

# Hybrid Renewable Energy Systems: An Integrated Approach to Rural Electrification

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**Abstract.** In recent years, there has been a marked shift in focus towards sustainable and renewable energy solutions, particularly in the context of developing nations. This article explores the immense potential of hybrid renewable energy (RE) systems for ushering in a transformative change in electrifying remote and rural areas within these countries. The importance of such endeavours becomes paramount as a multitude of nations globally seek strategies to diminish carbon footprints. Renewable energy systems, combining sources such as solar, wind, hydro, and biomass, emerge as crucial assets in this drive, especially when considering regions that remain largely isolated from major electrical grids. The growing emphasis on research in this domain, coupled with favourable policies, signifies a promising trajectory for RE in developing nations. Such hybrid models, by capitalising on the diverse spectrum of renewable resources at hand, are on the brink of initiating a revolution in rural electrification strategies. This review accentuates the urgency and significance of rapidly integrating these avant-garde systems, setting the stage for a future that is not only environmentally conscious but also ensures broader and more equitable access to energy.

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## 1 Introduction

In recent times, the urgency to transition towards sustainable energy solutions has gained significant momentum. Integral to this movement is an appreciation of the natural resources that offer continuous energy benefits, such as the untapped potential of solar and wind power. Kaabeche et al. (2011) determined that as the conventional energy resources diminish and environmental concerns rise, renewable energy sources emerge as a beacon of hope [1].

Solar energy, widely applauded for its negligible carbon footprint, stands poised to revolutionise the energy landscape in the coming years. This sustainable source of power, harnessing the immense potential of the sun, is increasingly viewed as a crucial component in the global shift towards environmentally-friendly energy alternatives. However, as highlighted by Deng et al. (2019), there remain pertinent challenges that need to be surmounted. Particularly, the issues of effectively scaling up solar energy installations to meet growing demands, and the complexities associated with transmitting this energy over vast distances, remain significant barriers. Addressing these concerns will be vital in ensuring that solar power realises its full potential and contributes meaningfully to a sustainable energy future[2][19].

Concurrently, wind energy is receiving significant attention in the renewable energy sector. Esteemed for its outstanding environmental virtues, it's progressively being seen as more than just a sustainable source but also an economically viable alternative to conventional power. According to Abbasi et al. (2016) this perspective on wind energy, both as a sustainable and economically beneficial resource, has been eloquently elucidated by [3].

On another front, hydropower stands tall amongst its renewable counterparts. Often held up as a paragon of green energy solutions, hydropower is particularly admired for its dynamic flexibility. Hafez et al. (2012) in their study stated that hydropower's capability for swift alterations to its output, which can be tailored to varying demand scenarios, underscores its uniqueness in the renewable sector—a sentiment strongly echoed by [4].

These renewable energy sources take on added importance in isolated locations. In such areas, setting up conventional energy infrastructures can be both expensive and logistically challenging. Hence, the notion of blending multiple renewable resources into hybrid energy systems presents a groundbreaking solution. Such systems not only promise a harmonious blend of varied energy sources but also venture to overcome the distinctive challenges posed by isolated terrains and their unique energy needs.

### 1.1 The Role of Hydrogen in Energy Storage

A crucial consideration in the renewable energy dialogue is the concept of energy storage, particularly through hydrogen, as noted in the study by Breeze et al. (2018). By harnessing off-peak electrical energy for hydrogen generation, a seamless energy supply can be maintained even when electricity demand spikes [5]. The most notable advantage of hydrogen is its environmental friendliness; its combustion yields only water. This attribute, coupled with its multifaceted applications, positions hydrogen as a linchpin in the renewable energy realm. Despite the potential offered by regions abundant in hydropower and favourable solar conditions, the logistical challenges associated with energy transmission can hamper their true potential [2]. An innovative solution to this conundrum

could be the conversion of surplus electricity into hydrogen, which can then be transported with minimal energy loss.

## **1.2 Proposed Hybrid System**

In light of the aforementioned developments, this study introduces a hybrid system, blending the strengths of wind and hydropower. Envision a scenario where excess electricity, especially during off-peak times, is redirected to produce hydrogen. This hydrogen, upon reaching its destination, is then transformed back into electricity. Such a mechanism could revolutionise the power supply to remote systems, particularly in regions where traditional transmission infrastructures fall short.

## **2 The Crucial Need for Electricity in Remote Areas**

In many parts of the developing world, remote rural communities grapple with the stark reality of limited or no electricity. This deficit in essential infrastructure casts a significant shadow over their everyday life, often relegating them to rely on rudimentary energy solutions that are neither sustainable nor efficient. The paucity of consistent electricity access transcends mere inconvenience; it acts as a formidable barrier to holistic development and modernisation. Without power, vital sectors such as healthcare and education suffer, leading to persistent gaps in quality and delivery, thus widening the disparity between rural and urban areas.

Electricity, or the lack thereof, has direct ramifications on local economies as well. The absence of stable power sources stunts entrepreneurial ventures and curtails the growth of small businesses that are pivotal for the economic upliftment of these communities. Not only does this impact livelihoods, but it also curtails opportunities for innovation and modernisation in agriculture and other predominant sectors in these regions. The resultant economic stagnation often leads to migration patterns, with individuals seeking better opportunities in urban centres, thereby exacerbating the challenges faced by these remote locales.

However, the silver lining in this scenario is the untapped potential of renewable energy (RE) resources present in many of these regions. By leveraging technologies that harness the power of nature – such as solar, wind, and hydropower – these areas can effectively bridge the energy gap. Hybrid renewable energy systems, which combine the strengths of various renewable sources, offer an optimised solution tailored for these challenging terrains and conditions. Embracing such systems not only addresses the immediate electricity needs but also paves the way for sustainable and resilient communities, aligned with a future that champions green and inclusive growth.

## **3 The Landscape of Renewable Energy in Developing Nations**

Developing nations, despite their diverse socio-economic challenges, are poised at a unique juncture that marries their geographical advantages with the inexorable global push towards renewable energy. The extensive and varied natural resources available in these countries – from unyielding sunshine to wind-swept terrains and river-rich landscapes – promise a future where energy is both sustainable and abundant. Furthermore, the burgeoning technological advancements are fast making these resources not just viable, but often the most economically advantageous energy options.

### **3.1 Solar Energy**

The Sun, a colossal fusion reactor that bathes our planet with energy daily, offers an incredible potential for power generation. Developing nations, especially those situated near the equator, benefit from longer daylight hours and more intense sunlight. According to the World Bank, as of 2019, solar photovoltaic (PV) installations in developing countries reached nearly 150 GW, representing a five-fold increase over the past five years (World Bank, 2019). The growth trajectory suggests that, with continued investments and technology advancements, solar energy might become the backbone of energy infrastructure in these regions.

### **3.2 Wind Energy**

From the vast plains of Africa to the towering heights of the Andes, the whisper of the wind carries with it the promise of power. Wind energy, with its diminishing costs and increasing efficiency, has made a compelling case for itself in the renewable mix. Its ability to be deployed both onshore and offshore gives nations the flexibility to harness it based on their geographical strengths. Wind energy has seen substantial growth in various regions, especially in coastal or high-altitude areas. By 2020, the Global Wind Energy Council reported that emerging economies added 53 GW of wind energy capacity, with the cumulative capacity crossing 651 GW globally (GWEC, 2020). Wind farms, apart from generating electricity, also act as symbols of progress, signalling a nation's commitment to a sustainable future.

### **3.3 Hydro Energy**

Rivers, having cradled ancient civilizations, are now being looked upon to power the future. Hydroelectric power, with its dual benefits of water storage for agriculture and electricity generation, is invaluable to developing nations. Many of these countries are blessed with expansive river systems, cascading waterfalls, and undulating terrains - all conducive to hydroelectric projects. By the end of 2020, the International Hydropower Association estimated that global hydroelectric capacity stood at 1,308 GW, with a significant portion from developing nations (IHA, 2020). As technologies evolve, even smaller water bodies and canals might be tapped for mini and micro hydro projects, decentralising energy generation further.

### **3.4 Biomass Energy**

Agriculture, the mainstay of many developing economies, offers more than just food. The waste - straw, husk, and foliage - can be transformed into energy. Biomass energy, rooted in ancient practices of burning wood and organic matter for heat, has now evolved into sophisticated systems producing electricity, heat, and biofuels. A 2018 report from the International Renewable Energy Agency (IRENA) highlighted that biomass electricity capacity reached 122 GW globally, with a noticeable contribution from developing countries due to their agricultural residues (IRENA, 2018). Biomass projects also offer an added advantage of waste management, turning agricultural residues and waste into wealth. Modern biomass conversion technologies like anaerobic digestion and gasification have further expanded the horizons, making biomass not just a stopgap but a long-term sustainable energy solution.

In conclusion, the renewable energy landscape in developing nations, backed by their inherent geographical advantages, presents a mosaic of opportunities. Embracing these

resources, aligned with technological advancements, promises a future of energy security, economic growth, and environmental sustainability.

## 4 Unpacking the Potential of Hybrid Renewable Energy Systems

Navigating the evolving landscape of energy consumption and generation reveals a pressing need for innovative solutions to address growing demand, environmental concerns, and reliability issues. The following collection of key findings [7-15] distils essential insights from a comprehensive examination of hybrid energy systems. These findings illuminate the intricate interplay between conventional and renewable energy sources, shedding light on the challenges posed by intermittency and the promise of hybridisation. Through an exploration of various system configurations, converters, and control strategies, these findings offer a holistic understanding of how hybrid systems are reshaping the energy landscape.

- Energy demand is increasing due to population growth, suburbanization, and industrial development, leading to energy shortages.
- Conventional energy sources, like coal, oil, and gas, are limited, and their consumption leads to environmental impacts, such as increased CO<sub>2</sub> emissions and global warming.
- Renewable energy sources, such as wind, solar, hydro, biogas, and fuel cells, are being considered as alternatives to conventional sources due to their environmental friendliness.
- Renewable energy sources are intermittent and dependent on environmental conditions like wind speed and solar irradiance, posing challenges for continuous power supply.
- Hybrid systems, which combine multiple renewable and non-renewable energy sources, offer a more reliable and efficient solution to address the intermittency issue.
- Different configurations of hybrid systems, such as DC coupled, AC coupled, and Hybrid coupled systems, can be chosen based on specific applications and requirements.
- Various types of converters and controllers, such as buck, boost, and buck-boost converters, are used in hybrid systems to efficiently manage energy conversion.
- Power management strategies, like maximum power point tracking (MPPT) and hysteresis control, play a crucial role in optimizing energy extraction from renewable sources.
- Advanced control strategies, such as adaptive neuro-fuzzy inference systems (ANFIS), are employed to enhance the performance and stability of hybrid systems.
- Hybrid systems incorporating energy storage, such as batteries and superconducting magnetic energy storage (SMES), help stabilize grid interactions and mitigate power fluctuations.

These findings underscore the complexity of integrating renewable and conventional energy sources within hybrid systems, highlighting the significance of efficient management, control, and optimisation strategies to achieve sustainable and reliable energy solutions.

The realm of energy generation is undergoing a transformative shift as the demand for sustainable and efficient power sources intensifies[16]. In this context, the integration of hybrid energy systems, amalgamating both renewable and non-renewable energy sources, emerges as a pivotal strategy. The first table presents a comprehensive comparison of various components intrinsic to these hybrid systems. It delineates the key characteristics of energy sources, encompassing renewable options such as wind, solar, and hydro, in contrast to non-renewable counterparts like gas and diesel. The table further elucidates the critical role played by power converters, which facilitate seamless energy conversion, including converters like buck, boost, and buck-boost that optimise efficiency. Additionally, the distinct attributes of energy storage systems, from batteries to superconducting magnetic storage, are outlined alongside their integral role in stabilising power supply and demand. Concluding the table are insights into control strategies, like MPPT and hysteresis control, pivotal for the precise orchestration of energy flow and ensuring an optimal utilisation of hybrid energy sources.

Table 1: Comparison of Different Hybrid System Components

Component	Characteristics	Application
Energy sources	Renewable (wind, solar, hydro, etc.)	Green energy supply
	Non-renewable (gas, diesel, etc.)	Backup power
Power converters	Buck, boost, buck-boost converters	Efficient conversion
	Inverters, rectifiers	AC/DC conversion
Energy storage controllers	Batteries, superconducting storage systems	Stabilising supply and demand
Control strategies	MPPT, hysteresis control, ANFIS, etc.	Optimizing power extraction

As global energy demands surge and concerns for environmental preservation intensify, the fusion of disparate energy sources into hybrid systems emerges as a promising avenue. The second table delves into the distinctive configurations underpinning these hybrid systems, each catering to specific applications and requirements. The table introduces the concept of DC Coupled configurations, where both energy sources and loads function in direct current, making them ideal for DC micro-grids[17-18]. Alternatively, the AC Coupled systems feature AC sources and loads, which can be categorised into power frequency and high frequency AC coupling, with the former offering ease of protection, and the latter catering to diverse needs including defence applications. Lastly, the Hybrid Coupled systems come to the fore as an amalgamation of AC and DC sources and loads, presenting heightened efficiency and versatility. The comprehensive overview of these configurations sheds light on their distinctive features and the diverse spectrum of applications they serve.

Table 2: Characteristics of Some Hybrid System Configurations

Configuration	Description	Application
DC Coupled	DC sources and DC loads	DC micro-grids
AC Coupled	AC sources and AC loads (power frequency or high frequency)	AC micro-grids Defense applications
Hybrid Coupled	Combination of AC and DC sources/loads (highest efficiency and flexibility)	Versatile, high efficiency

In the pursuit of harnessing clean energy while ensuring seamless power supply, adept control strategies hold a pivotal role within hybrid energy systems. The third table offers a succinct summary of some prominent control strategies deployed to optimise the functioning of these systems. At the forefront is the Maximum Power Point Tracking (MPPT) strategy, a sophisticated algorithm that meticulously follows the peak power output from renewable sources, like wind and solar, ultimately enhancing energy extraction efficiency. In tandem, the Hysteresis Control strategy meticulously regulates the voltage and current outputs based on preset thresholds, effectively curtailing power fluctuations and maintaining system stability. Lastly, the Adaptive Neuro-Fuzzy Inference System (ANFIS) stands as an advanced control approach, utilising neural-fuzzy algorithms to dynamically optimise power generation and storage. This table provides an insightful overview of these strategies, showcasing their distinctive contributions towards the effective operation of hybrid energy systems.

Table 3: Summary of Selected Hybrid System Control Strategies

Control Strategy	Description	Application
MPPT (Maximum Power Point Tracking)	Tracks maximum power output from renewable sources (wind, solar)	Efficient energy extraction
Hysteresis Control preset thresholds	Regulates output voltage/current based on fluctuations	Stabilizing power
ANFIS (Adaptive Neuro-Fuzzy Inference System)	Uses neural-fuzzy system to optimize power generation and storage	Enhanced stability, dynamic response

## 5 Broader Environmental Context

The conversation around adopting renewable energy (RE) systems extends far beyond a mere discourse on advanced technologies or economic viability. It encompasses a holistic environmental context that underscores the interconnectedness of ecosystems, economies, and societies. As the global narrative becomes increasingly concerned with environmental degradation and climate change, the focus on RE as a panacea for numerous environmental woes becomes all the more salient.

## **5.1 Climate Change Mitigation**

At the heart of the RE debate is the undeniable role of clean energy in mitigating climate change. Fossil fuel combustion remains one of the largest contributors to greenhouse gas (GHG) emissions, driving global temperatures upwards and intensifying extreme weather events. Shifting to RE systems enables nations to decarbonise their energy sectors, acting as a critical lever in reducing their carbon footprint. This transition, when scaled globally, holds the potential to keep global warming well below the stipulated 2°C threshold, as delineated in the Paris Agreement.

## **5.2 Preservation of Biodiversity**

RE projects, particularly when planned and executed with an emphasis on sustainability, can play a pivotal role in preserving biodiversity. Unlike large-scale infrastructural projects like dams or coal mines, which can disrupt habitats and endanger species, RE projects often have a lesser ecological footprint. Properly placed solar farms or wind turbines can generate energy with minimal interference in natural ecosystems, ensuring the survival and thriving of local flora and fauna.

## **5.3 Air and Water Quality**

One of the often overlooked benefits of transitioning to RE is the drastic improvement in air and water quality. Burning fossil fuels releases not just carbon dioxide but a slew of harmful pollutants, including sulphur dioxide, nitrogen oxides, and particulate matter. These pollutants are implicated in a range of health issues, from respiratory diseases to cardiovascular problems. By transitioning to RE, nations can ensure cleaner air for their citizens. Moreover, conventional power generation methods, especially coal, have been linked to water pollution and excessive water use. RE technologies, in contrast, typically use significantly less water, safeguarding this critical resource.

## **5.4 Soil Conservation and Land Use**

The expansive mining operations associated with fossil fuel extraction often lead to land degradation and soil erosion. RE systems, especially solar and wind, require far less land alteration, ensuring the preservation of fertile topsoil and preventing erosion. Furthermore, in many cases, the land around these installations can be utilised for dual purposes, such as agriculture or grazing, promoting harmonious coexistence with local communities.

## **5.5 Socio-economic Impacts**

While not strictly environmental, the socio-economic benefits of RE cannot be overstated. Cleaner environments often translate to healthier populations, reduced healthcare costs, and enhanced quality of life. Moreover, RE projects can foster local employment opportunities, ensuring a more equitable distribution of economic benefits.

In essence, the shift to renewable energy systems is not just a matter of technological innovation or economic feasibility. It's a profound testament to humanity's commitment to safeguarding the planet for future generations, ensuring a balance between development and ecological conservation. The broader environmental context thus provides a compelling and urgent impetus for this global transition.

## **6 Navigating the Economic and Regulatory Terrain**

The deployment of renewable energy (RE) in a country's energy mix doesn't merely hinge on the availability of resources or technological prowess. It's intrinsically linked to the economic and regulatory landscape that paves the way for sustainable, scalable, and economically viable RE projects. Recognising the pivotal role these twin factors play, several nations are recalibrating their policy frameworks and economic strategies to usher in a new era of clean energy.

### **6.1 Policy Initiatives**

Policies act as bedrocks for RE deployment, guiding investments, ensuring stakeholder participation, and setting out clear, achievable targets. In many nations, Feed-in Tariffs (FiTs) have been instrumental in incentivising renewable energy projects. These tariffs guarantee fixed payments to renewable energy producers, ensuring their economic viability and fostering a sense of security for investors. Besides, Renewable Portfolio Standards (RPS) or Renewable Purchase Obligations (RPOs) mandate certain sectors or utilities to source a specific percentage of their power from renewable sources, driving demand and ensuring a steady market for green energy.

### **6.2 Financial Instruments and Incentives**

A buoyant financial ecosystem is indispensable for the thriving of RE projects. Countries have introduced an array of financial instruments, from tax credits and rebates to green bonds, to mobilise the requisite capital. Moreover, the establishment of green banks or renewable-focused financial institutions has catalysed investments, providing specialised loans and financial products tailored for the renewable sector.

### **6.3 Grid Integration and Infrastructure**

A robust infrastructure, especially the electricity grid, is crucial for transmitting and distributing renewable energy. Policies are therefore being devised to upgrade grid infrastructure, ensuring it's compatible with variable RE sources like wind and solar. Grid integration also entails the development of energy storage solutions, such as battery storage and pumped hydro storage, which play a pivotal role in maintaining grid stability.

### **6.4 Capacity Building and Skill Development**

It's imperative to note that for RE projects to thrive, a skilled workforce is essential. Governments are initiating training programmes and workshops, partnering with academic institutions and industry players, to equip the local workforce with the necessary skills. These endeavours not only ensure the seamless operation of RE projects but also generate employment opportunities, fostering socio-economic growth.

## 6.5 Stakeholder Engagement and Public Awareness

Last but not least, public perception and awareness can make or break the success of RE projects. Proactive policies are therefore being framed to engage the community, address their concerns, and highlight the long-term benefits of renewable energy. Such community-centred approaches often lead to the faster adoption of renewable technologies and foster a sense of collective ownership.

In summation, while the economic and regulatory terrain can pose challenges, with thoughtful navigation and strategic interventions, these can be turned into opportunities. As nations rally to mitigate the effects of climate change, the marriage of robust policies with agile economic strategies will be instrumental in charting a sustainable future.

## 7 Conclusion and Future Directions

In conclusion, the literature review underscores the imperative of embracing hybrid renewable energy systems as a transformative solution to electrify remote and rural areas in developing nations. The synergy of solar, wind, hydro, and biomass sources within hybrid systems presents a promising avenue to address energy poverty and mitigate carbon footprints. The urgency to integrate these systems is underscored by the challenges of climate change, biodiversity loss, and air and water pollution. However, substantial progress requires strategic considerations:

**Diverse Renewable Resources:** Developing nations possess abundant renewable resources, with solar, wind, hydro, and biomass offering a mosaic of opportunities. Future research should explore synergies between these resources to maximize energy output.

**Energy Storage Innovation:** The role of hydrogen as an energy storage medium is crucial. Investigating efficient hydrogen generation and transportation systems can revolutionize energy supply in isolated areas.

**Hybrid System Configurations:** Further investigation into optimal hybrid configurations (DC, AC, Hybrid Coupled) and their adaptability to specific contexts is essential for efficient energy distribution.

**Advanced Control Strategies:** Refined control strategies, such as ANFIS, can enhance the stability and performance of hybrid systems, enabling seamless integration of intermittent energy sources.

**Policy Frameworks and Economic Incentives:** Governments must craft supportive policies, offering financial incentives, stable energy markets, and fostering partnerships with the private sector to ensure sustainable growth of renewable energy.

**Community Engagement and Capacity Building:** Public awareness and stakeholder involvement are key to successful deployment. Fostering skilled workforces and engaging communities in decision-making processes can accelerate adoption.

**Integration with Existing Infrastructure:** Integrating hybrid systems with existing conventional grids requires careful planning. Research should explore effective grid upgrades and integration mechanisms.

In navigating the nexus of technological innovation, economic viability, and environmental preservation, developing nations have the opportunity to forge a future that combines equitable energy access with sustainable development. Embracing hybrid renewable energy systems can be the cornerstone of this journey, transcending geographical barriers and ensuring a greener, more inclusive world.

#### Key Points:

- Hybrid renewable energy systems offer transformative solutions for electrifying remote areas and mitigating carbon footprints in developing nations.
- Solar, wind, hydro, and biomass resources within hybrid systems provide diverse and complementary energy options.
- Hydrogen-based energy storage holds promise for efficient energy supply in isolated areas with limited grid access.
- Strategic selection of hybrid system configurations (DC, AC, Hybrid Coupled) optimizes energy distribution.
- Advanced control strategies like ANFIS enhance stability and performance of hybrid systems.
- Supportive policy frameworks and economic incentives are crucial for sustainable growth of renewable energy.
- Public awareness, stakeholder engagement, and capacity building are pivotal for successful deployment of hybrid systems.

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