 26.69%, with significant disparity between urban areas (86.96%) and rural areas (only 5.49%).

In response, the government has committed to raising the rural electrification rate to 50% and national coverage to 80% by 2028. Additionally, the National Renewable Energy Action Plan (PANER) targets a 50% share of renewables in the national electricity mix by 2050. The country also benefits from substantial renewable energy potential, with average solar irradiance of 5.5 kWh/m²/day and average wind speeds around 5 m/s (Ouedraogo et al., 2015b). This creates an opportunity for exploring hybrid renewable systems to face the challenges related to electrification, especially in rural areas. Considering the high renewable energy potential the country has; it can also push to investigate the opportunity of incorporating hydrogen production in off-grid renewable power supply systems. According to Ahmed et al., (2025)Hydrogen offers a complementary solution to address energy storage challenges, while also enabling new uses such as clean cooking and green fertilizer production for agriculture.

- Problem statement

Despite Burkina Faso's renewable energy potential and favourable legal frameworks, access to modern electricity in rural areas remains among the lowest globally. The reliance on Solar Home Systems (Yamegueu et al., 2024) and/or single-source renewable systems like solar-only configurations often lead to unmet demand. While hybrid systems combining solar, wind, and battery storage (100% renewable energy systems) offer improved reliability in rural areas (Ceran et al., 2021) less studies have been done in Burkina Faso's context to the best of our knowledge, except studies on hybrid PV-Diesel that have been done by many researchers, including Ouedraogo, (2019) and Ouedraogo & Yamegueu, (2019). In addition, the potential of hydrogen production as a means of storing excess renewable electricity and supporting clean energy services has not yet been fully explored in off-grid rural electrification strategies, especially in West African countries, including Burkina Faso.

Moreover, there is a critical challenge regarding the affordability of hybrid renewable energy systems for low-income rural populations. According to Krishan & Suhag, (2019) while technical and economic feasibility are often analysed through metrics like Levelized Cost of Energy (LCOE) and capital expenditure (CAPEX), studies frequently overlook the direct financial burden on households. Without a robust evidence base that integrates both system costs and detailed assessments of household energy expenditure and willingness-to-pay, rural electrification initiatives risk failing to deliver truly accessible and sustainable energy solutions. Bridging this gap is essential to guiding effective planning and targeted investment, ensuring that rural green energy systems do not merely exist but are economically viable and affordable for the communities they are meant to serve.

- Research Question

To address this research gap, the following research questions constitute the focus of the current study:

1. What is the most techno-economically optimal renewable energy system configuration for off-grid electrification in Yalgo, Burkina Faso?
2. What is the impact of integrating hydrogen production from surplus renewable energy on the overall cost and system operation of the optimized hybrid renewable energy system?
3. How can tariffs be designed to ensure equitable access to electricity?

- Research Objectives

To properly respond to the research questions, the thesis aims to evaluate the technical and economic feasibility of hybrid renewable energy systems (HRES) for off-grid power supply, including hydrogen production in rural Burkina Faso. The research aims specifically to (1) design and simulate different hybrid energy system configurations (solar PV, wind, battery, electrolyser and hydrogen tank) based on the local resource availability and community load profiles; (2) assess the performance of each configuration in terms of energy reliability and excess generation; (3) assess the economic viability of the systems and select the most optimal and affordable energy solution that supports electrification of Yalgo community ensuring energy justice concerns with various electricity tariffs.

- Scope of the study

The study focuses on a techno-economic assessment of hybrid renewable energy systems (HRES) designed to supply off-grid electricity and green hydrogen in the rural context of Yalgo, Burkina Faso. It is limited to a small-scale, community-based system, using a combination of solar PV, wind turbines, battery storage, and an electrolyser for hydrogen production. The research will only focus on the production of hydrogen using excess electricity and will not focus on its end use. It will also focus on the economic analysis, including the evaluation of LCOE, NPC, LCOH, electricity unmet demand, tariffs, and affordability assessment.

The study will be sectioned in three main chapters to properly respond to the research questions, starting from an introduction and literature review in chapter one, followed by the method and materials used in chapter two. Chapter three will focus on presenting the results obtained after the simulation, and then the discussions. Finally, a conclusion will help summarise the research and propose recommendations.

Chapter 1: Review of HRES and hydrogen energy storage system

This chapter reviews hybrid renewable energy systems (HRES) with a focus on their technical, economic, and affordability aspects for rural electrification. It explores key concepts of HRES, their relevance in off-grid areas, and approaches for techno-economic analysis. The section also highlights rural energy challenges in Burkina Faso, the status of HRES-related studies, and the country's renewable energy potential. Finally, the role of Hydrogen Energy Storage Systems (HESS) in supporting HRES deployment for improved reliability and energy access is discussed

1.1. Overview of Hybrid Renewable Energy Systems

1.1.1. Need for hybridization of RESs

A Hybrid Energy System (HES) is defined as the combination of two or more energy supply systems (T. Ahmad & Zhang, 2021). It is particularly called hybrid renewable energy systems (HRES) when two or more energy sources are renewables like solar, wind, biomass, hydroelectricity, etc., and are used to provide power (Sood & Muthusamy, 2020).

Hassan, Algburi, et al., 2023 has grouped the Hybrid Renewable Energy Sources relevance in the following points:

- HRESs improve energy availability: Seasonal and weather-related fluctuations in renewable energy production are common. Hybrid systems help address this issue by blending different sources to ensure a continuous and dependable energy supply throughout the year, meeting ongoing demand (Hassan, 2021).
- HRESs increase production efficiency: Certain renewable sources, such as solar panels, may generate surplus energy during peak conditions. When combined with energy storage technologies, this excess can be stored and used during periods of low production, thereby boosting grid reliability and performance (Jaszczur et al., 2020). Additionally, combining, for example, solar and wind energy sources could help continuous energy supply by complementing each other.
- HRESs support remote and off-grid regions: In areas where access to a single, reliable renewable source is limited, hybrid systems offer a viable alternative. By combining various sources, these systems enable energy generation independent of costly fuel-based generators, supporting energy access and development (Hassan et al., 2016).

- HRESs enhance reliability: By integrating complementary sources such as solar and wind, which typically peak at different times of the day or year, hybrid systems can deliver a more consistent and stable power output (Hassan, 2021). This reduces the risk of power shortages during periods of low sunlight or weak wind conditions.
- HRESs facilitate a cleaner energy transition: Hybrid systems provide a transitional pathway by integrating renewable sources with low-carbon backup options such as battery storage or cleaner fossil fuels(Ceran et al., 2017).

The hybridization of renewable energy systems (HRESs) presents a promising solution for enhancing energy access and sustainability, particularly in off-grid and remote areas. However, the deployment of such systems is not without significant challenges.

1.1.2. Different types of HRES

Based on their type of connection, Hybrid Renewable Energy Systems can be broadly categorized into three types (Hassan, Algburi, Sameen, et al., 2023): on-grid, off-grid, and microgrid systems. The figure 1 below gives an illustration of the type of HRES. An on-grid system is directly connected to a centralized electricity grid. According to Hassan et al. (2017), a key advantage of such a system of HRES is the ability to feed surplus electricity back into the grid. However, the performance of this kind of system may be compromised because closely tied to grid stability. Additionally, this system is particularly suitable for urban settings where grid access is reliable and well-developed (Chennaif et al., 2022). This means that this system is not an option for remote areas where grid access is a key challenge. The second type of HERS is the off-grid systems, which are designed to function independently of the central grid. They are typically deployed in rural or remote areas lacking reliable grid access. In most cases, these systems rely on energy storage solutions such as batteries to store excess electricity produced for usage during periods of low supply (Ceran et al., 2021). This allows the off-grid systems to provide autonomy and energy security for rural communities, but it often involves higher upfront costs due to the need for storage infrastructure and more advanced control systems. The last classified type of HRES is the microgrid systems. These systems are positioned between on-grid and off-grid configurations. They can operate either autonomously or in coordination with the main grid (Jurasz et al., 2022). Additionally, the microgrids offer enhanced flexibility and are well-suited for institutions such as universities, industrial complexes, or military facilities.

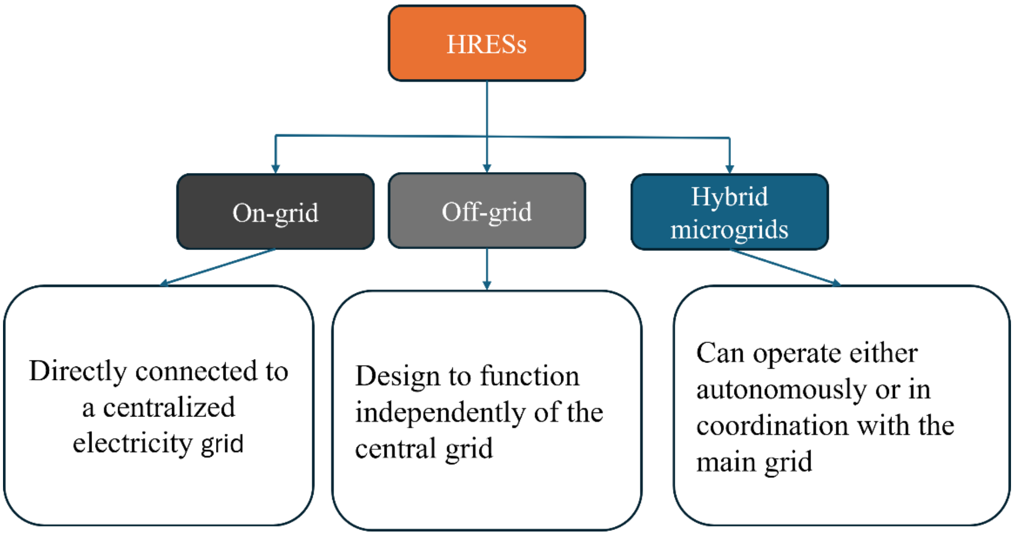

Figure 1. Classification of HRES.

Source : (Hassan, Algburi, Sameen, et al., 2023)

Hybrid Renewable Energy Systems integrate multiple energy generation sources, storage technologies, and power management components to ensure a reliable and continuous power supply, particularly in off-grid or weak-grid areas (In et al., 2021). According to Pandiyan et al., (2022) the typical components of an HRES include energy resources such as PV, Wind turbines, Hydro, bioenergy; energy storage like batteries and hydrogen storage units; and power conversion equipment, including inverters and charge controllers. Some configurations also incorporate backup generators like diesel gensets.

Several configurations of HRESs have been widely studied and implemented depending on specific resource availability and energy demand profiles. Among the most common are PV-Battery systems, which are simple but limited by solar resource intermittency. More advanced configurations combine both PV and wind turbines with battery storage, showing the complementarity between solar and wind generation to improve energy supply stability (Carlos et al., 2023). In more recent approaches, hydrogen technologies such as electrolysers, hydrogen storage tanks, and fuel cells are integrated into HRESs to convert excess renewable electricity into hydrogen for long-term energy storage (Hassan, Sameen, et al., 2023).

Studies by Boly et al., (2021) and Kelly et al., (2023) have shown that PV-Wind-Battery systems offer optimal reliability in regions with seasonal variation in solar and wind availability. Other works, such as (Ouedraogo et al., 2015b), have emphasized the potential of hydrogen in rural hybrid systems as a clean alternative for long-term storage and energy independence. However, research tailored to the socio-economic and climatic realities of West Africa, particularly

Burkina Faso, remains limited. Most existing studies focus on Asian or island contexts, leaving a gap in the literature regarding configurations optimized for the Sahel region's unique combination of high solar potential, moderate wind availability, and rural energy needs.

1.2. Hybrid Renewable Energy Systems in Rural Electrification (RE)

Rural electrification in Sub-Saharan Africa (SSA) presents a significant challenge, with electrification rates hovering between 32% and 35%, and only 14% of this figure represents rural access, leaving approximately 290 million people without modern energy services (Come Zebra et al., 2021). The development of HERSs in Africa shows significant efforts in expanding energy access, but important gaps persist in planning and deployment (Come Zebra et al., 2021). Literature has shown that many countries have implemented frameworks to increase rural electricity access from renewables. For instance, Nigeria has 30 operational mini-grids for about 1MW installed capacity (IRENA, 2021) Mali has successfully implemented over 200 diesel-PV mini grids to improve electricity access in rural areas of sub-Saharan Africa (Safdar, 2017) Kenya's experience with 21 mini grids, about 19.16 MW of total capacity, largely diesel-based systems (Pueyo & DeMartino, 2018) and Tanzania, with 16 grid-connected and 93 isolated diesel-based hybrid energy systems (Fadaeenejad et al., 2021). However, there remains a technological gap in achieving 100% renewable configurations, as in most cases, diesel and grid backup continue to dominate. Integrating or combining more variables RES can help not only to reduce the dependence on diesel generators as backup systems, decrease environmental impacts due to fossil fuels, but also to provide a more reliable electricity supply even in remote areas.

According to Narayanan et al. (2019), hybrid renewable energy systems provide a better solution than both diesel generators and single standalone systems. While numerous studies have established that hybrid renewable energy systems (HRES) can substantially reduce greenhouse gas emissions and offer operational efficiencies over single-source or diesel-based electrification solutions (Akikur et al., 2013), most literature emphasizes technical feasibility and cost optimization but pays insufficient attention to the end-user affordability and socio-economic impacts in rural, low-income settings. Indeed, many researchers and studies commissioned by international organizations such as IRENA and the World Bank estimated that the LCOE of HRES will significantly decrease in the future years (Come Zebra et al., 2021b). These findings on declining LCOE and improved reliability are necessary milestones; however, the underlying assumption is often that reducing the LCOE will automatically translate to affordable access for rural households, an outcome not consistently borne out in practice, leaving a gap in the literature for a proper assessment of the affordability for low-income communities. In addition, a recurring issue highlighted in recent review papers is that high initial capital costs, technical complexity, and lack of context-specific financial mechanisms often push the final tariff above the willingness or ability to pay of rural communities, even as the LCOE declines globally (Smith, 2025). According to Firdouse & Reddy, (2022) system costs and economic viability are heavily influenced by local parameters such as resource availability, component pricing, and O&M costs, yet few studies rigorously map these variables to actual affordability outcomes for users. As a result, there remains a critical knowledge gap in directly linking techno-economic optimization with inclusive, sustainable access at the community level, particularly in sub-Saharan Africa.

Given the high cost and logistical barriers of grid extension, Burkina Faso has prioritized hybrid renewable systems, with PV/diesel combinations widely studied and deployed (Boly et al., 2021). Evidence from Pissila village shows that PV/diesel hybrids are more cost-effective (LCOE ≈ 0.50 USD/kWh) than diesel-only (0.77 USD/kWh) or PV-only (0.75 USD/kWh) systems, reducing costs by over 50% compared to diesel (Ouedraogo, 2019). However, these systems remain highly sensitive to fuel prices and discount rates, with costs easily doubling under unfavourable conditions (Ouedraogo, 2019). Furthermore, despite being cheaper than diesel, PV/diesel hybrids are still nearly twice as costly as SONABEL's urban grid tariffs, mainly due to fuel supply and transport costs in remote areas (Bonkoungou et al., 2023) reducing considerably the affordability of low-income communities. In contrast, regional studies show that PV-wind-battery or PV-biogas hybrids can achieve much lower LCOEs (0.236 - 0.279 USD/kWh), suggesting a stronger economic case for renewable-based configurations (Rabetanetiarimanana et al., 2018). Yet, this evidence is largely drawn from outside Burkina Faso, leaving a critical gap: the cost-effectiveness of fully renewable hybrid systems (without diesel) remains underexplored in the Burkinabe rural electrification context.

According to SONABEL, (2023), rural electrification in Burkina Faso remains largely dependent on diesel generators, small-scale PV and fragmented systems. By 2022, installed capacity in rural areas included 2.04 MW of diesel generators and 2.18 MWp of solar PV, with total production reaching 316.3 GWh. The infrastructure consists of mini solar plants, hybrid solar–diesel systems, solar injection plants, and a few thermal generators, while the private sector contributed only about 760 kWp. In addition, decentralized solutions such as Solar Home

Systems (≈ 23,845 kits), community solar kits, and thousands of solar streetlights have been deployed. These efforts demonstrate tangible progress in extending electricity access to rural areas. However, most of the systems still face two major limitations: (i) lack of reliability due to the intermittency of solar generation and the absence of strong complementary resources (Oliveira et al., 2020), (ii) high electricity costs that remain unaffordable for low-income rural households (Brown et al., 2020). This creates a critical gap, as rural electrification strategies have expanded access but failed to ensure long-term sustainability, affordability, and resilience.

1.3. Hydrogen Energy Storage System (HESS) to enhance rural electrification

Hydrogen Energy Storage Systems (HESS) are increasingly explored as a solution to address the intermittency of renewables in rural off-grid applications. For instance, Ayodele et al., (2021) assessed a solar-wind-hydrogen hybrid microgrid for a South African health clinic, achieving full renewable autonomy and over 1,700 hours of hydrogen backup. However, the system showed high costs, with an LCOE of USD 2.34/kWh due to the elevated hydrogen production cost (USD 13.2/kg). Similarly, (Akarsu & Serdar Genç, 2022) evaluated an HRES in rural Pakistan and demonstrated high technical reliability but an LCOE of USD 0.41/kWh, well above national benchmarks. Other recent studies (Ahmed et al., 2025; Samson et al., 2024) confirm that hydrogen integration enables 100% renewable penetration but still results in relatively high LCOEs, ranging from USD 0.41/kWh to 0.68/kWh. These findings underline a consistent trade-off: hydrogen improves system reliability and long-term storage but remains cost-intensive, largely due to electrolyser costs. In the context of Burkina Faso, where rural electrification already faces affordability challenges, this raises a critical gap. Few studies assess how hydrogen could be integrated into hybrid renewable systems under local socio-economic and resource conditions. Addressing this gap is essential to determine whether hydrogen can contribute not only to reliability and decarbonization but also to economically viable energy access solutions tailored to low-income rural communities such as Yalgo.

1.4. Burkina Faso Renewable energy potential for adopting HERS

- Solar Energy Potential

According to the Global Solar Atlas, Burkina Faso exhibits a high solar energy potential due to its geographical position within the Sahel region, not very far from the equator. Satellite-derived datasets from the Global Solar Atlas indicate that the country receives Global Horizontal Irradiance (GHI) values exceeding 5.5 kWh/m²/day on average, with localized maxima reaching close to 6.0 kWh/m²/day in central and northern areas. According to estimates from the International Renewable Energy Agency (IRENA), Burkina Faso's technical solar potential is on the order of 20,000 MW with around 2000 to 3500 hours of sun availability per year.

- Wind Energy Potential

Wind energy potential in Burkina Faso is comparatively moderate but non-negligible, particularly in regions situated in the north and east of the country. Wind resource assessments performed at 80 meters above ground level suggest mean wind speeds ranging from 4.0 to 6.0 m/s, conditions conducive to small and medium-scale wind turbines. ResearchGate and Global Wind Atlas datasets (Landry et al., 2016) reveal localized wind corridors where wind power density could support hybridized energy systems. The technical potential for wind energy has been estimated at approximately 312 MW, corresponding to an annual generation capacity of 741 GWh. While these figures are modest relative to solar projections, they nonetheless represent a viable component of Burkina Faso's renewable energy portfolio.

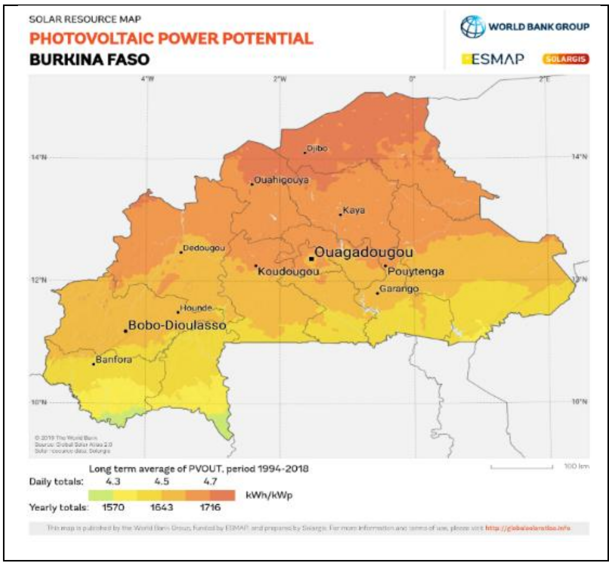

Figure 2. Solar photovoltaic potential

Source : (ESMAP, 2025)

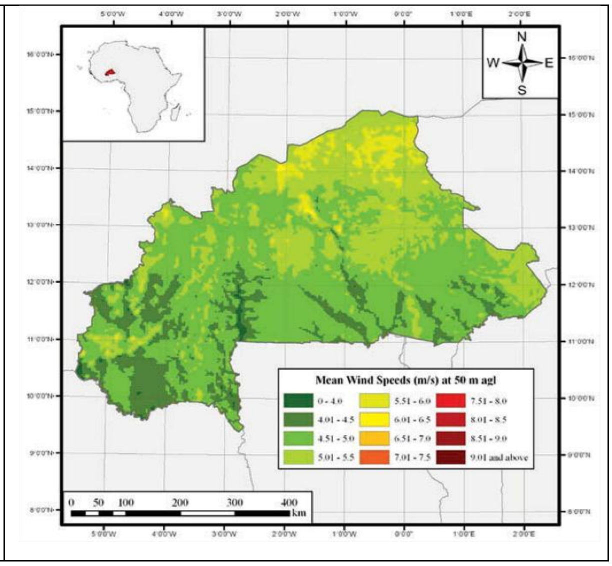

Figure 3. Wind speed potential

source: (Landry et al., 2016)

1.5. Review of Tariff design and affordability assessment

According to Reber et al., (2018), discussions on micro-grid tariffs must begin with the different incentives of stakeholders, who can broadly be grouped into three categories: governments (policy and regulation), developers (project implementation and financial accountability), and customers (whose willingness to pay influences tariff design) (Baring-gould et al., 2016).

Two main tariff approaches dominate (Reber et al., 2018): national utility tariffs and cost-reflective tariffs. National tariffs, often politically attractive, aim for equity across urban and rural users but are typically sustained by subsidies or cross-subsidies. However, low and inadequate tariffs remain a barrier to private investment and rural electrification, as illustrated by the financial struggles of TANESCO in Tanzania(Reber & Booth, 2018). In contrast, cost-reflective tariffs ensure financial sustainability by covering capital and operational costs (Safdar, 2017). These tariffs attract investment and accelerate deployment, but are generally higher, raising concerns about affordability and political acceptance in rural areas (Babatunde & Ighravwe, 2020).

To bridge the gap, hybrid and alternative approaches have been introduced. These include subsidies to align cost-reflective tariffs with grid rates, cost-plus regulation, or cross-subsidization mechanisms(Reber & Booth, 2018). Some models also benchmark electricity costs against alternatives like diesel and kerosene. Promising results have been reported in countries such as Rwanda and Tanzania (Reber et al., 2018). Additionally, community-based tariff models are emerging (Babatunde & Ighravwe, 2020), where local cooperatives own, manage, and regulate mini-grids with initial donor or grant support (examples include micro-hydro systems in Kenya and Sri Lanka).

Overall, while standardized tariffs promote equity and cost-reflective tariffs ensure sustainability, hybrid and community-based approaches offer a pragmatic balance between affordability, investment viability, and scalability for rural electrification.

Despite extensive international attention to rural electrification models and tariff setting, there remains a critical gap in the literature when it comes to case-specific techno-economic and affordability-focused studies for Burkina Faso (Ouedraogo et al., 2015). Much of the existing work is oriented towards generalized infrastructure planning, least-cost electrification pathways, or comparative analysis of off-grid versus grid-based approaches (Aly et al., 2011). However, studies commonly stop short of directly evaluating whether proposed hybrid renewable or mini-grid solutions are affordable for end users, particularly the poorest rural households.

Exploring the techno-economic of 100 % renewable energy hybrid system for power generation in rural areas in Burkina Faso, identifying the best configuration HRES with installed capacity shares according to a specific energy demand, assessing the affordability of such configuration for households and investigating the role hydrogen coproduction in such system are among others the gaps left in literature that the current study in going the fill.

Chapter 2: Materials and Methods

The methodology of the present study is designed to come up with concrete responses to the research questions. The study uses a techno-economic analysis to evaluate hybrid renewable energy systems for off-grid power supply and hydrogen production for a community in the Yalgo village, Burkina Faso. It includes a case study identification, description, and renewable resource assessment using solar and wind data from NASA's Prediction of Worldwide Energy Resource (POWER). Additionally, it involves energy demand assessment via community surveys covering households and public services. The system design is based on scenario-based analysis using HOMER Pro software to simulate four energy system configurations, including solar PV, wind, battery storage, and electrolyser. The following figure presents the methodology flow of the study.

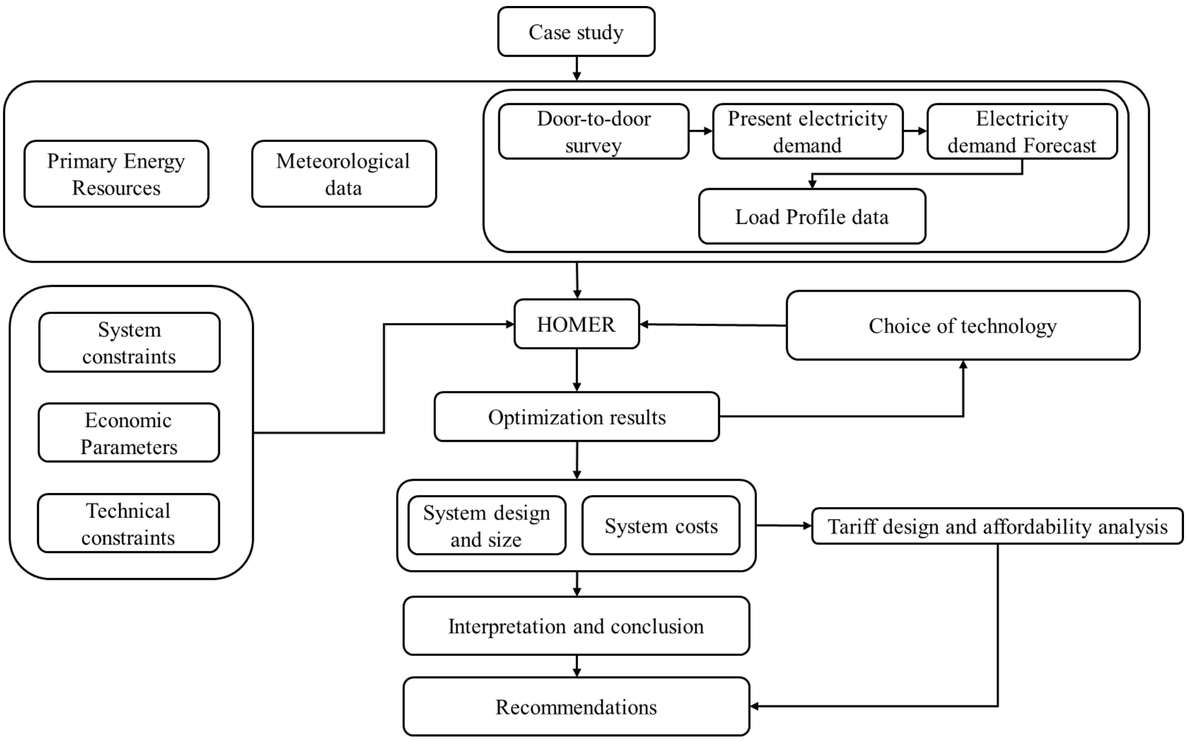

Figure 4. The study methodology flow chart

2.1. Description of the tool used (HOMER)

HOMER Pro (Hybrid Optimization of Multiple Energy Resources**)** was selected as the primary modelling tool for this study due to its global recognition and robust capability in the techno-economic optimization of hybrid renewable energy systems (HRES). The software offers detailed hourly simulations over an annual period, allowing accurate assessment of energy supply-demand balances while considering resource variability, component performance, and system economics. Its optimization engine, which combines exhaustive grid search with the advanced derivative-free HOMER Optimizer®, ensures comprehensive exploration of possible configurations and identification of the least-cost solution in terms of Net Present Cost (NPC). Beyond its technical strengths, HOMER Pro has been widely used in energy planning research across Africa, particularly for rural electrification and microgrid design. Many researchers in West Africa, including Minayégnan et al. (2021) in Côte d'Ivoire, (Odetoye et al., 2023), (Mathew et al., 2024) in Nigeria, and the wider African region have employed HOMER Pro to evaluate renewable-based microgrids, ensuring its credibility, comparability, and relevance to this study. Its proven applicability in similar African contexts further justifies its selection.

HOMER Pro is a software used as the primary tool for the techno-economic optimization of the hybrid renewable energy systems (HRES). It is a globally recognized simulation platform designed for the planning and optimization of microgrids in both off-grid and grid-connected contexts. The software has been widely applied across diverse sectors, including rural electrification, island utilities, campuses, and military installations. The modelling process in HOMER Pro involves inputting detailed data related to the available energy resources (such as solar irradiance and wind speed), component specifications (e.g., solar PV, wind turbines, batteries, electrolysers). The software performs time-step simulations, typically hourly over one year, calculating energy balance for each time step to match energy supply with demand. HOMER Pro's optimisation process employs both a grid search algorithm and a more advanced derivative-free optimizer (HOMER Optimizer®) to explore the full design space and determine the system configuration with the lowest Net Present Cost (NPC).

2.2. Case study description

The study focuses on two distinct rural communities in Burkina Faso: Imasgo village (location A) and Yalgo village (Location B). Imasgo, located in Koudougou province, Centre-Ouest region, served as the primary site for energy demand data collection, while Yalgo, in the Northern Sahel region, was selected as the target site for system implementation site as shown in the following figure.

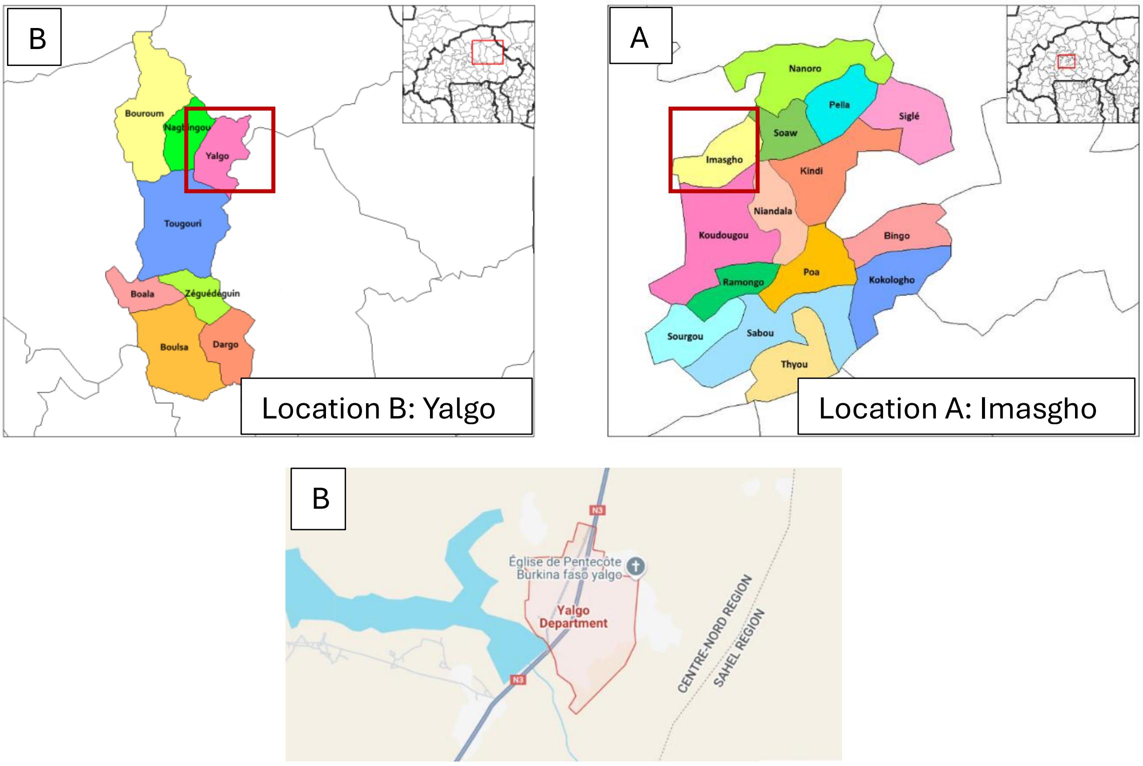

Figure 5. Case study description

(OpenStreetMap, 2023)

The methodological choice to work across these two locations was driven by both data availability constraints and resource optimization considerations. Yalgo was chosen as the implementation site due to its high renewable energy potential, characterized by average solar irradiance of 5.5 kWh/m2/day and favourable wind speed, making it highly suitable for a hybrid renewable energy system. Moreover, Yalgo represents a critical need zone, as the community has no prior access to electricity, limiting economic activities and social services. Unfortunately, this absence of electrification also means that no historical energy consumption data exists for Yalgo, making direct demand analysis impossible.

In response to this data gap, the study used Imasgo, a rural village with similar socio-economic and demographic characteristics, to conduct a detailed energy demand assessment through door-to-door household surveys. Data were collected using Kobo Toolbox, a mobile data collection platform, allowing for accurate recording of household energy use, appliance ownership, and consumption patterns. The survey covered residential, community services (schools, health posts), and small businesses to develop a comprehensive load profile.

The energy consumption data collected from Imasgo were then normalised and adjusted based on population size, environmental conditions, and temperature differences between the two sites to estimate the realistic energy demand for Yalgo. This approach ensures that the energy system design for Yalgo is evidence-based and adapted to the real needs of a typical rural Burkinabe community, despite the absence of direct consumption data for the target site.

Table 1 : Summary of characteristics of the two case study sites

Characteristics	**Imasgo**	**Actual case study (Yalgo)**
Population	578	1500
Temperature range	28°C – 35 °C	28°C – 40 °C
Average Household size	5 – 6 people	4 – 5 people
Socioeconomic activities	Agriculture, small businesses	Agriculture, small businesses
Geographic position	Latitude: 12.26 N	Latitude: 13.75 N
	Longitude: 2.19 W	Longitude: - 0.25 E

This method of using analogue communities as a baseline for energy demand estimation is a widely accepted approach in planning decentralized energy systems, especially in rural or off-grid areas. For instance, in the study by (Bonkoungou et al., 2023a), the authors used a bottom-up load estimation technique that relied on household and community-level assumptions in the absence of measured data. This allowed the study to size hybrid PV-diesel-battery systems by estimating probable daily consumption profiles for different consumer categories, like the present case. Their methodology serves as a strong precedent and supports the use of proxy village data in rural energy planning when real data is unavailable.

2.3. Data collection and Load profile assessment

The load profile assessment comprises the daily present electricity demand calculations, the yearly load profile estimation and normalisation, and finally the future effective electricity demand calculations. The following chart describes the load profile assessment flow process.

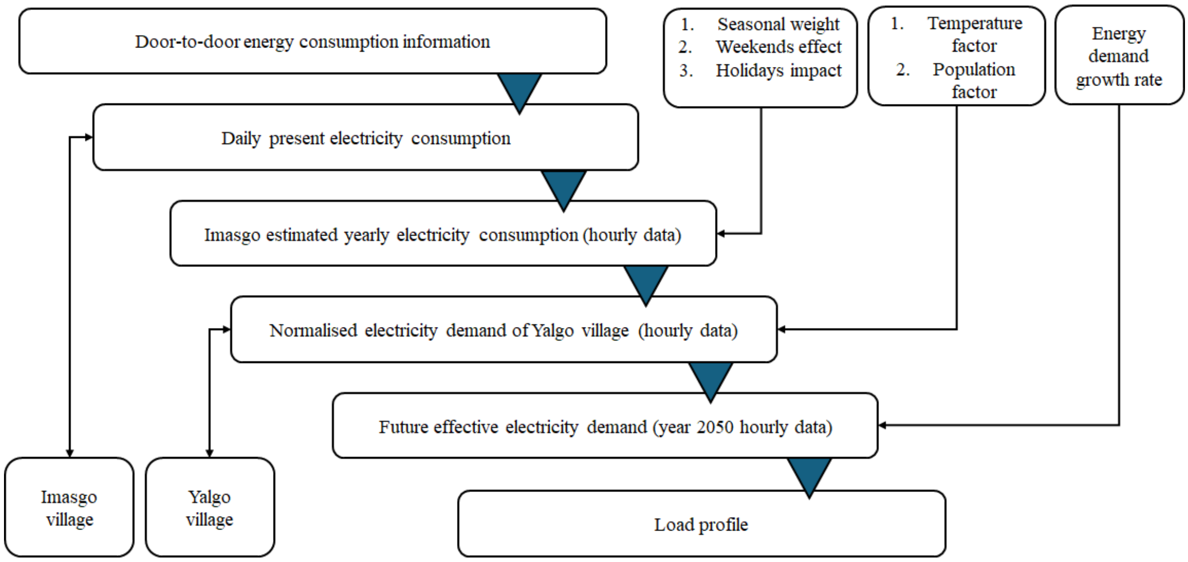

Figure 6 . Yalgo load profile estimation flow chart

Source: Adapted from (Blechinger et al., 2016)

2.3.1. Present electricity demand

The current electricity demand of the case study was assessed through a detailed door-to-door survey in Imasgo village using KoboToolbox. The survey collects information on personal and household details, electricity sources and appliance use, productive uses of electricity for economic activities, and people's willingness and ability to pay for improved or new electricity solutions. The structure include :

- General info : Details about the interviewer and interviewee (name, age, gender, education, household/workplace type, household size).
- Electricity and appliances : Source and availability of electricity, and ownership/use of appliances (fridge, fan, TV, radio, lamps, etc.).
- Productive use : Whether electricity is used for income-generating activities, types of equipment used, hours of use, and future interest.
- Willingness/ability to pay : Interest in new supply solutions, decision-making for payment, satisfaction with access, income levels, electricity expenses, and affordability

A total of 92 respondents participated, covering households, small businesses, and public services. The survey revealed that 59 households (64.13%) were connected to the national grid, 24 (26.09%) used Solar Home Systems (SHS), and 9 respondents (9.78%) had no access to electricity. To reflect accurate, stable electricity usage, this study focused only on the grid-connected consumers, as they represent the most reliable demand pattern. Additionally, the system to propose should be able to supply electricity like the grid with high reliability. The collected data provided detailed insights into appliance ownership, usage hours, and load profiles. The appliance types include fridge, TVs, Fans, lamps, and low-energy consumption devices like phones, tablets, laptops, etc. The following figure represents the daily energy consumption of the Imasgo community involved in the study.

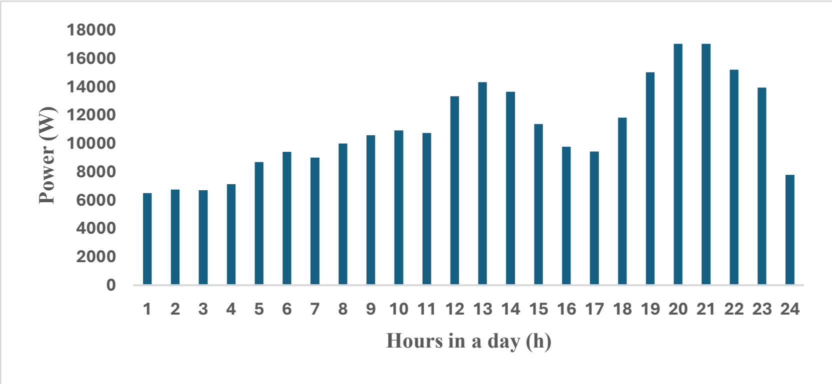

Figure 7. Imasgo daily energy consumption load profile

Based on daily energy consumption, this study aims to project daily energy use on a yearly basis. This is to establish the load profile for the entire year. To achieve this, the bottom-up load estimation method was used to expand the daily load profile into an 8,760-hour load profile for 2025. The method relied on four main parameters: appliance occupancy patterns, variations between weekdays and weekends, the impact of holidays, and seasonal changes throughout the year.

The expansion of the load profile into 8760 followed the following weight variations :

- Seasonal weight

Since the data was collected during April 2025, all months that have the same characteristics as April, especially in terms of temperature variations, have been considered as baseline. This means that the seasonal variation is mainly based on temperature. The higher the temperatures, the higher the energy consumption. According to Bonkoungou et al., (2023) the twelve months can be divided into 3 seasons : (1) March, April, May, Jun (dry and hot season implies high temperatures season then high energy consumption) is considered as baseline; (2) July, August, September (wet season considered as the lowest energy consumption period with 15% of electricity demand decreased (Tete et al., 2024)) ; (3) October, November, December, January and February (dry and cold season with moderate energy consumption. A decreased of 10% compared to the dry and hot season is considered (Tete et al., 2024).

- Week-end effect and Holidays impact

The data collected was obtained during weekdays; therefore, the energy demand will vary from weekday to weekday. According to Masumbuko, (2019) the energy consumption during the weekend will grow by 10 – 12 % if it is dominated by households and more specifically in rural areas. From the survey, 79% the energy demand is from households. Based on that, the study assumes that the energy demand will increase by 10% during the weekend due to the occupancy in residential areas.

The same thing has been applied to holidays after identifying all holidays in a year.

- Total weight calculation and expanded load profile

Putting together the different weights applied, the expanded load for the year 2025 has been obtained.

$$Total\_Weight = Seasonal\_weight \times Weekend\_weight \times Holidays\_weight$$

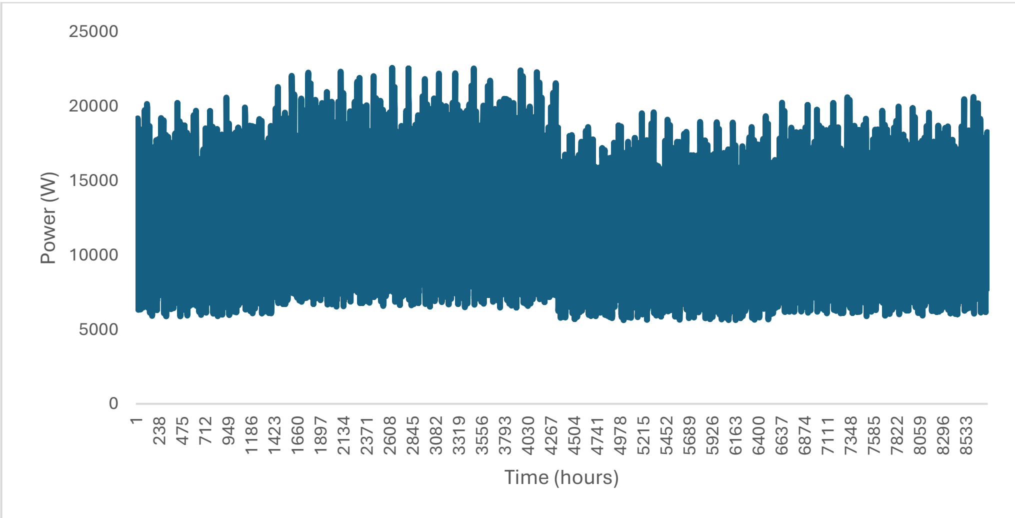

Figure 8. Expanded the daily load profile to an annual profile for the year 2025

Based on national grid maps and resource availability assessments, the village of Yalgo, in the northern part of the country, was selected as Location B. Yalgo is situated more than 20 km away from the nearest 33 kV grid line (African Energy Newsletter, 2025), making grid extension economically and technically less viable. Although Yalgo lacks historical energy consumption data due to its absence of electrification, the survey data from Imasgo were normalized and adapted to the demographic and climatic conditions of Yalgo, as shown in Figure 9. This approach allowed for a realistic estimation of the potential electricity demand of Yalgo's population, supporting the design and sizing of an optimized hybrid renewable energy system tailored to its context.

2.3.2. Load normalisation of Yalgo community

After obtaining the load profile of the year 2025 of the Imasgo village, the study focused on normalizing such a load profile to estimate that of the Yalgo community. To normalize the hourly electricity load profile from Site A (village of Imasgo) to reflect the conditions at Site B (Pensa community), the study applied a two-factor scaling approach based on population and temperature differences. The normalization accounts for the fact that electricity demand generally increases with both population size and ambient temperature, particularly due to cooling or heating needs. First, we aligned the hourly temperature data from both sites and matched it to the load profile's timestamps. Then, for each hour t, the following equation (Bonkoungou et al., 2023) is applied to ensure that the normalized load profile reflects realistic hourly variations due to environmental and demographic differences between the two locations

$$P_{B,t} = P_{A,t} \times \frac{N_B}{N_A} \times \left(\frac{T_{B,t}}{T_{A,t}}\right)^{\alpha t} \tag{1}$$

where $\boldsymbol{P_{A,t}}$ is the original load from Site A, $\boldsymbol{P_{B,t}}$is the normalized load for Site B, N_A and $\boldsymbol{N_B}$ are the populations of Sites A and B, respectively, $\boldsymbol{T_{A,t}}$and $\boldsymbol{T_{B,t}}$ are the hourly temperatures at Sites A and B, and αt is the temperature sensitivity coefficient. We defined $\boldsymbol{\alpha t}$ as 0.6 during the day (07:00 am – 7:00 pm) when cooling loads are higher, and 0.3 during the night.

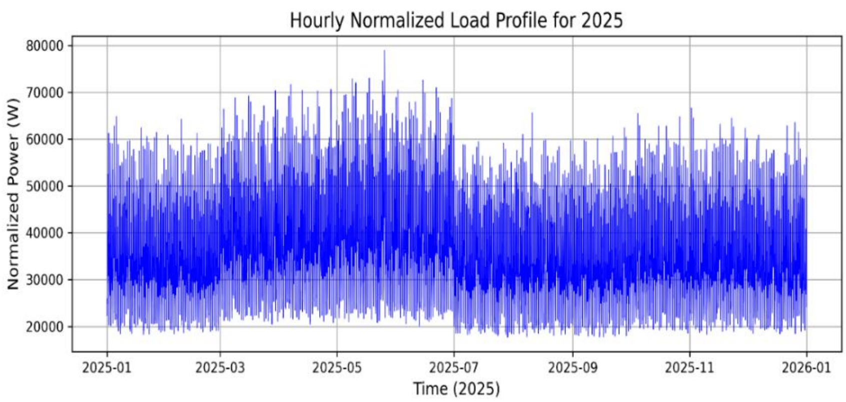

Figure 9 . Normalised load profiles for the Yalgo location

2.3.3. Future effective electricity demand Forecast

Beyond estimating current demand, it is also important to forecast the future effective electricity demand over the next several years, typically aligned with the project lifetime or investment horizon. The load forecast for Yalgo community was conducted using a compound growth rate method with gradual decline to account for expected demand saturation over time. The process began with a base annual demand of 324,000 kWh in 2025, projected forward to 2050. An initial 5% annual growth rate was applied to reflect the expected rapid increase in demand during the early years of electrification. However, since rural demand growth typically slows as access stabilizes and efficiency measures improve, the growth rate was reduced by 1% every five years. This stepwise decline allows the forecast to capture both the early acceleration in energy needs and the long-term stabilization trend. The result, illustrated in Figure 10, shows demand rising steadily until the mid-2030s, after which growth slows, reaching around 645,000 kWh by 2050. This method provides a realistic projection that aligns with rural electrification patterns in Sub-Saharan Africa, where initial demand spikes are followed by slower, sustained growth.

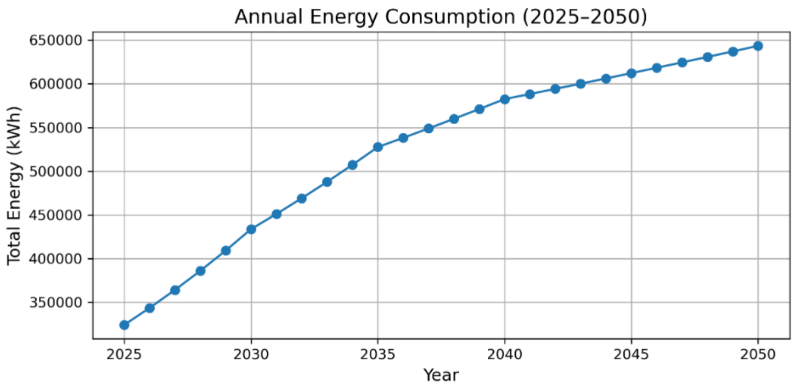

Figure 10. The 2050 forecasted load trend 2025-2050

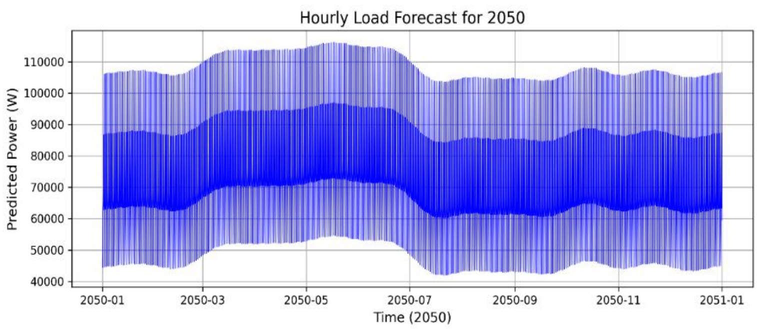

Figure 11. The 2050 forecasted load profile

2.4. Techno-economic data collection

The techno-economic analysis in this study required gathering key technical and financial parameters essential for simulating the hybrid renewable energy systems (HRES) in HOMER Pro. These data points include capital expenditure (CAPEX), operation and maintenance costs (OPEX), replacement costs, equipment lifetimes, and various technical performance metrics, such as efficiency and derating factors. The data were collected from a combination of scientific literature, manufacturer datasheets, and international energy reports. These techno-economic parameters are critical inputs in HOMER Pro, where they are used to simulate system performance, calculate economic indicators such as the Net Present Cost (NPC) and Levelized Cost of Energy (LCOE), and optimize component sizing. The collected data covered all major system components, including solar PV modules, wind turbines, battery storage, inverters, and electrolysers, as well as hydrogen storage.

Table 2. Project's main inputs and assumptions

Project details	**Values**	**Source**
Discount rate	8%	(Ouedraogo & Yamegueu, 2019)
Inflation rate	1%	(Ouedraogo & Yamegueu, 2019)
Project lifetime	25 years	(Amoussou et al., 2023)

Table 3. Components' capital expenditures

	Capex	**Source**
PV system	1,110 USD/kW	(Abid et al., 2021), (Ouedraogo & Yamegueu, 2019)
Wind Turbines	2,500 USD/kW	(Fosso Tajouo et al., 2023)
Batteries	350 USD/kWh	(Abid et al., 2021),
Electrolyser	1000 USD/kW	(Mongird et al., 2020) (Amoussou et al., 2023)
H2 Tank	415 USD/kg	(Amoussou et al., 2023) , (Elberry et al., 2021)
Converter	650 USD/kW	(Abid et al., 2021), (Fosso Tajouo et al., 2023)
Fuel cell	600 USD/kW	(Kharel & Shabani, 2018), (Amoussou et al., 2023)

Table 4. Components' O&M and replacement cost

	Opex	Replacement cost	Source
PV system	1.5% of Capex € /kW/year	---	(Abid et al., 2021), (Ouedraogo & Yamegueu, 2019)
Wind Turbines	25 USD/kW/year	---	(Fosso Tajouo et al., 2023)
Batteries	3.5 /kWh/year	350 USD/kWh	(Abid et al., 2021),
Electrolyser	14.48 USD/kW and 0.5125 USD /Wh	960 USD/kW	(Mongird et al., 2020) (Amoussou et al., 2023)
H2 Tank	2% of capex	---	(Amoussou et al., 2023) , (Elberry et al., 2021)
Converter	98.5 USD/kW/year	650 USD/kW	(Abid et al., 2021), (Fosso Tajouo et al., 2023)

Table 5. Technical parameters of the components

Components	Lifetime (years)	Efficiency	Ref.
PV system	25	22.50%	Canadian Solar Maxpower CS6X-325P
Wind turbine	25		WES100
Batteries	10	90%	Abid et al., 2021
Electrolyser	20	77%	Amoussou et al., 2023
H2 Tank	25		Elberry et al., 2021
Converter	20	95%	Abid et al., 2021

2.5. Renewable energy resources assessment

Two main renewable energy sources are used in the present study, solar Photovoltaic and wind energy. The research, therefore, focuses on assessing the potential of such a source in the system implementation site. This is to be sure of the availability of the resources and their capacity to be considered in the context of planning for 100% renewable energy for communities.

2.5.1. Solar irradiance

The solar resource assessment for the Yalgo community obtained from NASA POWER database reveals a strong and consistent solar potential throughout the year. The analysis of monthly solar radiation data shows that the highest average daily radiation occurs in April, reaching approximately kWh/m²/day, while the lowest value is recorded in January, with around

5.3 kWh/m²/day. Across the year, the average daily solar radiation is approximately 6.1 kWh/m²/day, indicating solar energy availability. When converted to annual energy availability, Yalgo receives approximately 2226 hours of full sun equivalent per year, providing a solid foundation for solar-based power systems. The clearness index, which reflects the fraction of solar radiation reaching the surface, follows a similar seasonal pattern, ranging from about 0.58 to 0.66, suggesting relatively stable atmospheric conditions suitable for photovoltaic generation. These two factors make Yalgo a highly favourable site for solar PV deployment, capable of supporting reliable energy generation for off-grid rural electrification.

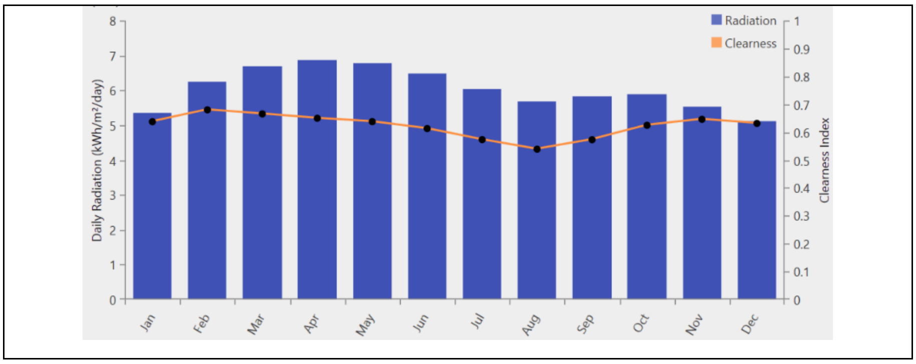

Figure 12. Monthly solar irradiance in the Yalgo location

Source: HOMER

2.5.2. Wind speed availability

The assessment of wind resources in Yalgo was conducted using hourly wind speed data obtained from the NASA POWER database, a reliable global climate data platform widely used for renewable energy studies. Yalgo has an average wind speed of approximately 5.31 m/s, reflecting a moderate wind potential that can be suitable for small to medium-scale wind energy generation. The maximum wind speed recorded was 13.24 m/s, indicating that the area occasionally experiences strong wind conditions that could significantly boost power production. Conversely, the minimum wind speed was observed at 0.3m/s, representing calm periods with little or no wind energy generation. These results confirm that Yalgo possesses a viable wind resource, which, when integrated with solar PV and battery, can contribute to the development of a reliable hybrid renewable energy system.

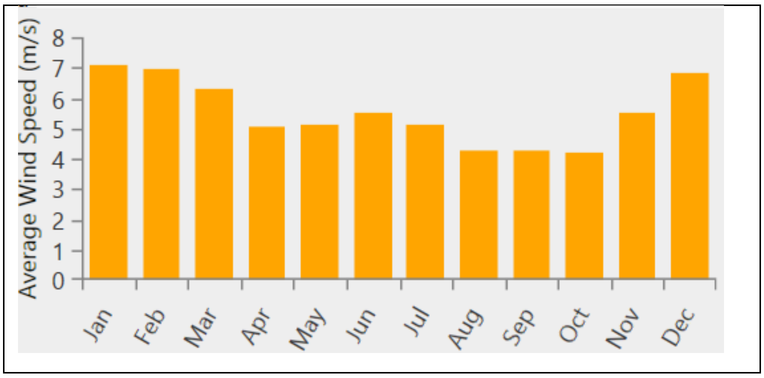

Figure 13. Monthly wind speed variation in the Yalgo location

Source: HOMER

2.6. System design and Optimum sizing using HOMER

The following optimisation chart (figure 14) explains how HOMER software optimises energy system components by displaying the least-cost configuration based on NPC. This represents typically HOMER optimisation flow chart.

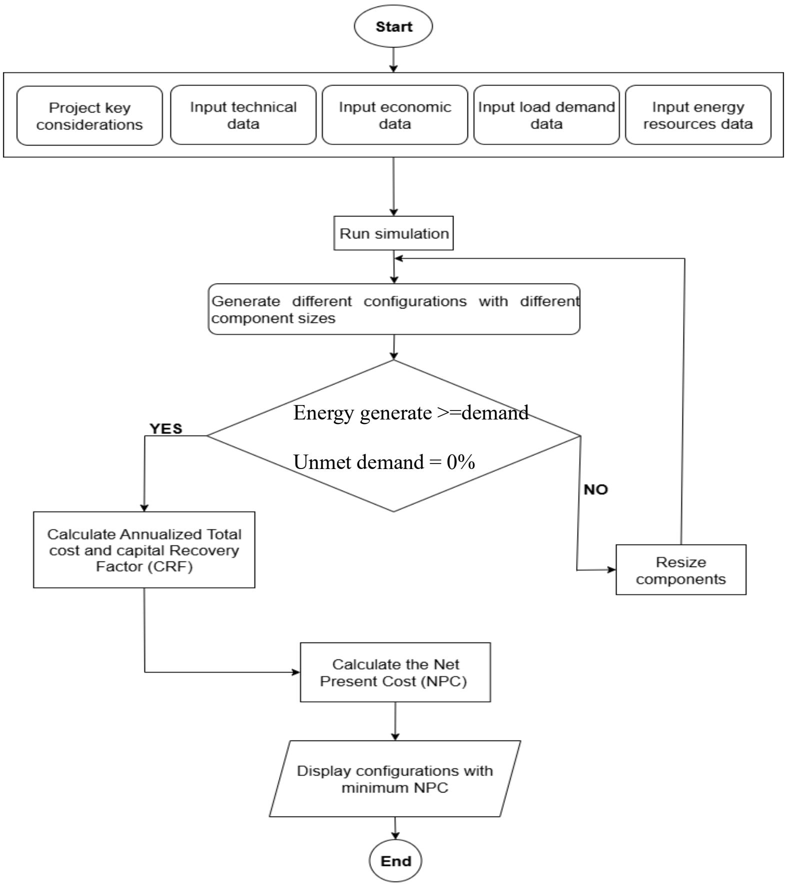

Figure 14. The optimization flow chart by HOMER software

2.6.1. Solar PV power system

Solar photovoltaic (PV) power systems are a cornerstone of renewable energy technology, converting sunlight into electrical energy through the PV effect. This process takes place in solar panels comprised of interconnected solar cells, usually made of silicon. The instantaneous power generated by a PV system in (kW) can be described as follows (Hassan, Algburi, Zuhair, et al., 2023):

$$P_{pv} = C_{pv}.\eta_{pv}.\left(\frac{G}{G_{r,stc}}\right).[1 + \alpha_{pv}(T_{pv} - T_{c,stc})] \quad (2)$$

where C_{pv} is the rated capacity of the PV array (kW), η_{pv} denotes the PV derating factor (%), *G* is the incident solar radiation (kW/m2), $G_{r,stc}$ is the incident solar radiation (kW/m2) at Standard Test Conditions (STC), α_{pv} denotes the PV cell temperature coefficient of power (%/ °C), T_{pv} is the temperature of the PV cell (°C) and $T_{c,stc}$ is the temperature of the PV cell (°C) at STC. Solar PV power systems offer numerous advantages over time, but they also face challenges related to intermittency, upfront costs, and storage. Balancing these strengths and weaknesses is essential for maximizing the benefits of solar energy and addressing its limitations effectively, as presented in Table 7.

For the simulation, the Canadian Solar Maxpower CS6X-325P PV was selected after considering multiple simulation results from several PV modules to arrive at the optimal solution. There are no replacement costs for the PV system over the project's 25-year life cycle since the PV system's life span is the same as the project's life cycle. Due to conditions such as ambient temperature influence, dust, shading, wiring losses, and PV degradation, the PV panels are bound to suffer losses. This PV's derating factor is 88%, and its temperature coefficient is -0.41% per degree Celsius. The efficiency of this PV system in standard conditions is 16.94%. There are 72 polycrystalline cells in this PV module with a capacity of 325 watts. Polycrystalline PV panels are less expensive than single-crystalline silicon cells and perform better in slightly shadowed circumstances. No tracking system is employed for the PV system in this HBMG design. The following contains additional PV specifications.

Table 6. Technical properties of the selected PV module

Parameter	Value	Parameter	Value
Rated Power (Pmax)	325 W	Open Circuit Voltage (Voc)	45.5 V
Module Efficiency	16.94%	Short Circuit Curent (Isc)	9.34 A
Voltage at Max Power (Vmp)	37.0 V	Cell Type	Polycristalline Silicon (6-inch)
Current at Max Power (Imp)	8.78 A	Number of Cells	72 (6 × 12)
Dimensions (L × W × H)	~1960 × 990 × 40 mm	Weight	~22 kg

Source: HOMER libraries

2.6.2. Wind power system

Wind power systems harness the kinetic energy of moving air to generate electricity, offering a sustainable and renewable source of energy. Wind turbines (WT), the primary components of these systems, consist of blades that capture wind energy and spin a rotor connected to a generator, producing electrical power through electromagnetic induction. The power output of a WT can be calculated (Krishan & Suhag, 2019):

$$P_{WT} = \frac{1}{2} \rho A {V_S}^2 C_p(\beta, \lambda) \eta_t \, \eta_g \tag{3}$$

Where,

P_{WT} : Output power of Wind turbines (Watt)

ρ: Air density (kg/m3)

A: Area swept by rotor blades (m2)

Vs: Velocity of wind (m/sec)

Cp: Performance coefficient of wind turbine

λ: Tip-speed ratio of the blade

β: Blade pitch angle (degree)

η_t and η_g: Wind turbine and generator efficiency, respectively (%)

The WES100 wind turbine was selected for this study due to its proven reliability, medium-scale capacity, and suitability for rural hybrid energy systems. Manufactured by Wind Energy Solutions (WES) in the Netherlands, the WES100 is based on the well-established Lagerwey LW18/80 platform, which has been modernized with upgraded electronics and control systems. With a rated power output of 100 kW, a rotor diameter of 18 meters, and a swept area of approximately 254.5 m², the turbine can deliver consistent power in areas with moderate to strong wind resources. From a techno-economic perspective, the WES100's design lifetime is 20 to 25 years, making it a durable and long-term investment for hybrid power systems. Its asynchronous generator and grid-compatible output (400 V, 50/60 Hz) ensure seamless integration into both grid-tied and off-grid configurations. Moreover, the turbine's modular, low-maintenance design makes it highly appropriate for deployment in remote rural areas, where access to spare parts and technical servicing may be limited.

Table 7. Selected wind turbines properties

Parameters	**Value**	**Parameters**	**Value**
Rated Power output	100 kW	Cut-out Wind Speed	~25 m/s
Rotor Diameter	18 meters	Survival Wind Speed	>50 m/s
Swept Area	~254.5 m²	Tower Height Options	18 m, 24 m, 30 m (free-standing tubular tower)
Rated Wind Speed	12.5 m/s	Number of Blades	2
Cut-in Wind Speed	~3.5 m/s	Generator Type	Asynchronous, 400 V, 50/60 Hz

Source: HOMER libraries

2.6.3. Battery storage system (BSS)

The Battery Storage System (BSS) plays a critical role in supporting the hybrid Renewable Energy System (HRES) by ensuring stable and reliable operation. One of its roles is to maintain a constant voltage, particularly during periods of imbalance between power generation and consumption. The battery’s ampere-hour capacity (Ah) and watt-hour capacity (Wh) should be carefully selected to ensure the system can supply energy for long periods during times of low solar irradiance or reduced wind speeds. The watt-hour capacity of the battery can be determined using the following equation (Krishan & Suhag, 2019):

$$C = \frac{E_L \times AD}{\eta_{bat} \times DoD} \quad (4)$$

Where,

E_L : the average daily load energy (kWh/day),

AD: Daily autonomy of the battery (day),

DoD: Battery depth of discharge (%),

η_{bat} : battery efficiency (%).

The battery storage system selected for this study is the Kinetic Model based on the Intensium Max lithium-ion (Li-ion) technology, developed by Saft. This high-performance storage solution is tailored for commercial and industrial energy applications and is particularly well-suited for hybrid renewable energy systems. Each unit provides a nominal voltage of 720 V and a nominal energy capacity of 55 kWh, with a maximum capacity of 76.4 Ah. The system demonstrates an excellent round-trip efficiency of 97%, which directly enhances system energy performance by minimizing losses during charge/discharge cycles.

Table 8. Battery characteristics

Parameters	Value	Parameters	Value
Battery Type	Lithium-ion (Li-ion)	Rate Constant	0.989 1/hr
Nominal Voltage	720 V	Roundtrip Efficiency	97%
Nominal Capacity	55 kWh	Max Charge Current	82 A
Maximum Capacity	76.4 Ah	Max Discharge Current	200 A
Capacity Ratio	0.927	Max Charge Rate	1 A/h
		Operating Temperature Range	20°C to 50°C

Source: HOMER Libraries

2.6.4. Electrolyser and Hydrogen Tank

The electrolyser used for the simulation is a generic model sourced from the HOMER library, designed for flexible integration within energy systems. It has a 1kW capacity and an efficiency of 85%, with the ability to operate at any load level due to its 0% minimum load ratio. This unit is connected to the AC bus, enabling seamless interaction with alternating current systems. With a 15-year lifespan, it's built for reliability over long-term modelling scenarios.

The hydrogen tank, as well, is a generic component from the HOMER library with a lifespan of 25 years.

2.6.5. Different optimization scenarios description

To identify the most reliable and cost-effective energy solution for the target community (Pensa, Burkina Faso), four different hybrid renewable energy system configurations were developed and evaluated using techno-economic analysis. Each scenario represents a distinct combination of energy sources (Solar PV and wind), and storage technologies (batteries) tailored to meet rural electricity demand under varying technical and financial specifications. These configurations were modelled in HOMER software, considering the site's solar and wind resource availability, load profile, and system constraints such as reliability, cost, and renewable energy penetration.

- Scenario 1: Stand-alone Solar PV & Battery system

This configuration consists of a solar photovoltaic (PV) array connected to a battery storage system, which together supply electricity to the load. The PV modules serve as the primary energy source during the day, while excess solar power is stored in the battery bank. The stored energy is then used during periods of low or no solar irradiance, such as at night or during cloudy weather. The system includes an inverter to convert DC to AC power for household use.

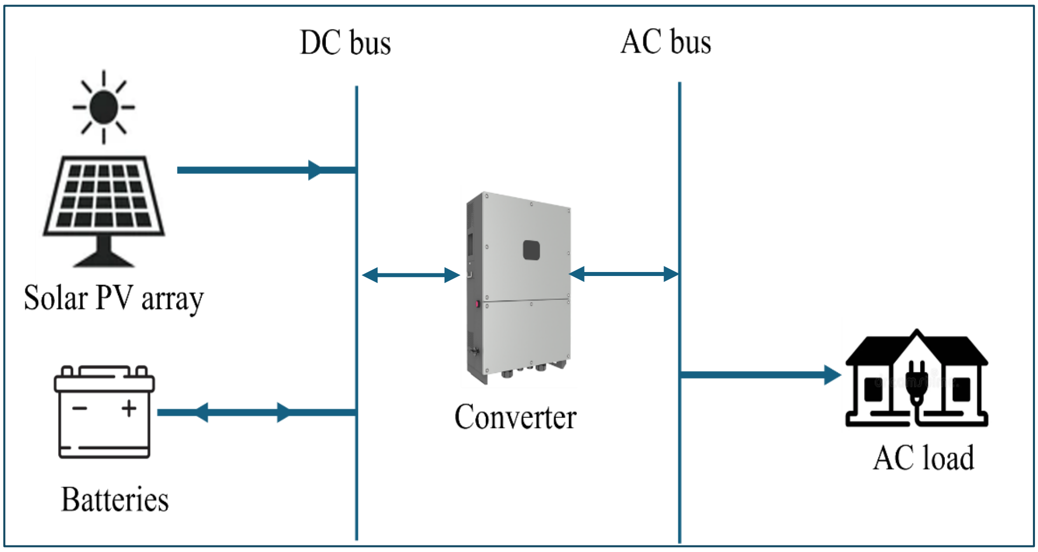

Figure 15. Scenario 1 technical configuration

- Scenario 2: Stand-alone Wind & Battery System

This scenario incorporates wind turbines as the main source of energy, supported by a battery storage system and an inverter for AC power delivery. Wind energy is used to directly power the load, and any excess is stored in the battery for later use. The batteries ensure a continuous supply during periods of low wind or variable load demand.

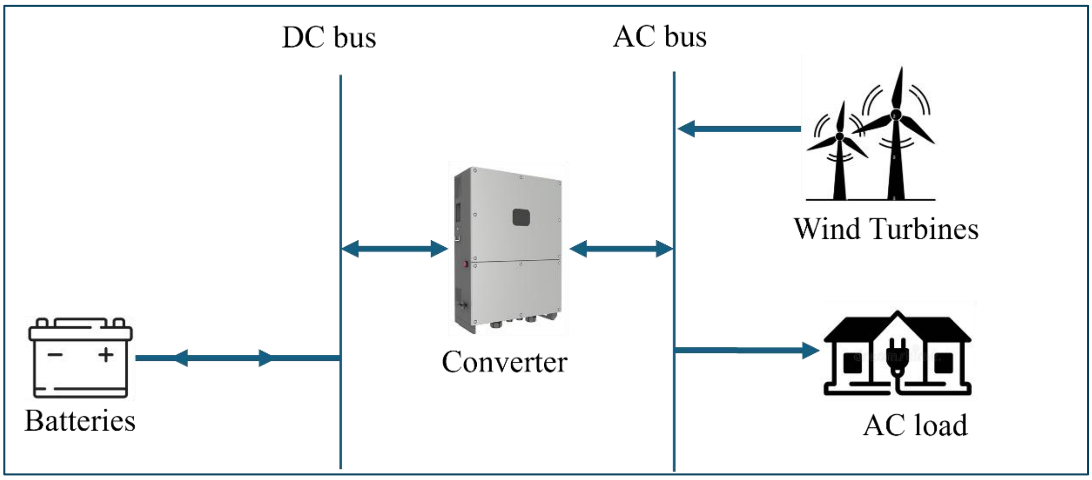

Figure 16. Scenario 2 technical configuration

- Scenario 3: Hybrid Wind-PV & Battery configuration

The third scenario combines solar PV, wind turbines, and a battery bank to form a robust hybrid system. Both solar and wind sources contribute to meeting the energy demand, while batteries store any surplus generation to ensure energy availability during periods of low renewable supply.

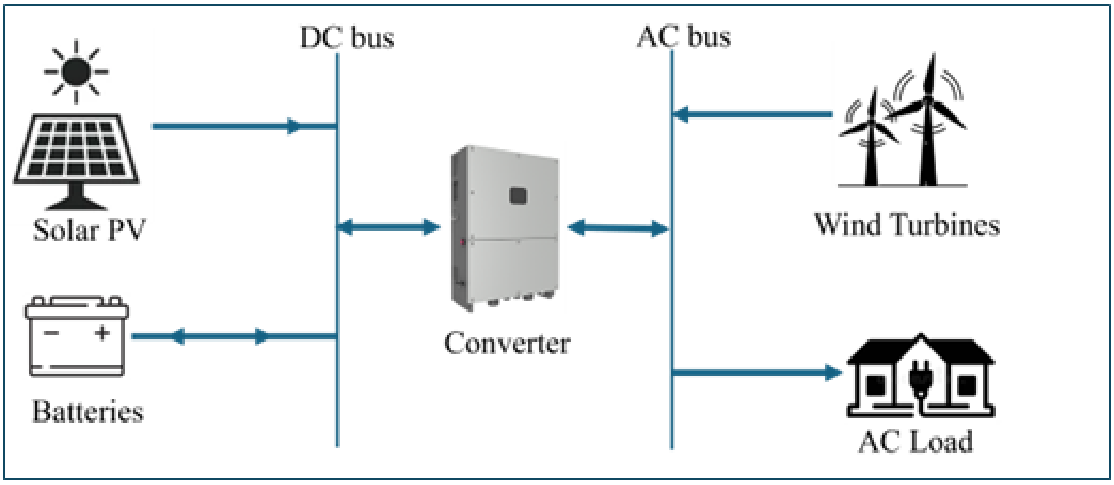

Figure 17. Scenario 3 technical configuration

- Scenario 4: Renewable energy sources and Electrolyser configuration

This configuration includes typically solar, wind, or both solar and wind sources together with an electrolyser. The system aims to select the most techno-economically efficient system among the first three and combine it with an electrolyser to use the excess electricity produced to generate hydrogen.

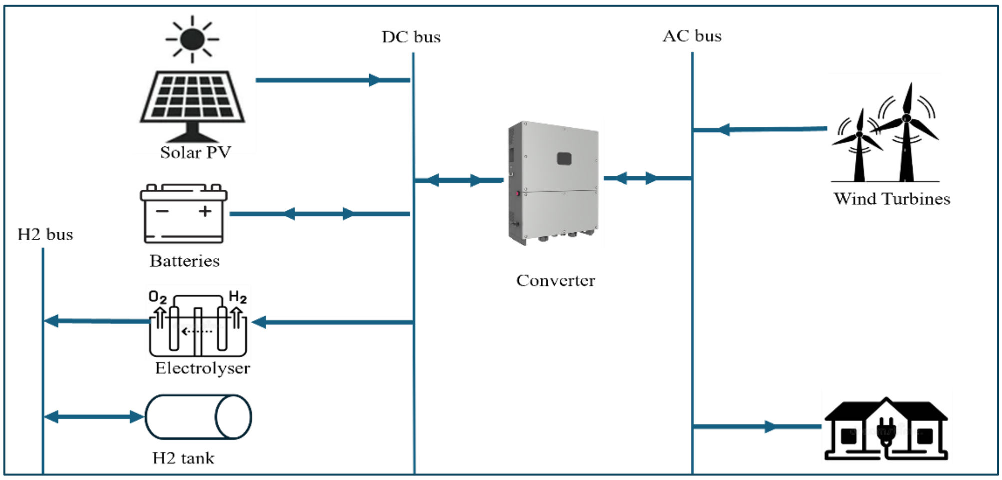

Figure 18. Typical scenario 4 technical configuration

2.7.Economic analysis using HOMER

In this study, the economic evaluation focuses on three primary indicators: the Net Present Cost (NPC), the Levelized Cost of Energy (LCOE), and the Levelized Cost of Hydrogen (LCOH). These metrics are used in HOMER Pro to compare different system configurations over the project lifetime, accounting for investment, operating, and replacement costs.

- Net Present Cost (NPC)

The Net Present Cost (NPC) represents the total cost of installing and operating the energy system throughout its lifespan, discounted to present value. It provides a comprehensive measure of the overall economic burden of the system. It can be computed as per the following equation:

$$NPC = \frac{C_{tot,an}}{CRF\ (i,t)} \quad (5)$$

Where,

$C_{tot,an}$ is the total annual cost ($/year), *i* is the annual real interest rate (%), *t is* the project lifetime (years), and *CRF (i, t)* is the capital recovery factor, which can be expressed as Eq. (6):

$$CRF(i,t) = \frac{i\ (1+i)^t}{i\ (1+i)^t + 1} \quad (6)$$

The annual effective interest rate is a percentage of the balance at the end of the year in which interest is paid or earned, and it is represented as:

$$i = \frac{i' - f}{1 + f} \qquad (7)$$

Where,

i': Nominal interest rate

f: Annual inflation rate.

- Levelized Cost of Energy

$$LCOE = \frac{I_s + \sum_{t=0}^{n} \frac{(OPEX)_s}{(1+i)^t}}{\sum_{t=1}^{n} \frac{E_d}{(1+i)^t}} \qquad (8)$$

Where,

I_s: Initial Investment Cost

$OPEX_s$: Operational and maintenance cost

i: Discount rate

t: Lifetime of the project

E_d: Energy generation

- Levelized cost of hydrogen is calculated using the following equation:

$$LCOH = \frac{I_s + \sum_{t=0}^{n} \frac{(OPEX)_s}{(1+i)^t}}{\sum_{t=1}^{n} \frac{H_d}{(1+i)^t}} \qquad (9)$$

Where:

I_s: Total capital expenditure (USD)

OPEX: Operational expenditure in year (USD/year)

H_d: Hydrogen production in year (kg/year) n: Project lifetime (years)

i: Discount rate

2.8. Affordability analysis method

The affordability analysis in this study follows the World Bank's widely accepted benchmark, which defines electricity as affordable when household expenditures on electricity do not exceed 5% of monthly income (world bank & ESMAP, 2022). This threshold was consistently applied across three distinct tariff scenarios, A, B, and C, to evaluate the ability of distinct consumer groups within the Yalgo community to bear the cost of electricity tariffs derived from the optimized hybrid renewable energy system.

The affordability assessment was conducted through a three-step process reflecting increasing tariff complexity and support measures:

Flat Tariff Assessment: Initially, affordability was evaluated using a uniform flat tariff of 0.308 USD/kWh applied to all consumer groups. Monthly electricity expenses were calculated by multiplying this tariff by each group's consumption level. These expenses were then compared to the 5% income benchmark to identify groups unable to afford the flat rate.

Cross-Subsidy assessment: The second step introduced consumer group-specific tariffs incorporating cross-subsidies designed to redistribute costs more equitably. Affordability was reassessed by recalculating monthly electricity expenditures (from the survey) under these differentiated tariffs, again benchmarking against the income threshold to capture improvements or persistent vulnerabilities.

Subsidized Tariff assessment: The final step incorporated targeted subsidies, further reducing tariffs for vulnerable groups. Here, affordability was evaluated against both the income-based threshold and household-specific willingness-to-pay (WTP) values obtained from the survey. This dual comparison ensured reflection of both objective economic capacity and subjective payment readiness. The required subsidy amounts were calculated to close affordability gaps where tariffs exceeded these thresholds. By integrating these three progressive assessments, the analysis captures not only general affordability under standard pricing but also the positive impacts of tariff design strategies (cross-subsidies and targeted subsidies) on enhancing electricity access across consumer segments in the community. This comprehensive approach balances economic feasibility with social equity considerations.

2.9. Structuring tariffs for the Yalgo community

Cross-subsidization is an effective way to promote fairness and affordability in micro-grids by charging higher tariffs to certain consumer groups (like businesses or heavy users) to subsidize lower rates for low-income or essential service users. This can be structured by consumer class, quantity used, peak demand, or time-of-use. For example, anchor clients such as telecom towers can help fund affordable access for households (Reber et al., 2018). While this approach supports equitable energy access, it requires advanced metering and must be carefully balanced to avoid discouraging larger consumers from remaining on the system. Well-designed schemes ensure sustainable operations and social inclusiveness in rural electrification.

To ensure both financial sustainability and equitable access to electricity in the Yalgo community, the tariff-setting strategy in this study adopts a structured, multi-scenario cross-subsidization approach grounded in national utility practices. Building on the Levelized Cost of Electricity (LCOE) of 0.282 USD/kWh derived from HOMER Pro simulations, tariffs are calculated to include a 10% profit margin aligned with SONABEL's operational benchmarks (SONABEL, 2023). Three distinct tariff scenarios are designed: (1) based on consumption levels (low vs. high users), (2) consumer types (residential, business, public services), and (3) socio-economic conditions (willingness and ability to pay). Each scenario applies internal cross-subsidies, ensuring that more capable or intensive users support affordability for vulnerable groups. This model supports cost recovery while promoting fairness and inclusion.

$$\text{Selling Price (Tariff)} = \text{LCOE} \times (1+\text{Profit Margin}) \tag{10}$$

- **Scenario A: Tariff based on energy consumption level**

Two user groups were identified, low consumers (≤30 kWh/month) and high consumers (>30 kWh/month) (SONABEL, 2023). Tariffs were designed to reflect cross-subsidization, where low-income, low-consuming users pay a slightly lower price, while higher-consuming users contribute more, ensuring cost recovery and system profitability.

- **Scenario B: Tariff based on user type**

Based on the survey and specifically on the respondent type, users were categorized as public services (schools, health centres), residential users, and small businesses. Differentiated tariffs were designed to reflect usage type and economic capability, with public services paying the lowest rate to promote equitable access, and small businesses paying the highest to support sustainability. The price for residential usage is set just at 0.308 USD/kWh, corresponding to LCOE plus the profit margin.

- **Scenario C: Tariff based on willingness to pay**

Using survey data collected through Kobo Collect, users were segmented into willingness to pay (WTP-low) and willingness to pay- high (WTP-high) groups. These categories were used to assign tariffs reflecting respondents expressed willingness.

The affordability assessment applies the 5% of household income threshold, as recommended by the world bank & ESMAP, (2022), which is widely used in energy access studies to evaluate electricity affordability in developing countries. If a household spends more than 5% of its monthly income on electricity, the service is considered unaffordable. To operationalize this, the study adopts a cross-subsidy framework inspired by Rajwanshi, (2018), which highlights redistributing costs among consumer categories to balance affordability and cost recovery.

The baseline tariff of 0.308 USD/kWh was adjusted to reflect different abilities to pay. High-consumption households were charged +15% (0.354 USD/kWh) and small businesses +20% (0.370 USD/kWh). This principle reflects real African practices where wealthier or commercial users cross-subsidize vulnerable households. For example, in Ghana, the Public Utilities Regulatory Commission applies a lifeline tariff for households consuming less than 30 kWh/month, subsidized by higher residential and industrial tariffs (PURC, 2022). In Senegal, the utility SENELEC implements differentiated tariffs where commercial and high-voltage users help sustain lower tariffs for residential and rural customers (World Bank, 2022).

In Yalgo's context, reductions were thus applied to vulnerable groups: -15% for low-consumption households, -20% for public services (schools, clinics), and -10% for low willingness-to-pay households. These adjustments are consistent with regional tariff differentiation practices, ensuring affordability for vulnerable users while protecting revenue sufficiency. Overall, this redistribution reflects both global affordability thresholds and regional policy precedents, making the analysis transferable to other Sahelian contexts. It also aligns with Burkina Faso's own subsidy approach, where SONABEL tariffs remain below cost due to direct state transfers (IMF, 2022), indicating that subsidies and cross-subsidies are already institutionalized practices in the national energy sector.

Table 9. Estimated scenario-based cross-subsidy Tariffs

	Baseline: 0.308 USD/kWh		
	User Group	**Assumed adjustment**	**Tariff (USD/kWh)**
Energy consumption level	Low Consumption	-15%	0.262
	High Consumption	+15%	0.354
User type	Public Infrastructure	-20%	0.246
	Small Businesses	+20%	0.370
	Residentials	Baseline	0.308
WTP	WTP-Low	-10%	0.277
	WTP-High	+10%	0.354

In this study, a subsidy of 0.1 USD/kWh was assumed across all tariff scenarios and consumer groups to assess its impact on affordability and vulnerability reduction. This assumption is consistent with the policy context of Burkina Faso(Korgo et al., 2017), where electricity tariffs are kept below cost-reflective levels through significant state subsidies. As highlighted in national energy sector reports (SONABEL, 2023), the government regularly compensates SONABEL for the gap between actual generation costs and consumer tariffs, with subsidies justified by the country's low household incomes and the need to ensure equitable access to electricity. Although the exact subsidy levels fluctuate with fuel costs and fiscal constraints, historical evidence confirms that electricity subsidies in Burkina Faso have been substantial. Notably, SONABEL's national average selling price of 0.235 USD/kWh is lower than cost-reflective values (ranging from 0.27 to 0.36 USD/kWh in different studies), implying an implicit subsidy in the order of 0.08-0.12 USD/kWh (Korgo et al., 2017). Therefore, adopting a benchmark of 0.1 USD/kWh in this study provides a conservative yet realistic estimate of subsidy support, ensuring that the affordability analysis remains both contextually grounded and aligned with national practices.

2.10. Environmental benefits analysis

To evaluate the environmental benefits of the proposed HRES, the analysis focused on estimating the amount of carbon dioxide (CO_2) emissions avoided annually compared to a conventional fossil-fuel-based generation system. The rationale is that rural electrification in Burkina Faso, when not based on renewables, typically relies on diesel generators (Moner-Girona et al., 2016), which are both carbon-intensive and costly (Ahmad & Zhang, 2021).

Therefore, quantifying avoided emissions provides a clear indication of the climate benefits of adopting a renewable hybrid system. The calculation was performed by multiplying the annual renewable electricity generated by the system ($E_{gen,}$ in kWh/year) by an emission factor (EF, in kgCO2/kWh) that reflects the average CO_2 intensity of diesel-based generation:

$$CO2\ Avoided\ (kgCO2/year) = \text{Egen (kWh/year)} \times \text{EF (kgCO2/kWh)} \quad (11)$$

The emission factor applied (EF=0.84kgCO_2/kWh) was adopted from Morales-españa et al., (2021), which falls within the typical diesel generation range of 0.8 - 1.0 kgCO_2/kWh (Thomson et al., 2017). By using this factor, the study establishes a baseline for emissions that would have occurred under a diesel-based electrification scenario.

This approach enables a straightforward estimation of environmental benefits in terms of avoided CO_2, providing a quantifiable measure of the contribution of the HRES to climate change mitigation. Although the analysis does not extend to other environmental indicators (such as air pollutants, lifecycle impacts of renewable components, or land use), avoided CO_2 remains the most relevant and widely used metric to assess the climate benefits of decentralized renewable energy systems (Olabi et al., 2023).

Chapter 3: Results and Discussions

This chapter presents and discusses the results and insights from the analysis of hybrid renewable systems for rural electrification in Yalgo, Burkina Faso. It highlights optimal system configuration that addresses unmet demand, minimizes excess generation, and ensures suitable component sizing. Key indicators such as Net Present cost, levelized cost of energy, cost of hydrogen, unmet demand, and excess electricity are used to compare different scenarios. The chapter also evaluates affordability and tariff strategies aligned with local socio-economic conditions. Some insights on environmental profitability are also presented and discussed in this chapter.

3.1. First three scenario simulation results

3.1.1. Different system sizes and energy production

The optimum sizes of the main components for each configuration of the HRES are reported in the following Table 10. To meet the demand at 100% an installed capacity of PV of 1.15 MW, 0.9 MW, and 0.729 MW is required, respectively, with scenario 1 (PV & Battery), Scenario 2 (Wind & Battery), and scenario 3 (Wind-PV & Battery).

Table 10. The different scenarios of system sizes

	PV array (kW)	Wind Turbine (kW)	Battery (kWh)	Converter (kW)	Battery Autonomy (h)
PV & Battery	1,150.00	0	518.40	270.00	25.60
Wind & Battery	0	900	878.4	172	48.40
PV-Wind & battery	529	200	446.4	125	22.10

Table 11 below presents the energy production, load served, unserved load, as well as the excess energy produced from each of the three scenarios. The reported results show that all scenarios meet the energy requirements, but the excess energy generated differs. For instance, 67.4% of the total energy generated is excess from the first scenario, and 66.90% of the total energy and 52.70% for the second and third scenarios. Overall, the third scenario scored the lowest installed capacity, leading to the lowest excess energy generation.

Table 11. The different scenarios of energy production

	Total Energy generated (kWh)	Load served (kWh)	Unmet Demand (%)	Excess Electricity (%)	Renewable Energy Fraction (%)
Scenario 1	2,083,371.00	642,787.00	0.07	67.40	100.00
Scenario 2	2,002,086	642,732	0.06	66.90	100.00
Scenario 3	1,403,577	642,732	0.06	52.70	100.00

3.1.2. Different System Simulations

The optimization results for electricity generation and demand within the hybrid PV-wind and battery system, the grid-connected PV system, and the stand-alone PV and battery system are depicted in Figures 19, 20, and 21, respectively.

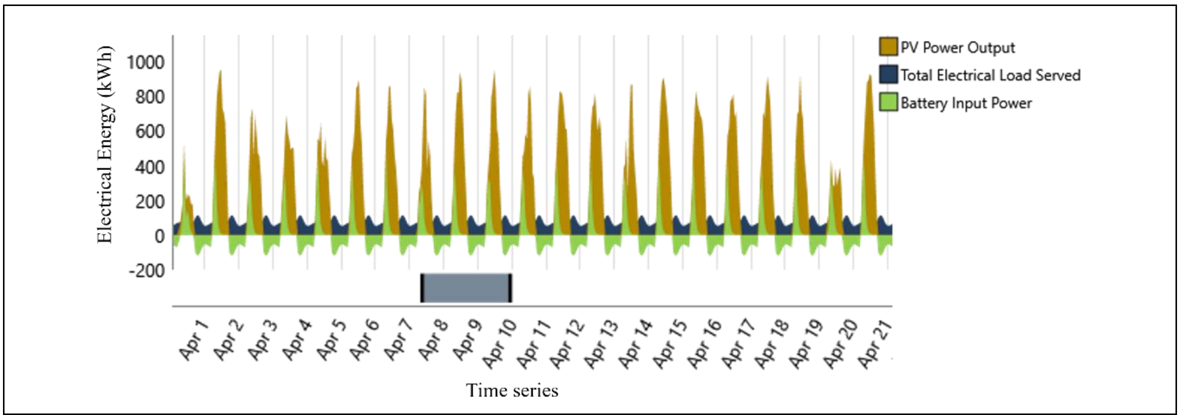

Figure 19. Electricity generation and demand in scenario 1

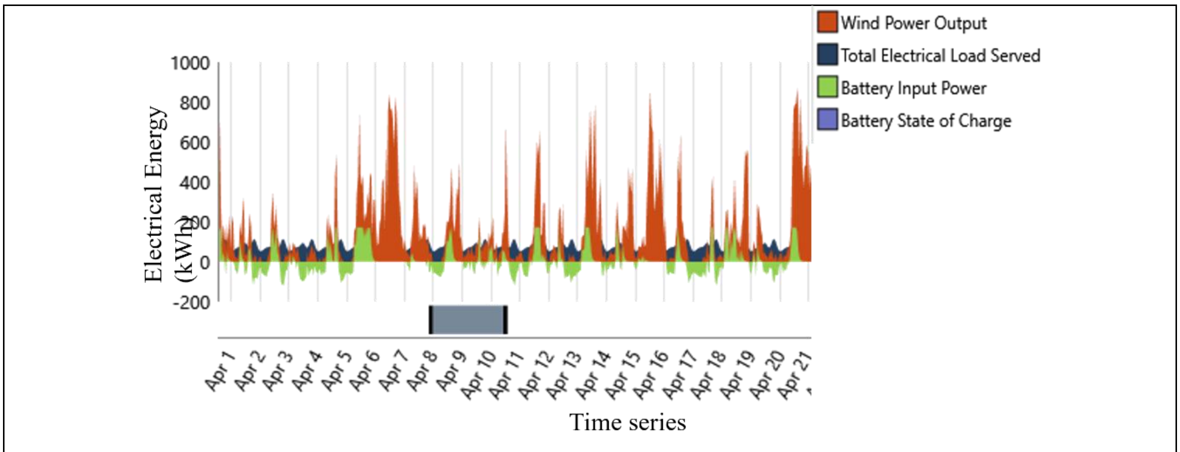

Figure 20. Electricity generation and demand within scenario 2

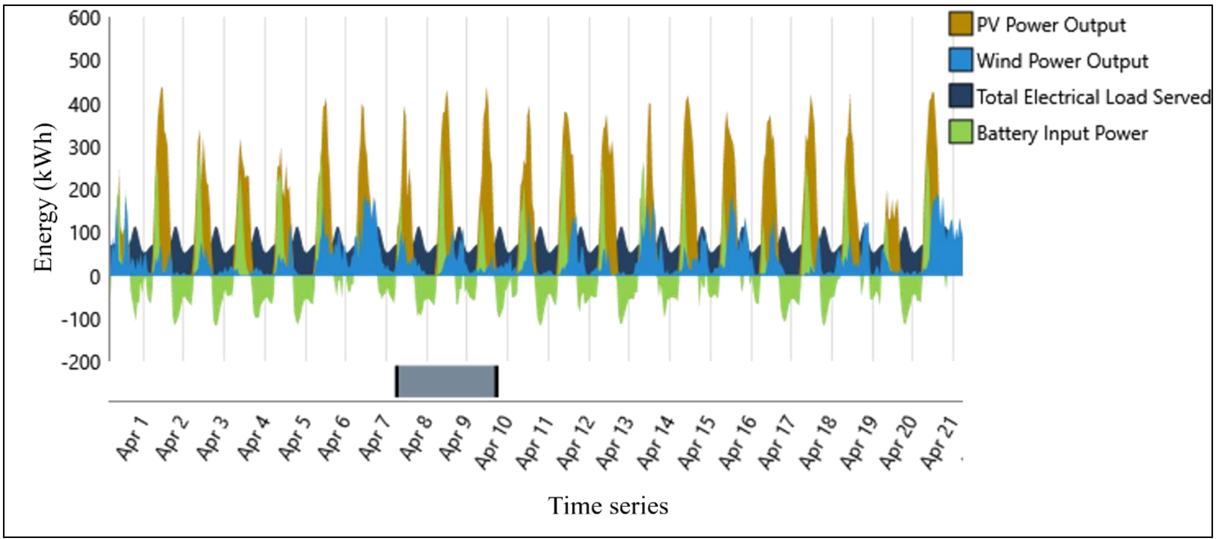

Figure 21. Electricity generation and demand within scenario 3

The simulation of Scenarios 1, 2, and 3 shows April as the month of highest electricity consumption, providing a clear benchmark to evaluate system performance. In Scenario 1 (PV-Battery), the system relies mainly on solar power, with batteries playing a central role in covering nighttime demand and cloudy-day deficits; while effective, this leads to significant pressure on storage. In Scenario 2 (Wind-Battery), electricity generation becomes more variable, with wind supplying power, but due to the intermittency of wind, battery usage remains important to buffer fluctuations and maintain a stable supply. Scenario 3 (PV-Wind-Battery) demonstrates the most balanced and resilient configuration: solar dominates during the day, while wind contributes during the evening and early morning hours, smoothing out the generation curve and reducing the depth of battery discharge. This complementarity lowers the required battery size compared to Scenarios 1 and 2, since storage is used primarily for short-term balancing rather than long-term supply. Overall, the hybrid PV-Wind configuration enhances reliability, reduces storage dependence, and provides a more resilient system for meeting Yalgo's energy demand throughout the year.

3.1.3. Different systems investment cost breakdown

- PV & Battery configuration

The results obtained after simulating the PV & Battery HRES configuration are reported in the following Table 12. The total system cost is about 2,718,513.80 USD with an LCOE of 0.360 USD/kWh. The system total cost is mainly influenced by the initial investment, which has the highest share due to the CAPEX of different main components such as PV, converter, and Battery.

Table 12. PV & battery system cost breakdown

	CAPEX (USD)	Replacement cost (USD)	OPEX (USD)	Salvage (USD)	Total (USD)
PV	1,437,894.42	---	168,617.60	---	1,606,512.02
Converter	175,542.88	---	20,585.41	---	196,128.29
Battery	720,000.00	188,488.50	84,432.28	101,119.34	891,801.44
Others	10,000.00	---	14,072.05	---	24,072.05
System	**2,343,437.30**	**188,488.50**	**287,707.33**	**101,119.34**	**2,718,513.80**

- Wind & Battery

The NPC of the Wind & Battery system stood at 4,109,569.51 USD, which is almost two times the PV & Battery system due to the high initial investment of wind turbines. The system scored a LCOE of 0.545 USD/kWh. The investment costs of this system configuration are reported the Table 13.

Table 13. Wind & battery system cost breakdown

	CAPEX (USD)	Replacement cost (USD)	OPEX (USD)	Salvage (USD)	Total (USD)
Wind	2,250,000.00	---	26,385.09	---	2,276,385.09
Converter	111,520.80	---	13,077.74	---	124,598.5
Battery	1,360,000.00	356,033.84	159,483.2	191,003.19	1,684,513.8
Others	10,000.00	---	14,072.05	---	24,072.05
System	**3,731,520.80**	**356,033.84**	**213,018.07**	**191,003.19**	**4,109,569.5**

- Wind-PV & Battery system

The following table 14 presents the optimum investment cost for the Wind-PV & Battery system. In this scenario, the investment is moderated compared to the two previous scenarios. The considerable Capex and Opex reduction are due the investment in battery energy storage, which dropped from 1,360,000 USD (scenario 2) to 620,000 USD.

Table 14. Wind-PV & Battery system cost breakdown

	CAPEX (USD)	Replacement cost (USD)	OPEX (USD)	Salvage (USD)	Total (USD)
PV	661,651.04	---	77,589.86	---	739,240.9
Converter	81,309.56	---	9,534.98	---	90,844.54
Battery	620,000.00	162,309.54	72,705.57	87,074.9	767,940.1
Wind turb.	500,000.00	---	5,863.35	---	505,863.3
Others	10,000.00	---	14,072.05	---	24,072.05
System	**1,872,960.60**	**162,309.54**	**179,765.82**	**87,074.9**	**2,127,960.9**

3.2. Configurations comparison and identification of the optimal system

Variables such as NPC, LCOE, UD, and excess electricity produced (EEP) were considered to compare the first three system configurations to select the most techno-economically viable system. The optimal system should record the lowest NPC, LCOE, unmet demand, and excess electricity produced. The following figure presents the comparison results of different variables.

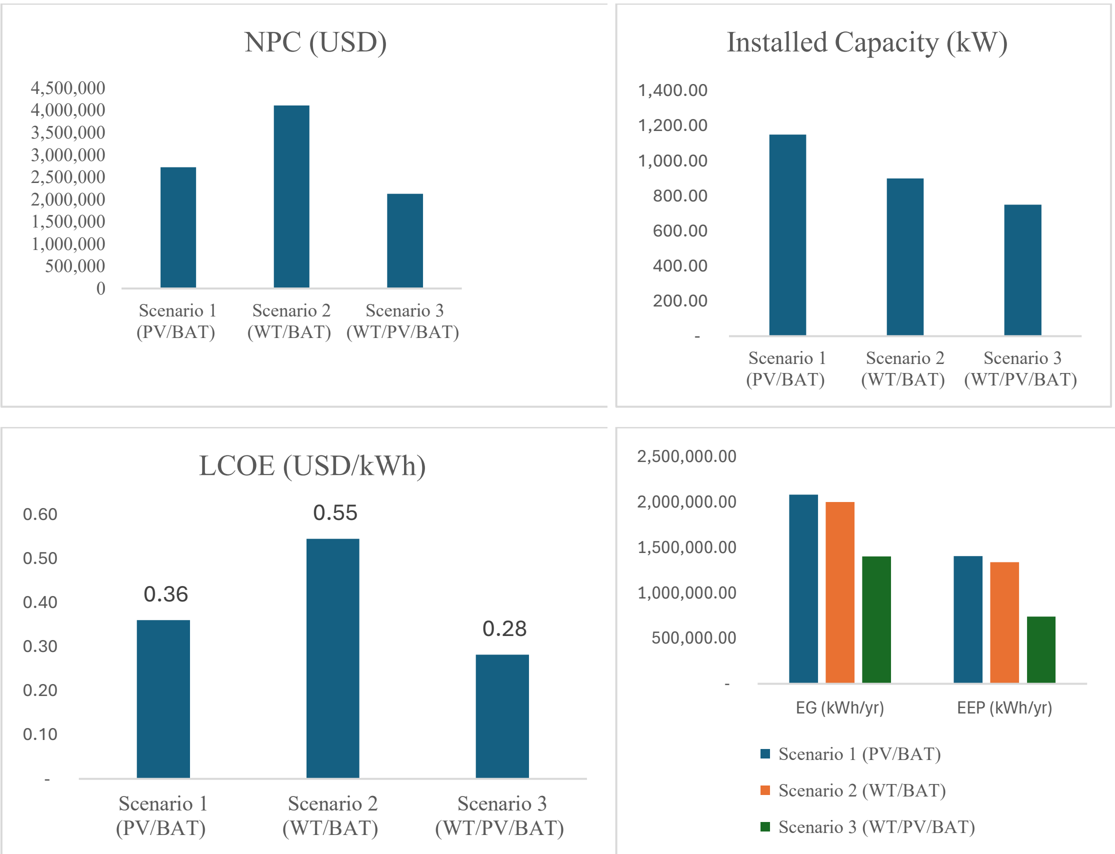

Figure 22. Different scenarios comparison based on NPC, LCOE, EG, EEP, and UD

For the same energy demand to be covered in a year, three different total capacities to be installed were optimised based on the three scenarios presented. The PV & battery system requires the highest installed capacity of (1150 kW), followed by the Wind & battery system (900 kW), and the lowest from the Wind-PV & battery system (729 kW). This directly affected the total investment cost. Based on the NPC, which considers the total capital cost, replacement cost, and O&M, scenario 3 recorded the lowest investment (2,127,960.9 USD), followed by scenario 1 (2,718,513.80 USD). The second scenario has the highest NPC (4,109,569.5 USD) due to the very high initial investment in Wind turbines. By this, scenario 3 recorded the lowest LCOE of 0.282 USD/kWh, while scenarios 2 and 1 recorded respectively 0.360 USD/kWh and 0.545 USD/kWh.

As part of the simulation assumptions and considerations, the capacity shortage is fixed at 0% this means that all electricity demand should be met at 100% by all energy systems proposed in the three different scenarios. The focus is now turned to the excess electricity production to be compared. Scenario 1 creates the highest excess of about 67% of the total electricity produced by the system PV & battery, followed by Scenario 2 similarly high excess of about 66% of the excess from the Wind & battery system. The lowest excess was recorded with scenario 3, with about 52.7 % of the total electricity.

An optimal renewable energy system in this context consists of one that meets the demand at 100% with the lowest LCOE, NPC, and excess electricity produced. Based on these conditions, the third scenario (Wind-PV & battery) was considered as the most optimal energy system to not apply electricity in the Yalgo community, but also to integrate an electrolyser for green hydrogen production using 52.7% of excess electricity.

3.3. Electrolyser integration and hydrogen production with the optimal system

3.3.1. Hybrid PV-Wind-Battery & electrolyser system size

The electrolyser and hydrogen tank were integrated into the optimized energy system (Wind-PV-battery) to absorb the excess electricity. The results are summarised in the following tables 15 and 16. The installed capacity of PV and wind turbines is kept the same as in scenario 3 (729 kW of total installed capacity). The optimisation of the system proposed an electrolyser capacity of 569 kW to be installed to absorb the excess electricity production. The required energy to meet the electricity demand at 100% is first provided by the system (just like in scenario 3), and the excess energy, evaluated at 1491286 kWh/yr, will be directed as electrolyser input energy.

A total quantity of hydrogen of about 32,136 kg/yr will be generated from excess with an LCOH of about 8.4 USD/kg. The optimised H2 tank has a capacity of 2000 kg of hydrogen with an energy storage capacity of 66,667 kWh.

Table 15. Electrolyser and hydrogen production key results (scenario 4)

	Generic Electrolyser	
	Values	**Unit**
Energy input	1 491 286	kWh/yr
PV	529	kW
Wind	200	kW
Battery	446.4	kWh
Capacity Factor	29.9	%
Specific energy consump.	46.4	kWh/kg
Electrolyser capacity	569	kW
H2 output	32 136	Kg/yr
Remaining electricity excess	220 790	kWh/yr
Electricity excess percent.	9.25	%
LCOE	0.8	USD/kWh
LCOH	8.4	USD/kWh

3.3.2. Hybrid PV-Wind & battery-electrolyser system cost breakdown

The related costs of the hybrid renewable energy system combining PV, wind turbines and batteries with an electrolyser are reported in the following table 17.

Table 16. Wind-PV & Battery system cost breakdown

	CAPEX (USD)	Replacement (USD)	OPEX (USD)	Salvage (USD)	Total (USD)
Battery	380,000.00	99,480.04	44,561.48	53,368.54	470,672.98
Converter	173,635.10	---	20,361.67	---	193,996.77
Electrolyser	568,518.30	199,746.86	66,668.43	34,067.08	800,866.51
Hydrogen Tank	1,300,000.00	---	1,524,471.72	---	2,824,471.72
Other	10,000.00	---	14,072.05	---	24,072.05
PV	912,500.00	---	107,006.19	---	1,019,506.19
Wind	1,250,000.00	327,236.98	14,658.38	175,554.41	1,416,340.96
System	**4,594,753.40**	**626,463.88**	**1,791,858.55**	**262,990.02**	**6,750,085.81**

3.3.3. Hybrid PV-Wind-Battery & Electrolyser system simulation results

The following graphs illustrate the interaction between renewable generation, hydrogen production, and storage dynamics in the proposed hybrid system for Yalgo.

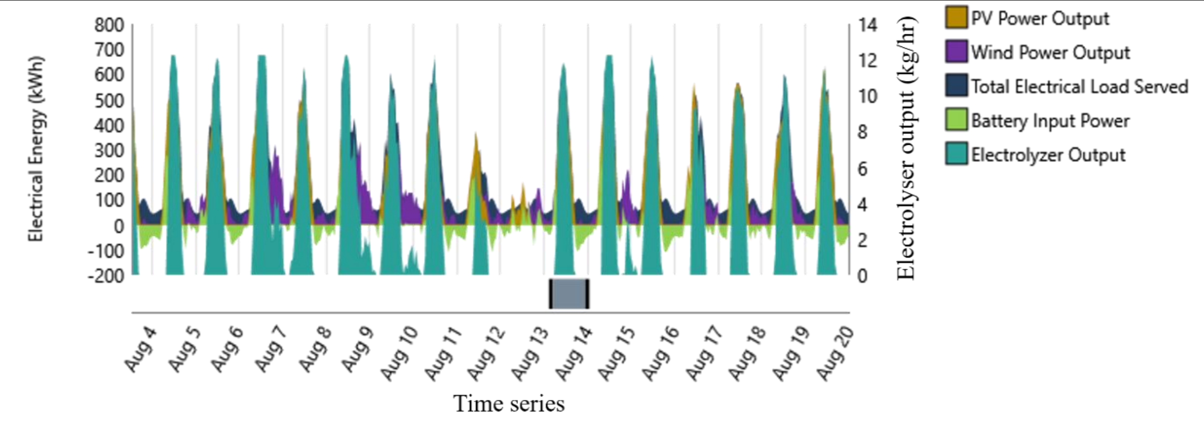

Figure 23. Hydrogen production with the hybrid PV-Wind & battery system (scenario 4)

Hydrogen production is strongly concentrated during daylight hours, largely driven by PV output, with wind providing additional support and batteries smoothing short-term fluctuations. The electrolyser effectively absorbs excess energy that would otherwise be curtailed, converting it into hydrogen as a storable energy carrier. For instance, in August (12^{th} to 13^{th}), no hydrogen is produced because there is no excess electricity while the electricity demand is being met.

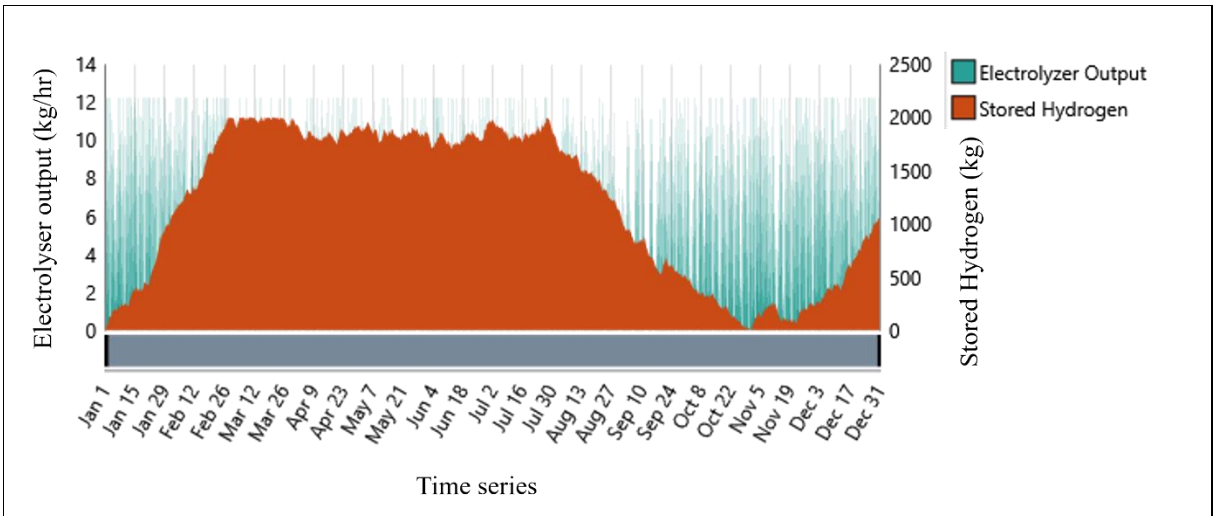

Figure 24. Stored Hydrogen variations in a year

Over the year, storage levels show clear seasonal patterns, remaining consistently high between February and July (often above 1,500 kg and peaking beyond 2,000 kg in March), reflecting abundant renewable generation. In contrast, storage drops sharply in October–December, falling below 600 kg due to reduced energy surplus. This dynamic confirms that hydrogen integration improves renewable utilization and provides a strategic buffer for periods of low generation.

3.4. Tariffs and affordability analysis

The following figures summarize the stepwise affordability analysis conducted across three tariff structures: (1) a uniform flat tariff, (2) group-specific cross-subsidized tariffs, and (3) a fully subsidized tariff framework. Each step is evaluated under the three scenarios reflecting different consumer groupings, tariff based on energy consumption level, tariff based on user type, and tariff based on willingness to pay.

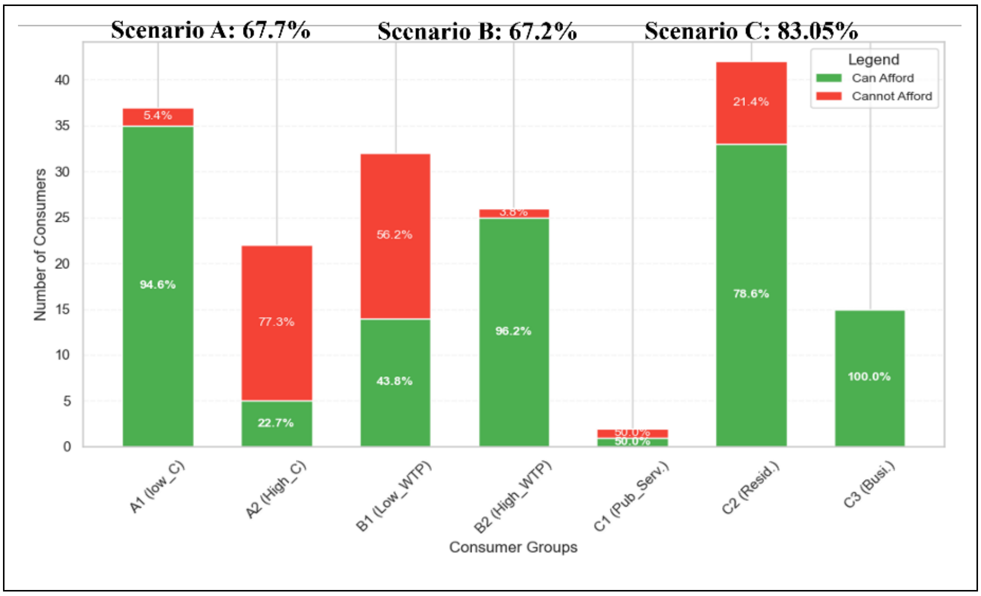

Figure 25. Affordability level based on a flat tariff of 0.308 USD/kWh

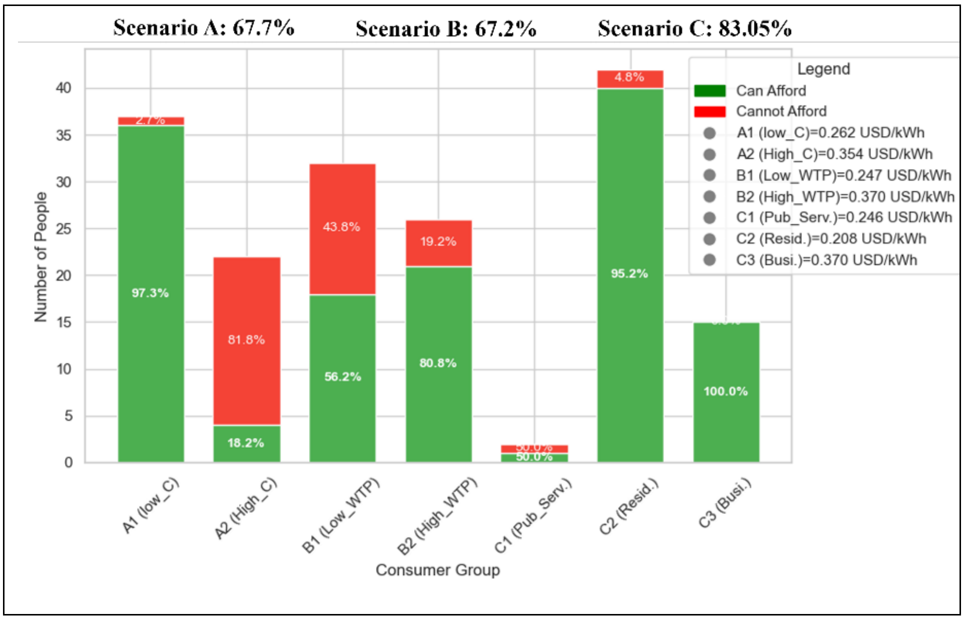

Figure 26. Affordability level based on consumer group Cross-subsidies

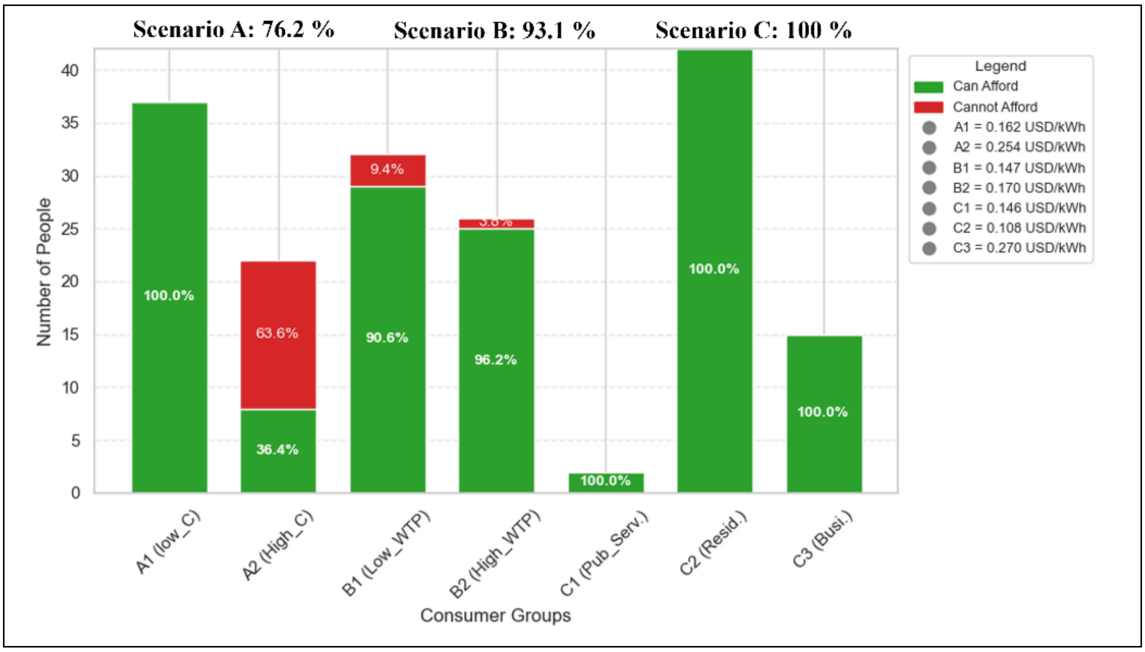

Figure 27. Affordability level based on subsidized tariffs

The results reveal significant improvements in affordability across the three steps. Under the flat tariff of 0.308 USD/kWh (figure 25), overall affordability is limited, with scenario scores ranging from 67.2% to 83.05%, and several consumer groups (A2 and B1) showing high vulnerability. Introducing cross-subsidies in step two (figure 26) noticeably enhances affordability, particularly for vulnerable groups; scenario scores now reach up to 95.2% for residential consumers, although disparities remain. The final step, employing targeted subsidized tariffs (Figure 27), yields the highest affordability overall. Scenario C achieves universal affordability (100%) across all consumer groups, attributed to both the lowest tariff (0.108 USD/kWh for the C2 group) and subsidy targeting; scenario A and B still show marked improvement (up to 93.1%) but retain pockets of vulnerability, especially within higher-cost and lower willingness-to-pay groups. These findings illustrate that while cross-subsidies meaningfully reduce vulnerability compared to a flat tariff, a well-designed subsidy has the greatest impact, fully addressing affordability gaps for the most at-risk groups in scenario C. Thus, scenario C at the final step demonstrates the optimal outcome, with zero affordability vulnerability due to comprehensive subsidy coverage.

3.5. System Environmental Benefits Results

This section presents the environmental benefits of deploying the proposed HRES in the Yalgo community, focusing specifically on avoided carbon dioxide (CO_2) emissions compared to a diesel-based alternative. As shown in Table X, the system produces approximately 1,403,577 kWh/year of renewable electricity. By applying an emission factor of 0.84 $kgCO_2/kWh$, which represents the average emissions intensity of diesel-based generation, the annual avoided emissions amount to 1,179,005 $kgCO_2$ (≈1,179 tons/year). Over the 25-year lifetime of the project, this results in a cumulative avoidance of about 29,475 tons of CO_2.

These avoided emissions are significant when viewed in the national and global context. For instance, they represent the equivalent of removing more than 6,400 passenger cars from the road for one year based on U.S. EPA conversion factors (U.S. EPA, 2025). This demonstrates that, beyond its role in providing reliable electricity access, the system directly contributes to climate change mitigation by reducing reliance on fossil fuel generators, which dominate off-grid rural electrification in the country.

Furthermore, this aligns with Burkina Faso's Nationally Determined Contribution (NDC) under the Paris Agreement, which emphasizes renewable energy deployment as a key strategy for reducing greenhouse gas emissions while supporting rural electrification (SAWADOGO, 2025). While the current analysis focuses only on avoided CO_2, future assessments could integrate co-benefits such as reductions in local air pollutants (NOx, SO_2, and particulate matter), which would further improve community health outcomes, especially for vulnerable groups such as women and children.

Table 17. CO2 reduction quantity

	Values	Units
Yearly Energy Production	1,403,577	kWh/yr
Emissions Factor	0.84	KgCO2/kWh
CO2 Avoided/yr	1,179,005	KgCO2/yr
Total CO2 Advoided	29,475,117	KgCO2/25yrs

3.6. Discussion

This study is aimed to design, simulate, and evaluate a hybrid renewable energy system tailored to the needs of the off-grid Yalgo community in northern Burkina Faso. The core objectives were to ensure reliable and affordable electricity access while enabling the use of excess energy for green hydrogen production. By conducting a comprehensive techno-economic and affordability analysis, the study sought to identify the most cost-effective system configuration and develop inclusive tariff models that support long-term financial viability and social equity.

Among the first three scenarios, the hybrid PV-Wind & Battery system scored the lowest LCOE, NPC, excess electricity produced of 0.282 USD/kWh, 2,127,960.9 USD, and 52.7% respectively, underscoring the complementary nature of wind and solar sources in Yalgo's climatic context. On the other hand, the Wind and PV only scenarios presented the highest LCOE (respectively 0.545 and 0.360 USD/kWh); (respectively 4,109,569.5 USD and 2,718,513.80 USD of NPC); and (respectively 67% and 66% of excess production). The calculated LCOE of 0.282 USD/kWh for the Wind - PV - Battery hybrid system positions it as a potentially cost-effective and competitive solution for off-grid electrification in Burkina Faso, particularly given its favourable comparison to alternatives. This figure sits well below the 0.4 - 0.405 USD/kWh range reported for PV-diesel systems(Ouedraogo & Yamegueu, 2019) and is only marginally above the 0.27 USD/kWh for PV - diesel - storage mini-grids (Abid et al., 2021).However, the excess electricity was reduced from 52.7% (hybrid PV-Wind & Battery) to 9.25% with the PV-Wind - Battery & electrolyser. More than 43% of the excess electricity has been absorbed to produce hydrogen. However, there has been an increase of the system's overall cost, leading to a high LCOE of 0.8 USD/kWh and LCOH of 8.4 USD/kg. This increase in LCOE is particularly due to the additional components added in the system such as electrolyser and H2 tank. Indeed, the overall system cost increases but the quantity of electricity to meet the electricity demand still unchanged. Only the excess electricity is used as input electricity to the electrolyser, it does not account in the electricity generated for power supply.

The affordability analysis revealed that cross-subsidy between consumer groups is not sufficient to ensure that everyone is able to afford their energy needs while keeping the system cost recovery possible. Indeed, around 33% of the Yalgo community will not be able to pay for electricity under the affordability threshold of 5% with the best tariff scenario. This could partly be related to the community's low income, which ranges from 63 USD/month to 650 USD/month, but it could also be because of the relatively high tariff, which is quite above the SONABEL subsidized selling price in Burkina Faso (0.235 USD/kWh) (SONABEL, 2023). By considering a subsidy of 0.1 USD/kWh from the government, internal or external donors, only 100 % of the community will be able to afford their monthly electricity needs with the scenario C tariff structure (tariff based on consumer type, residential, businesses, or public infrastructure). The cross-subsidy plays a crucial role in energy justice here, but still, there should be supported to make it more realistic and possible.

To make the hybrid system more economically viable in the Yalgo context, interventions are required to lower capital and operational expenses. Strategies could include bulk procurement or local assembly of components, optimizing battery cycles to extend lifespan, and leveraging concessional financing or grants to lower investment risks. By maintaining system flexibility and locality (unlike grid extensions), the hybrid solution offers tangible environmental and independence benefits yet realizing those benefits will depend on pragmatic cost management and targeted subsidy schemes suited to Burkina's realities.

The findings of this study confirm that a hybrid renewable energy system is both technically feasible and highly relevant for the Yalgo community, where access to the national grid is absent and income levels are generally low. By leveraging abundant solar potential and complementing it with wind, the proposed system provides a balanced solution that enhances reliability while lowering overall system costs compared to single-source options. Such a system directly addresses Yalgo's electrification challenges and creates opportunities for socio-economic transformation. Reliable electricity access would enable income-generating activities such as small businesses, food processing, and cold storage, while also improving healthcare services and educational facilities (Odou et al., 2020). In this way, electrification is positioned not merely as a technical solution but as a foundation for community development and poverty reduction.

Affordability remains a central concern for Yalgo, where household purchasing power is limited. The analysis highlights that a cross-subsidy mechanism, where higher-income or business users absorb part of the cost burden, combined with external subsidies, can ensure cost recovery for operators while maintaining affordability for vulnerable groups. This approach aligns with principles of energy justice, ensuring equitable access while securing the financial viability of the system. Moreover, segmenting tariffs by consumer type (residential, business, and public services) ensures that energy pricing reflects both ability and willingness to pay, preventing exclusion of the poorest households. In the long run, a transparent regulatory framework that sets profit margins and supports subsidies will be essential for scaling such hybrid systems beyond Yalgo.

Integrating hydrogen production within the proposed hybrid renewable energy system introduces both opportunities and challenges. A key concern in rural electrification projects is whether additional components, such as electrolysers and hydrogen storage, could jeopardize electricity affordability for the local community. In the Yalgo case, however, affordability is safeguarded by the fact that the system is designed to fully recover its costs of supplying electricity through consumer tariffs independent of the hydrogen component. The electrolyser and storage tank are introduced solely to utilize surplus electricity that would otherwise be curtailed, meaning they do not compete with local consumption. Cost recovery for hydrogen infrastructure can be achieved instead through revenues from hydrogen sales, either to meet potential local needs (e.g., fertilizer production for agriculture, small-scale industries, or backup energy services) or, in the longer term, to access international hydrogen markets at global market prices. This dual-revenue model can ensure that community access and affordability are not compromised, while positioning Yalgo as a pioneer in linking rural electrification with Burkina Faso's broader energy transition.

While the proposed hybrid renewable energy system demonstrates strong technical and economic potential for Yalgo, its real-world implementation could face institutional, financial, and technical barriers. Institutionally, Burkina Faso's energy sector is still dominated by SONABEL, with limited space for independent operators, and there is no clearly defined regulatory framework for tariff setting, profit margins, or cross-subsidization in rural mini-grids. The absence of explicit policies on integrating new technologies such as electrolysers or hydrogen storage further increases uncertainty and may discourage private or community-based initiatives. Financially, the high upfront capital cost of hybrid systems, combined with the limited ability of low-income rural households to pay, presents a challenge for project bankability. Without concessional finance, subsidies, or results-based financing schemes, system deployment may remain unaffordable.

From a technical perspective, deploying a hybrid PV-wind-battery system with electrolyser integration in Yalgo presents several challenges that go beyond the simulation results. First, the intermittency of both solar and wind resources requires sophisticated energy management systems to ensure a continuous supply and avoid instability. While the model assumes optimal dispatch and smooth complementarities, in practice, this demands advanced forecasting tools and smart control systems, which are not yet widely available in rural Burkina Faso. Second, the integration of hydrogen through electrolysis introduces further technical complexity. Electrolysers require stable input power for efficient operation, yet the variability of renewables may cause frequent partial-load operations, reduce system efficiency, and increase wear. Additionally, hydrogen storage and conversion involve safety concerns (such as leakage risks, pressure management, and handling protocols), which require specialized expertise and strict compliance with international standards. Third, battery systems in rural environments face shortened lifespans due to high ambient temperatures, dust, and limited maintenance capacity, raising concerns about replacement costs and system reliability. Finally, the remoteness of Yalgo poses logistical difficulties for sourcing spare parts, performing technical maintenance, and training local operators. Without strong local technical capacity and reliable supply chains, the long-term operation of such a complex hybrid-hydrogen system could be compromised, despite its theoretical feasibility.

Conclusion, Recommendations, and Limitations

Conclusion

This study evaluated the techno-economic viability and affordability of hybrid renewable energy systems for rural electrification in Yalgo, Burkina Faso. The results revealed that a PV-wind-battery setup is the most cost-effective, providing 100% of the community's electricity needs at an LCOE of 0.282 USD/kWh, which is lower than many alternatives documented in the literature. The complementary nature of solar and wind resources reduces dependence on oversized storage, enhancing system stability. Affordability analysis, based on SONABEL's 10% profit margin and the World Bank's 5% income threshold, highlights disparities among consumer groups but shows that cross-subsidies and targeted support mechanisms can greatly improve access. The integration of hydrogen production increases the overall system cost mainly due to the high capital and operational costs of electrolysers and storage. However, this does not affect the affordability of electricity for the Yalgo community, since household tariffs are based on the optimized hybrid system alone. Instead, hydrogen should be viewed as a strategic option to valorise surplus electricity, enhance long-term storage, and create future opportunities in productive uses or international markets, rather than as a direct cost burden on local consumers. Overall, the findings confirm the technical feasibility, economic competitiveness, and social importance of deploying hybrid renewable systems in off-grid Sahelian communities like Yalgo.

Recommendations

To facilitate the implementation of the theoretical findings into practice, the following recommendations are made.

- For Yalgo, a hybrid PV - Wind system is recommended for power supply, as it minimizes capital and operational costs while ensuring supply reliability.
- To fully benefit from surplus generation, the use of smart metering systems to enable real-time energy monitoring and prioritization of hydrogen production without compromising local demand should be introduced
- To ensure system profitability for mini-grids operators and equitable energy access, future studies should aim to establish a localized and dynamic tariff-setting model that reflects both cost-recovery needs and socio-economic conditions of local communities.

- There is also a pressing need for policies that fix acceptable profit margins while mandating tariff segmentation by consumer type. A robust cross-subsidy mechanism (where high-capacity consumers support vulnerable groups) should be institutionalized, supported by targeted external subsidies to ensure energy justice and affordability.
- To ensure that hydrogen co-production in off-grid renewable energy systems, research should focus on assessing in detail the socio-economic impact of hydrogen on rural communities, end-use of hydrogen at the local level, as well as hydrogen and potential e-fuels distribution networks.
- Burkina Faso should adopt a legal and regulatory framework that facilitates and oversees hydrogen integration into off-grid mini-grids, including guidelines for surplus usage, hydrogen safety measures, and distribution networks.

Limitations

Despite the results obtained, some limitations must be acknowledged. These limitations are:

- The energy demand profile used for system optimization was based on data from the Imasgo community due to the lack of real consumption data for Yalgo. While Imasgo is socio-economically comparable, this may not accurately reflect Yalgo's specific demand dynamics.
- The techno-economic parameters such as components CAPEX and OPEX used in this study are taken from literature in similar case studies; their actual cost in Burkina Faso might influence a bit the results obtained, especially the LCOE and NPC.
- The absence of a clearly defined national tariff-setting framework for mini-grids in Burkina Faso led the study to adopt assumptions based on SONABEL's operational benchmarks and international practices.
- Scope for the affordability analysis: Only a test of estimated tariffs based on the calculated LCOE is made to analyse the ability of the community to afford the electricity. A proper tariff design model has not been developed for the affordability analysis.
- Hydrogen co-production: the study only analyses the techno-economic aspect of integrating hydrogen co-production with the hybrid renewable energy system, without considering its end-use or proper socio-economic impact.

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Appendix

Appendix A: Survey used for data collection in Yalgo community

Question No.	Question	Response Category
General information on the collector and the interview		
1	Collector’s name and surname	Choice among collectors
2	Collector's profession	Student, Professional
3	Date of interview	Date (yyyy-mm-dd)
4	GPS coordinates of the surveyed location	Latitude, longitude, altitude, accuracy
General information on the interviewee		
5	Interviewee's name and surname	Free text
6	Gender	☐Male ☐Female
7	Age	Numeric
8	Level of education	☐None ☐Primary ☐Secondary ☐Higher
9	Status in household or institution	☐Head of family ☐Responsible of a business ☐Member ☐Worker
10	Number of people living or working at this place	Numeric
11	Type of place	☐Household, ☐Business ☐Public infrastructure
Inventory of electric appliances		
12	Main source of electriciy	☐National grid ☐Generator ☐Solar ☐Other
13	Electricity availability (hours per day)	Numeric
14	Do you use a refrigerator?	☐Yes ☐No
15	Power ?	Numeric
16	Quantity ?	Numeric
17	Hours per day ?	Numeric
18	Do you use an air conditioner?	☐Yes ☐ No
19	Power ?	Numeric
20	Quantity ?	Numeric
21	Hours per day ?	Numeric
22	Do you use a fan?	☐Yes ☐No
23	Power ?	Numeric
24	Quantity ?	Numeric
25	Hours per day ?	Numeric
26	Do you use a television?	☐Yes ☐No
27	Power ?	Numeric
28	Quantity ?	Numeric
29	Hours per day ?	Numeric
30	Do you use a radio?	☐Yes ☐No
31	Power ?	Numeric
32	Quantity ?	Numeric
33	Hours per day ?	Numeric
34	Do you use lamps ?	☐Yes ☐No
35	Power ?	Numeric
36	Quantity ?	Numeric

37	Hours per day ?	Numeric
38	Do you use other electrical devices?	☐Yes ☐No
39	Specify the type of devices	☐Laptop ☐Desktop ☐Mobile phone ☐Tablet ☐Others (Specify)
Productive use of electricity		
40	What are the main economic activities you engage in?	☐Agriculture ☐Fishing ☐Small-scale manufacturing ☐Retail business ☐Services (e.g., barbershop, tailoring, welding) ☐Others (specify)
41	Do you use electricity for your economic activities?	☐Yes ☐No
42	If yes, what type of electrical equipment do you use?	☐Refrigeration (for storage of food or medicine) ☐Grinding/milling machines ☐Water pumps ☐Welding machines ☐Sewing machines ☐Others (specify)
43	How many hours per day do you use electricity for your business?	☐Less than 2 hours ☐2 to 4 hours ☐4 to 8 hours ☐More than 8 hours
44	If you do not currently use electricity for productive purposes, would you consider using it if it were available and affordable?	☐Yes ☐No
45	What type of electrical equipment would you be interested in using to improve your business if electricity were more accessible and affordable?	text
Willigness to pay		
46	Are you interested in new electricity supply solutions?	☐Yes ☐ No
47	What can motivate you to request electricity connection?	☐Because neighbours want to connect ☐I have a crucial need
48	Can electricity from a mini grid improve your life or business?	☐Yes ☐I don't know ☐No
49	How should electricity access be?	☐Free ☐Paid ☐I don't know
50	Who decides for you to pay for electricity?	☐Myself ☐My employer ☐My family
51	Do you have an individual solar system?	☐Yes ☐No ☐Planning to get one
52	How do you feel about your current electricity access?	☐Very satisfied ☐Managing with it ☐Not satisfied at all
Ability to pay		
53	What is your household’s main source of income?	☐Agriculture ☐Formal employment

		☐Informal business ☐Remittances ☐Others (specify)
54	What is your average monthly income?	☐Less than 50 euro ☐50 – 100 euro ☐100 – 200 euro ☐200 – 500 euro ☐More than 500 euro
55	how much do you spend on electricity per month?	☐Less than 5 euro ☐5 – 10 euro ☐10 – 20 euro ☐20 – 50 euro ☐More than 50 euro

Appendix B: community appliances and their energy consomption

Time (hours)	Fridge_P	TV_P	Fan_P	Radio_P	Lamp_P	Printer_P	Week-days Energy demand (kW)	Week-ends Energy demand	Energy demand of residentials	Energy demand of non_Residentials
1	4060	0	1615	10	829	0	6514	7165.4	4484	200
2	4410	0	1515	0	829	0	6754	7429.4	4374	200
3	4410	0	1515	10	779	0	6714	7385.4	4334	200
4	4410	215	1565	0	950	0	7140	7854	4499	461
5	4160	2400	1105	10	1013	0	8688	9730.56	6497	261
6	4180	2750	815	75	1599	0	9419	10549.28	6964	275
7	4410	2000	1345	125	1128	0	9008	10088.96	5650	2078
8	6360	580	1460	137	1467	0	10004	11204.48	4050	2574
9	6280	550	1535	152	1467	600	10584	11642.4	4260	2574
10	6360	575	1775	152	1467	600	10929	12021.9	4375	3174
11	6310	675	2135	152	1467	0	10739	11812.9	4710	3249
12	6510	2300	2935	127	1467	0	13339	14939.68	7110	2849
13	6510	2400	3555	112	1161	600	14338	16058.56	7779	2579
14	6510	2420	2915	50	1161	600	13656	15294.72	7097	3179
15	6510	775	1970	50	1467	600	11372	12736.64	4543	3449
16	6510	450	990	140	1395	300	9785	10763.5	4377	2328
17	6510	665	890	140	1223	0	9428	10370.8	5428	920
18	5580	1450	1025	140	3635	0	11830	13013	7325	1355
19	6510	2550	1310	115	4558	0	15043	16547.3	10473	1190
20	6510	2750	2440	115	5232	0	17047	19092.64	12387	1280
21	6510	2550	2755	40	5196	0	17051	19097.12	12316	1355
22	6010	1355	2855	0	4998	0	15218	17044.16	10483	1355
23	6510	500	2410	0	4534	0	13954	15349.4	9219	1355
24	4410	50	1135	0	2185	0	7780	8558	5364	236

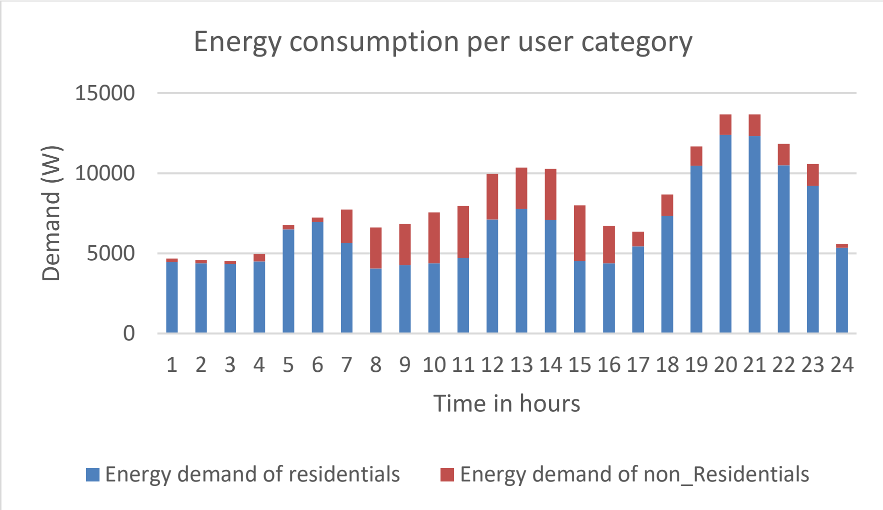
Appendix C: Household Energy consumption

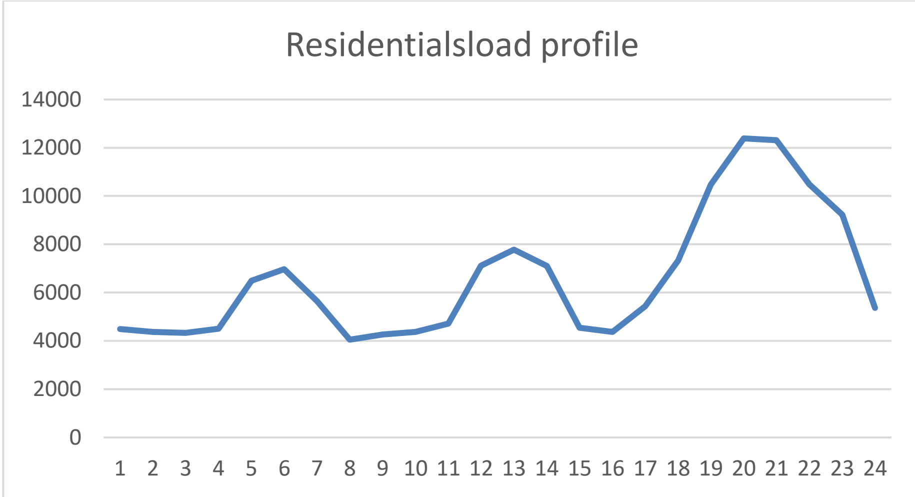
N. O	Household	MTF	Consumer Type	Monthly Energy (Wh)	Monthly Energy consumption (kWh)	Monthly Energy Expenses (USD)	Households monthly income (USD)	Households Willingness to Pay (USD/Month)	Affordability Threshold (5% of income)
1	Kabre Arnaud	Tier 5	Residential	122130.8	122.1308	26.868776	495.00	9.225	24.75
2	Bayala Jean paul	Tier 3	Residential	8736	8.736	1.92192	153.00	7.83	7.65
3	Kietga Ignance	Tier 2	Small business	3628.8	3.6288	0.798336	84.60	7.2	4.23
4	Kietga Ignance	Tier 3	Residential	9072	9.072	1.99584	63.00	6.75	3.15
5	Claude baseire	Tier 2	Residential	6804	6.804	1.49688	72.00	3.06	3.6
6	Ouedraogo Sophie	Tier 3	Residential	16581.6	16.5816	3.647952	70.00	9.27	3.5
7	Yameogo sayouba	Tier 0	Residential	0	0	0	81.00	0	4.05
8	Swily celine	Tier 3	Residential	10029.6	10.0296	2.206512	88.20	4.5	4.41
9	Ouedraogo Marcel	Tier 5	Residential	75852	75.852	16.68744	333.00	10.35	16.65
10	Tenonté Jean baptism	Tier 3	Residential	28434	28.434	6.25548	297.00	8.1	14.85
11	Ramdé Justine	Tier 3	Residential	26157.6	26.1576	5.754672	522.00	9.9	26.1
12	Poline Ouedraogo	Tier 3	Residential	11113.2	11.1132	2.444904	81.00	3.15	4.05
13	Jean ouedraogo	Tier 3	Residential	16648.8	16.6488	3.662736	333.00	6.3	16.65
14	Zongo Emile	Tier 2	Residential	3276	3.276	0.72072	117.00	5.85	5.85
15	Ramde Salifou	Tier 4	Small business	47308.8	47.3088	10.407936	171.00	3.33	8.55
16	Ramde rasmané	Tier 4	Residential	38472	38.472	8.46384	135.00	6.3	6.75
17	Ouedraogo solange	Tier 2	Residential	5728.8	5.7288	1.260336	66.60	2.61	3.33
18	Zongo paulin	Tier 3	Residential	13120.8	13.1208	2.886576	99.00	2.43	4.95
19	RAMDE ousseni	Tier 5	Residential	142422	142.422	31.33284	345.00	2.25	17.25
20	KABORÉ INA	Tier 5	Residential	203616	203.616	44.79552	554.00	9	27.7
21	RAMDE issa	Tier 4	Small business	54432	54.432	11.97504	225.00	10.35	11.25
22	OUEDRAOGO FATIMATA	Tier 3	Residential	23520	23.52	5.1744	150.00	3.6	7.5
23	Mme KABRE	Tier 4	Residential	62512.8	62.5128	13.752816	288.00	2.88	14.4

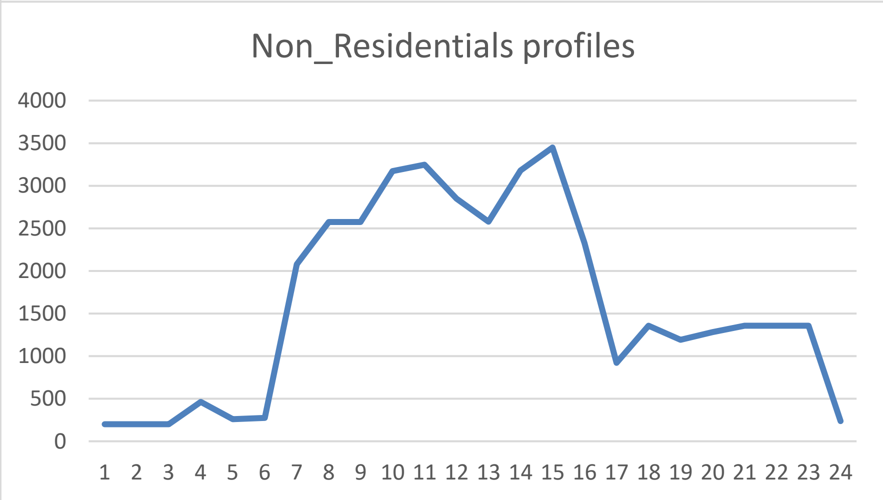
24	OUEDRAOGO MOUSTAPHA	Tier 3	Residential	28560	28.56	6.2832	150.00	2.7	7.5
25	OUEDRAOGO LASSANÉ	Tier 4	Residential	46200	46.2	10.164	405.00	3.06	20.25
26	Ouedraogo zenabo	Tier 3	Residential	12566.4	12.5664	2.764608	171.00	6.84	8.55
27	Ramde blandine	Tier 2	Residential	3133.2	3.1332	0.689304	63.00	2.25	3.15
28	Ramde Jean baptism	Tier 2	Residential	4662	4.662	1.02564	66.60	3.15	3.33
29	Kabore Iliass	Tier 3	Residential	8526	8.526	1.87572	135.00	4.5	6.75
30	Kabre Seni	Tier 2	Residential	6190.8	6.1908	1.361976	153.00	2.61	7.65
31	Ouedraogo Josephine	Tier 3	Residential	15523.2	15.5232	3.415104	153.00	6.21	7.65
32	College Notre dame de imansgo	Tier 5	Public Service	124588.8	124.5888	27.409536	423.00	8.1	21.15
33	Lycee department de imansgo	Tier 3	Public Service	13288.8	13.2888	2.923536	495.00	0	24.75
34	Kanyily	Tier 5	Residential	72676.8	72.6768	15.988896	320.40	6.57	16.02
35	Ramdé Safiatou	Tier 3	Residential	15724.8	15.7248	3.459456	117.00	2.25	5.85
36	Kaboré Bouriema	Tier 4	Small business	53222.4	53.2224	11.708928	153.00	7.65	7.65
37	Kaboré Achille	Tier 4	Residential	46536	46.536	10.23792	261.00	7.83	13.05
38	Ramdé Abdoul	Tier 3	Residential	19353.6	19.3536	4.257792	135.00	6.3	6.75
39	Oudraogo ousmane	Tier 2	Small business	2268	2.268	0.49896	81.00	0	4.05
40	Ramde mathias	Tier 4	Residential	61622.4	61.6224	13.556928	354.00	6.21	17.7
41	Kabore simeon	Tier 5	Small business	126856.8	126.8568	27.908496	458.00	8.208	22.9
42	Sawadogo Boukari	Tier 3	Residential	19622.4	19.6224	4.316928	414.00	4.41	20.7
43	Ramde samba	Tier 3	Residential	9256.8	9.2568	2.036496	81.00	4.509	4.05
44	Ramdé pascal	Tier 3	Residential	13036.8	13.0368	2.868096	117.00	1.8	5.85
45	Zabré ousseni	Tier 3	Residential	20529.6	20.5296	4.516512	441.00	3.6	22.05
46	Kaboré Mariam	Tier 2	Small business	6468	6.468	1.42296	135.00	9	6.75
47	Bamogo rachide	Tier 2	Small business	2419.2	2.4192	0.532224	153.00	3.78	7.65
48	ZONE HERMAN	Tier 5	Small business	127428	127.428	28.03416	450.00	9.18	22.5
49	BATIONO JULINI	Tier 4	Residential	55608	55.608	12.23376	495.00	4.5	24.75

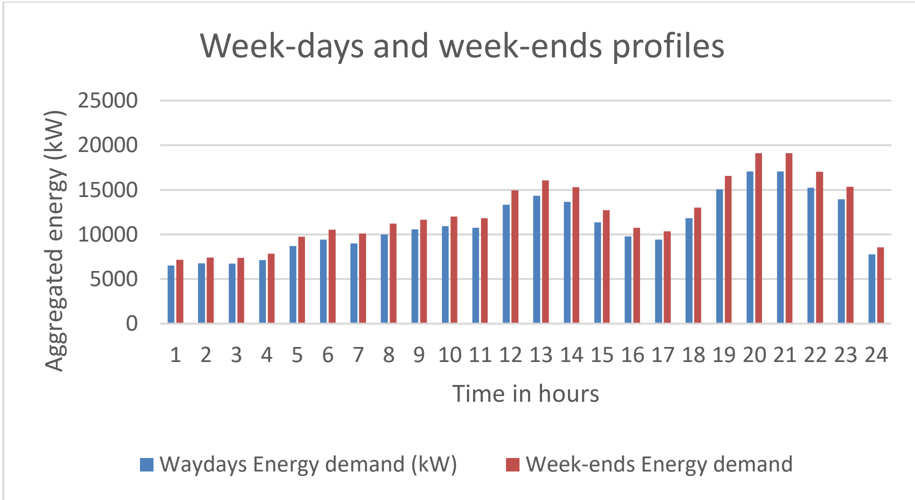
50	IL BOUDOIR ARSÈNE	Tier 4	Residential	56280	56.28	12.3816	567.00	5.4	28.35
51	ZONGO Mahamoudou	Tier 3	Residential	27216	27.216	5.98752	171.00	6.3	8.55
52	RAMDE ISSAKA	Tier 3	Residential	16800	16.8	3.696	117.00	3.6	5.85
53	ZONGO ADAMA	Tier 3	Small business	20160	20.16	4.4352	513.00		25.65
54	Ouedraogo Ismaël	Tier 5	Small business	96768	96.768	21.28896	513.00	12.6	25.65
55	OUEDRAOGO RASMANE	Tier 4	Small business	60228	60.228	13.25016	378.00	8.1	18.9
56	Ouedraogo Issouf	Tier 2	Small business	6048	6.048	1.33056	141.30	6.3	7.065
57	RAMDE Moïse	Tier 5	Small business	213696	213.696	47.01312	650.00	10.8	32.5
58	SAWADOGO SALAMATA	Tier 4	Small business	35280	35.28	7.7616	477.00	5.4	23.85
59	RAMDE NOUFOU	Tier 3	Residential	19152	19.152	4.21344	135.00	3.6	6.75

Appendix D: Community energy consumption behaviours









Appendix E: SONABEL Tariff model

SOCIÉTÉ NATIONALE D'ÉLECTRICITÉ DU BURKINA

DEPANNAGE
80 00 11 30 (N° Gratuit)

Société d'Etat au capital de 63 308 270 000 Francs CFA
Siège social : 55, Avenue de la Nation
01 B.P. 54 Ouagadougou 01
Tél. : (226) 25 30 61 00 / 02 / 03 / 04 / Fax : (226) 25 31 03 40
Site web : www.sonabel.bf

DEPANNAGE
80 00 11 30 (N° Gratuit)

Grille tarifaire applicable à partir du 1er octobre 2023

Arrêté n° 2023 -…………. /MEMC/MEFP/MDICAPME du……………………………

TENSION	Catégories et tranches tarifaires	FACTURATION DES CONSOMMATIONS – Tarifs du kWh (F CFA)			Redevance mensuelle (F CFA)	Prime fixe mensuelle (F CFA)	FRAIS D'ABONNEMENT TTC – Prépayé (F CFA)	Postpayé (F CFA)
BASSE TENSION BT – MONOPHASE 2 FILS	Tarif type A (monophasé social)	Tranche 1 (0 à 75 kWh)	Tranche 2 (76 à 100 kWh)	Tranche 3 (plus de 100 kWh)				
	1A à 3A	75	128	138	1 132	0	1 229	3 375 + K
	Tarif type B1 (monophasé normal)	Tranche 1 (0 à 50 kWh)	Tranche 2 (51 à 200 kWh)	Tranche 3 (plus de 200 kWh)				
	5A - 15A	96	102	109	457	355 par Ampère	1 229	1 135 par Ampère + K
	20A - 30A	96	102	109	764	355 par Ampère	1 229	1 135 par Ampère + K
	Tarif type B2 (monophasé spécial)	Tranche unique						
	5A - 15A	160			457	355 par Ampère	1 229	1 135 par Ampère + K
	20A - 30A	160			764	355 par Ampère	1 229	1 135 par Ampère + K
BASSE TENSION BT – TRIPHASE 4 FILS	Tarif type C1 (triphasé normal)	Tranche 1 (0 à 50 kWh)	Tranche 2 (51 à 200 kWh)	Tranche 3 (plus de 200 kWh)				
	10A - 15A	96	108	114	1 226	1 061 par Ampère	1 918	5 130 par Ampère + K
	20A - 30A	96	108	114	1 373	1 061 par Ampère	1 918	5 130 par Ampère + K
	Tarif type C2 (triphasé spécial)	Tranche unique						
	10A - 15A	160			1 226	1 061 par Ampère	1 918	5 130 par Ampère + K
	20A - 30A	160			1 373	1 061 par Ampère	1 918	5 130 par Ampère + K
BASSE TENSION BT – POSTES HORAIRES	Tarif type D	Heures pleines (00h00 – 17h00)	Heures de pointe (17h00 – 24h00)					
	Tarif type D1 Non industriel	88	165		8 538	2 882 par kW		PS x 100 x 130 + K
	Tarif type D2 Industriel	75	140		7 115	2 402 par kW		PS x 100 x 118 + K
	Tarif type D3 Spécial	160	160		8 538	2 882 par kW		PS x 100 x 160 + K
MOYENNE TENSION (MT)	Tarif type E	Heures pleines (00h00 – 17h00)	Heures de pointe (17h00 – 24h00)					
	Tarif type E1 Non industriel	64	139		8 538	5 903 par kW		PS x 100 x 118 + K
	Tarif type E2 Industriel	54	118		7 115	5 366 par kW		PS x 100 x 118 + K
	Tarif type E3 Spécial	160	160		8 538	5 903 par kW		PS x 100 x 160 + K
INDUSTRIES EXTRACTIVES ET HAUTE TENSION (HT)	Tarif type G	Heures pleines (00h00 – 10h00)	Heures de pointe (10h00 – 24h00)					
	Tarif type G	70	140		7 115	5 366 par kW		PS x 100 X 155 + K
ECLAIRAGE PUBLIC	Tarif type F	Tarif unique						
	5A - 15A mono	122			381	- PS = Puissance Souscrite et K = Frais de police + impôts et taxes		
	20A et plus mono	122			637	- Pour la tarification à postes horaires BT, MT et HT : Pénalisation si Cos phi < 0,93		
	10A - 15A triphasé	122			1 022	- L'administration est dispensée du versement de l'avance sur consommation		
	20A et plus triphasé	122			1 144			

NB : le tarif spécial est appliqué aux polices d'abonnement qui sont prises en charge par les banques et autres établissements financiers, les sociétés d'assurances, les compagnies de télécommunications, les institutions internationales, les ambassades et autres enclaves diplomatiques et les industries du l

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Source: SONABEL

Appendix F: Classification of HRES challenges.

Challenge[1]	Specific challenge	Explanation	Ref.
Technical Challenges	Intermittency	Renewable sources like solar and wind are intermittent, making prediction and management more complex.	(Nyarko et al., 2023)
	Integration complexity	Different energy sources may require specific control and management systems to be integrated seamlessly.	(Uwineza et al., 2021)
	Infrastructure Development	Building new infrastructure or retrofitting existing infrastructure for HRES can be complicated.	(Nyarko et al., 2023)
	Energy Storage	Choosing, integrating, and managing energy storage solutions to ensure energy reliability can be challenging.	(Nyarko et al., 2023)
Economic Challenges	High Initial Costs	Hybrid systems may have higher initial investment costs compared to single-source systems.	(Chennaif et al., 2022)
	Market Maturity	Some technologies in HRES might not be mature, leading to economic uncertainties.	(Chennaif et al., 2022)
	Payback periods	The variability of renewable energy can affect the predictability of returns on investment.	(Chennaif et al., 2022)
Environmental Challenges	Land use	Combining multiple energy sources may require more land or specific types of land, leading to environmental concerns.	(Kelly et al., 2023)
	Resource Assessment	Accurate assessment of renewable resources (e.g., wind speeds, solar irradiance) is crucial but can be challenging.	(Kelly et al., 2023)
Regulatory and Policy Challenges	Licensing and standards	There might be a lack of standardized regulations for HRES, leading to uncertainties in licensing and operation.	(Nyarko et al., 2023)
	Inconsistent Policies	Different energy sources might be subjected to varying policies and regulations, complicating system design.	(Nyarko et al., 2023)

(1) (Hassan, Algburi, et al., 2023)