Hydrogen as a solution for a stable and sustainable low-carbon energy system in Sub-Saharan Africa

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Abstract

The increasing penetration of renewable and distributed energy resources in Sub-Saharan Africa has intensified concerns about energy security, frequency deviations, and overall grid instability. Addressing these challenges requires reliable energy storage solutions capable of supporting a stable, low-carbon electricity supply. This study adopts a combined qualitative and quantitative approach to examine the role of hydrogen energy storage systems in enhancing renewable energy integration and advancing decarbonisation across the region. Qualitatively, policy and regulatory preparedness is assessed across twelve Sub-Saharan African countries, while a quantitative decarbonisation cost–benefit analysis evaluates hydrogen's potential for peak-load management and grid reliability at the national level. Hydrogen storage is proposed as a scalable, low-carbon solution, with South Africa, Kenya, and Ghana emerging as the most promising case studies due to their stronger renewable energy profiles and implementation capacities. The findings show that strategic investment in hydrogen energy storage can significantly reduce CO_2 emissions and improve grid flexibility, although high upfront costs and regulatory constraints remain key barriers. This study contributes a cross-country readiness assessment, empirical evidence of hydrogen's system-level benefits, and a framework incorporating both green and other hydrogen pathways. These insights highlight the broader applicability of hydrogen storage for developing regions seeking robust, long-term strategies to stabilise renewables-based power systems and accelerate the transition toward low-carbon energy futures.

Keywords: hydrogen; energy storage; renewable energy; decarbonization; grid stability; peak load; low carbon; cost benefit; Sub-Saharan Africa.

Introduction

1.1 Background

The hydrogen energy storage systems (HESS) are widely recognized because of their potential in enhancing the stability of power grids when coupled with renewable energy sources (RES) [1]. Recent studies highlighted that HESS systems provides a wide range of advantages [2]. The advantage of HESS includes high energy density, grid stability and flexibility [3]. Due to the increased concerns on energy security and climate change issues, a quest for producing clean electricity led to significant penetration of RES thus HESS and distributed energy resources (DER), particularly inverter-based resources such as electric vehicle (EV) charging infrastructure, to the grid [4]. The HESS offers a diverse and versatile promising approach for enhancing the reliability and the sustainability of modern energy systems. Variable renewable energy sources are being integrated in both grid-connected and islanded configurations [5]. Increased penetration of RES in power systems poses issues such as large frequency deviations and grid stiffness hence, grid instability. Conventional power generation systems can allow the addition of a few variable renewable energy sources [6]. However, with the ongoing rapid integration of HESS and other RE sources, the power system will not be able to balance the power and energy, hence becoming unreliable [7]. Also, the system will not be able to sustain the imbalance between grid-connected RES and the load demand for longer periods [8].

Integration of DERs such as wind, HESS, energy storage systems (ESS) and solar photovoltaic (PV) systems create low-voltage (LV) and medium-voltage (MV) networks called active distribution networks (ADNs) and microgrids (MG) [9]. Grid-tied DERs, together with the internet-of-things (IoT), convert conventional grids into cyber-physical systems called smart grids [10]. Future smart grids are predicted to consist of 100% RES integrated into conventional systems, and HESS provides great potential in facilitating this [11]. The intermittent nature of RESs, since they are dependent on weather conditions, requires generation-load balancing and sufficient energy reserves to ensure reliability [12]. Supported by the decrease in ESS prices in recent years, this enables ESSs to be integrated into grids with a high share of variable renewable energy sources [13]. ESS increases reserve capacity, enhances power system efficiency, and provides real-time balancing in generation and transmission, thus enabling flexible electricity consumption for consumers [14]. Several studies reviewed and critically analyzed HESS technologies that can support 100% penetration of RES into the conventional grids [15]. In power systems with a high share of variable renewable energy, HESS can be employed to smooth short-term electricity fluctuations [16]. The process of storing energy involves converting electricity into a form most suitable for storage, and HESS technologies are classified according to the type of energy stored [17]. These classes are discussed in the following sections.

This paper highlights the critical role of HESS in transforming SSA's energy landscape by enabling the large-scale integration of renewable energy and advancing decarbonization efforts. What makes this study particularly compelling is its focus on the unique challenges and opportunities in SSA, a region where energy access and grid reliability are pressing concerns. Nevertheless, there are challenges related to cost and efficiency, which need advanced review for broader adoption and integration of green hydrogen storage in various applications [18].

This article provides a novel exploration of how various energy storage systems, for example green hydrogen energy storage systems, can specifically enhance renewable energy integration and decarbonization in SSA, supported by country-specific case studies and an analysis of policy frameworks and regulatory approaches tailored to the region's unique energy challenges. Existing literature consistently highlights a fragmented policy and regulatory landscape for green hydrogen in SSA, with no comprehensive national or regional strategies delineating deployment targets, licensing pathways, or market frameworks [19] [20]. Analysis further reveals deficient institutional coordination and unclear regulatory regimes, particularly in the Southern African Development (SADC) region [21] and while regional frameworks such as Economic Community of West African States - ECOWAS's 2023 Green Hydrogen Strategy mark progress, implementation remains under-developed. These regulatory gaps undermine investment for enhancing hydrogen supported technologies needed to stabilize the current electrical grids and sustaining clean mobility, as hybrid financial instruments depend on policy predictability [22]. This research addresses this critical void by offering an integrated policy-investment framework and tailored regulatory pathways (such as licensing, standards, and off-take structures) coupled with country-level case studies, thus bridging the divide between technical storage solutions and real-world policy implementation. Additionally, this paper introduces new insights into the economic and policy barriers specific to SSA while offering innovative policy and investment frameworks tailored to the region. In bridging the gap between technical feasibility and policy implementation, this study provides a fresh perspective on how HESS can catalyse electrification and decarbonization in one of the world's fastest-growing energy markets. The necessity to decarbonize the global energy system has intensified as climate change impacts worsen. SSA, rich in renewable energy resources, presents a unique opportunity for a consistent transition to a low-carbon future.

1.2 Motivation of the current study

The growing population and industrialization threaten SSA's environment and clean energy future status. As a result, maintaining its global position as the least emitting region and attaining the indicators and targets of the sustainable development goal of clean and affordable energy may be challenging. Additionally, the SSA region faces significant challenges in achieving this goal, including increasing industrial urbanization [23], inefficient electricity grid capacity [24] , and limited access to reliable and affordable energy [25]. These result in less access to electricity and clean cooking and burden the rapidly growing population. Consequently, the numerous electricity grid-dependent sectors in SSA countries are surpassing their conventional national network capacities, hence resulting in electricity blackouts and economic consequences [24] [26]. Energy storage systems and distributed energy resources connected to the grid hold great potential for addressing these difficulties. They could increase reserve capacity, improve power system efficiency, balance generation and transmission in real-time, facilitate renewable energy integration, and reduce emissions potentials in Africa [27] [28].

Storage technologies aid in demand response, demand-side management, and power quality; they also affect electricity generation, transmission, distribution, and consumption. Recent studies have explored the role and potential contributions of different energy carriers and storage in advancing a resilient SSA energy system. Muktar et al. [29] considered the renewable energy potential in SSA and juxtaposed it with how it can contribute to ending energy poverty and energy costs. By lowering energy poverty in a bid to achieve carbon neutrality [30], increasing electrification [31] from hydrogen-based system, Olówósejéjé et al. [27] discussed different practical approaches, of which hydrogen adoption and implementation serve to be highly instrumental.

Hydrogen, often referred to as the "energy carrier of the future," has emerged as a feasible solution to address these challenges. Its versatility and efficient combustion properties position it as a potentially transformational element in the energy sector. Sub-Saharan Africa can decarbonize its energy infrastructure and reduce its reliance on fossil fuels by producing hydrogen from different clean energy sources such as solar, wind, and hydroelectric power. Fonou et al. [32] discussed the prospects of hydrogen-natural gas systems in SSA for electrical power plants, and Ude et al. [33] carried out a comprehensive review of the current status of hydrogen in SSA, followed by how it can enable energy access in remote and off-grids areas of SSA. Mapping hydrogen cost potentials is pertinent to determining the worst-case-best-case scenarios [34] needed for developing legal frameworks and policies that will serve as a tool [35] to facilitate hydrogen adoption and implementation in SSA as an enabler of a decarbonized electricity sector.

Compared with past reviews and studies, the cost-benefits of hydrogen production are scarcely empirically examined for SSA. Hence, this study attempts to bridge the gap in existing studies that need to empirically address hydrogen's potential in maintaining and promoting a decarbonized electricity grid in SSA. In contributing to bridging this gap, two key research questions are hypothesized.

a) How prepared is SSA to host hydrogen in its electricity grid?
b) What is the cost-benefit of integrating hydrogen for a decarbonized electricity grid in SSA?

This study aims to address both research questions (a) and (b) through a comprehensive energy technology with emphasis on impact of hydrogen integration, hydrogen preparedness discussion of hydrogen programs, policies and plans in SSA and the cost-benefit analysis of the viability of hydrogen production and its integration to manage the growing peak electricity demand of selected SSA countries, respectively. It investigates the environmental cost implications of hydrogen integration from different energy technologies, providing essential insights into the possible benefits and challenges associated with each technology for hydrogen generation. The study will specifically elucidate hydrogen's significance in achieving a sustainable and low Carbon energy future for SSA. This study is organised into six sections, as follows: after the introduction, and motivation, it covers energy storage technologies, the effects of grid integration of HESS technologies with mitigation measures, hydrogen programmes, policies and plans in SSA, a cost-benefit analysis of selected case studies, and concludes with prospect for future work.

Energy storage system technologies

Energy storage systems store energy when the supply is at peak and convert that energy to electricity when there is a high demand. ESSs in AC power systems cannot store electricity directly. Thus, electrical energy is stored in different forms, and ESSs are classified according to the form of energy stored [36] . Various classes of ESS technologies are shown in Figure 1, [37] [38] [39] [40], and brief explanations for the most common ones are given after that.

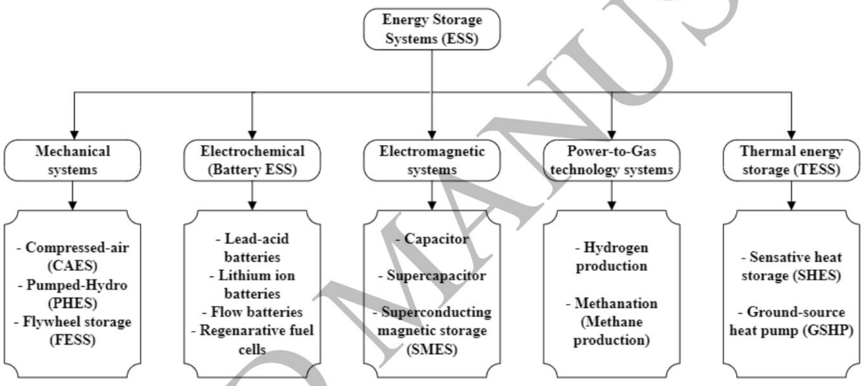


Figure 1. Classification of Energy Storage Systems.

Battery energy storage systems (BESS)

Battery energy storage systems store electricity as chemical energy. Common BESS technologies are lithium-ion, lead-acid, and nickel-cadmium, among others [9]. Depending on the technology implemented, BESS exhibits large energy densities of up to 7000 kJ/kg and higher efficiencies of up to 97%. However, this efficiency and the average lifetime can be gradually reduced by deep discharging or excessive cycling. In a battery pack, the cells are parallel to obtaining the desired power rating and series connected to get the desired voltage rating. A low-pass filter links the voltage source converter and point of common coupling (PCC) to the grid.

Due to their fast response times, BESSs are employed to improve transient stability, regulate both frequency and voltage and provide low-frequency oscillation damping. Lead-acid batteries are commonly used for stationary applications due to availability and are cheaper compared to other battery technologies, but they have high discharge rates and severe metal pollution [41] [42].

However, lithium-ion is more beneficial since its lifetime is greater than that of the lead-acid [43] [44] .

Superconducting magnetic energy storage (SMES)

Superconducting magnetic energy storage (SMES) exhibits no pollution and is suitable for enhancing the transient power and output stability of wind turbines [3]. In a SMES system, a current source inverter links the superconducting coil to the AC system to charge and discharge the coil. A dc flow within a superconducting coil produces a magnetic field in which energy is stored. The coil is cooled using liquid nitrogen or helium to maintain a certain operating temperature. A voltage source converter (VSC) and a DC (direct current)-DC chopper are used to charge and discharge the system [8].

Flywheel energy storage systems

Flywheel energy storage system (FESS) technology uses the rotating mass principle to convert electrical energy from the grid or any other source to mechanical energy, which is stored as rotational kinetic energy. This technology makes use of a heavy disk encapsulated in a vacuum chamber and rotating at very high speeds. Depending on the design, FESSs can reach speeds as high as 100,000 rpm [45] [46]. An electrical machine drives the rotor of the flywheel, and two back-to-back VSCs link the PCC and the machine to charge and discharge the flywheel. Electrical energy is then stored as inertia, and the storage capacity is based on the flywheel's rotor speed and inertia, as well as the machine rotor's inertia [46] [47].

Compared to BESSs, both technologies have fast responses and comparable efficiencies, but FESSs can achieve more cycles and are not affected by depth of discharge [48] . Some of FESS technology's desirable characteristics include less environmental impacts, low operational costs, high storage capacity and shorter charge-discharge rates. Also, it can discharge large amounts of stored energy and recharge within seconds. However, FESS has higher self-discharge rates, and poorly designed flywheel rotors can be risky to both the system and the system operators [48].

Compressed-air energy storage

In compressed-air storage (CAES) systems, power from the grid is drawn by a motor that drives a compressor to pressurize air. This air is carried by pipes and is stored in natural reservoirs. This enables electricity to be stored as pressurized air in, for example, underground salt caverns [49] [50]. To retrieve this electrical energy, the pressurized air is extracted from the reservoir and expanded into a turbine that drives a synchronous generator to inject the power into the grid . Since the black start capability and decreasing grid inertia are crucial issues considering the massive grid integration of variable renewable energy sources, CAES is a potential solution as it provides inertia to the grid and can provide a black start with fast ramping capabilities. Moreover, it is economically feasible for bulk energy storage applications , though terrain conditions can restrict its operation [51] [52].

Thermal energy storage systems

Thermal energy storage systems (TESS) provide a flexible and efficient method for storing and utilizing surplus energy, thereby enhancing energy conservation and decreasing dependence on fossil fuels [53]. Various forms of thermal storage media exist, with underground boreholes being a prevalent example [54]. Boreholes function as reservoirs, retaining thermal energy or cold within the subsurface. The borehole depth and configuration can be optimized to enhance storage capacity and efficiency. A heat exchanger serves as the intermediary in this process. It removes heat from the thermal load when excess energy is present and transfers it to the thermal storage. In contrast, when the thermal load necessitates heat, the heat exchanger draws heat from the thermal storage and delivers it to the load. The thermal load is generally equipped with an electrical interface to regulate the charge and discharge processes [55]. This interface enables accurate regulation of the heat transfer rate, ensuring optimal operation of the storage system and fulfillment of load demands.

Pumped-hydro energy storage systems

In the case of energy storages with capacities of at least 100 MW, pumped hydro energy storage (PHES) systems proved to be efficient, with an installed capacity of 120 GW from more than 300 plants as of 2017 [56]. However, its capacity can be limited by geological and hydrological conditions [57]. It is commonly used in commercial large-scale projects. It employs electric pumps to move water between two reservoirs during off-peak hours, thus energy storage, and peak hours, thus energy generation. The storage capacity depends on the upper reservoir; hence the possibility of having higher capacities comparable to other technologies, and the amount of energy stored depends on the mass of the water and the difference in heights of the reservoirs [57].

Power-to-X

Power-to-X (P2X) is a method that converts surplus electrical energy into a storable energy carrier by using excess renewable energy, such as wind or solar power, to produce synthetic fuels or chemicals. In this process, hydrogen is generated, with key P2X technologies including Power-to-Gas (PtG), Power-to-Liquid (PtL), Power-to-Heat (PtH), and Power-to-Ammonia (PtA). P2X offers advantages like energy storage, flexibility, lower carbon emissions, and grid stability. It tackles the inconsistency of wind and solar energy, promotes the use of renewable energy in sectors that are difficult to electrify directly, and supports decarbonisation by creating synthetic fuels and chemicals with reduced or negligible carbon emissions compared to fossil fuels. However, P2X faces challenges such as energy losses, high initial capital costs and operational expenses, infrastructure needs, and environmental impacts. Despite these limitations, P2X is a promising technology for integrating renewable energy into the energy system and fostering a sustainable future. With technological progress and decreasing costs, P2X is expected to play an increasingly important role in energy storage and decarbonisation efforts.

Applications of ESS technologies

Energy storage systems contribute to all aspects of the power system, that is generation, transmission, distribution, and consumption. They seek to address power quality issues such as voltage drops and inrush currents, and in the case of future smart grids, they also consider the consumption side in demand response and demand side management [17] [58]. ESS is employed in crucial scenarios such as in islanded MGs that rely on RES, in peak shaving to promote installation of behind-the-meter ESS technologies and reduce energy consumption during peak hours, and most commonly, in electricity arbitrage due to their high ramp rates and fast responses [59] . To alleviate grid power unreliability resulting from instantaneous supply disruptions, ESS technologies can also be used as emergency backup during peak periods .

Frequency deviation is a common and critical concern in grids with high penetration of RES. It occurs when system frequency deviates from a certain nominal value, and this has adverse effects on frequency-sensitive loads such as electric machines. To resolve this, technologies with fast frequency response capabilities are used and on the other hand, generation units must control their output power accordingly [8]. Fast frequency response also provides virtual inertia control for wind farms, hence supporting the rapid penetration of variable renewable energy sources on power grids [58].

Flywheel energy storage technology is commonly used for frequency regulation, while PHES and CAES are commonly known for bulk energy storage [47] [48]. In [60], FESS technology is used in a PV-wind-modular multi-level converter-based high voltage direct current (MMC-HVDC) system to control voltage on the HVDC link during low voltage faults and to address power fluctuations due to instantaneous load changes. According to the authors, RE sources could be integrated without limiting their power during low-voltage faults [3] .

Superconducting magnetic storage systems are employed to enhance voltage stability in utility networks by limiting active and reactive power grid losses. However, they are not used for longer periods because of the higher costs required to implement superconductive wire and refrigeration in the system. According to [42] [11], lithium-ion technology is dominating the battery energy storage market. However, only a few models exist for stationary applications, such as solar PV, as compared to models implemented in traction applications. On the other hand, thermal energy storage systems are common in ground-source heat pump systems, household water heating, and HVAC systems. Typically, they charge when RES power is abundant and discharge when the power is not available. According to [61], TESS can effectively realise peak shaving when integrated with a concentrated solar power (CSP) plant.

According to [62], the European Network of Transmission System Operators for electricity (ENTSO-E), focused on two broad ESS applications (energy management and ancillary services provision), classified the services provided by ESS as outage services, balancing, congestion management and system operation. These classes are illustrated in Figure 2.

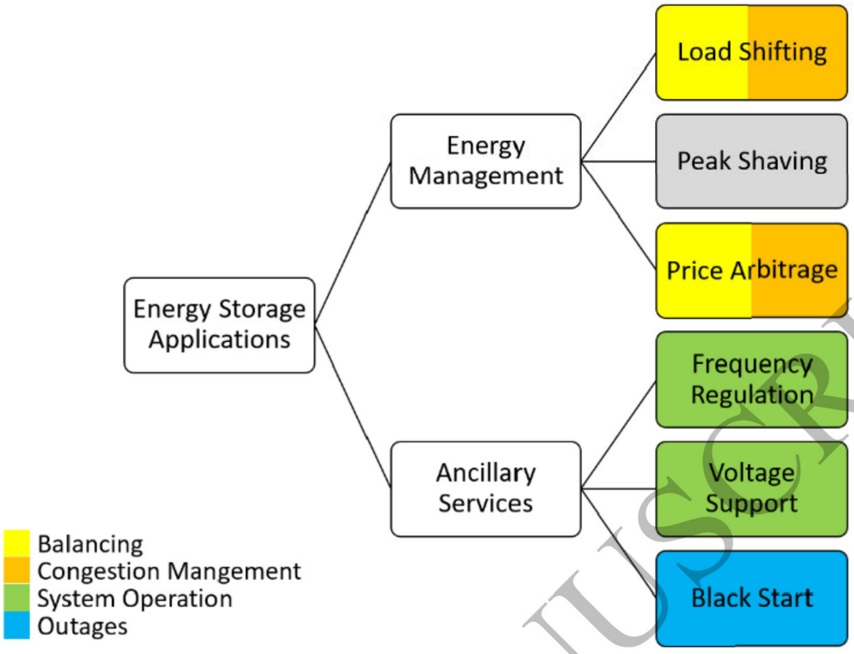


Figure 2. Applications of ESS technologies [62] .

Impacts of grid-integration of HESS technologies

Hydrogen energy storage systems produce hydrogen using a variety of techniques, for example electrolysis of water [63]. The integration of HESS into electrical grids is becoming increasingly important as the demand for cleaner, more reliable energy grows across the globe [64] . The integration enhances grid performance and facilitates in enabling a more sustainable and resilient energy infrastructure. The utilization of HESS technologies within individual distributed frameworks is economically inefficient due to high capital and maintenance costs [65]. However, centralized shared ESS between RE entities boosts operational profits and minimizes the running costs of ESS infrastructure for each entity [66] . Moreover, having a power system with multiple energy storage technologies can provide better performance compared to systems with a single HESS. For example, considering the intermittency of RES and geographic limitations of PHES, authors in [67] investigate the impacts of having doubled energy storage in a single system. A PV-wind-CSP-PHES system had a lower loss of power supply probability (LPSP) compared to a PV-wind-PHES system with limited storage capacity. The authors concluded that a PV-wind-CSP-PHES system is highly reliable and exhibits better economic performance.

This operation reduces operational and maintenance costs, hence increasing savings in peak shaving units [68]. According to [43], lead-acid battery is a mature technology with the most economically reliable bulk storage system generating 50 MW for 5 hours, and it costs about $3 800/kW. For transmission and distribution (T&D) and frequency regulation applications, systems capable of generating 1 MW in 1 hour and 0.25 hours, respectively, had the most promising results. Nevertheless, having a properly designed operational scheduling enhances the usage and maximizes the economic benefits of HESS technologies [12] .

In the case of electricity market participation, mechanisms that encourage the adoption of HESS, fast regulation services and policies must be put in place, for example, based on performance, speed of regulation services or the period that the capacity can be provided [69]. Since participation of HESS models in electricity markets requires a specific operational model for each ESS technology, obtaining detailed information such as cycling limitations, fast ramp rates, and ability to charge or discharge and including it in the market structure helps distinguish ESS models from other participants already in the market. This gives them a chance to participate in capacity, ancillary services, and wholesale markets.

HESS systems are pivotal in upgrading power systems across the globe [70] [71]. They offer a significant benefit in terms of grid integration of renewable energy sources. Integrating HESS systems enhances grid stability, reliability and flexibility in energy use and efficiency. The HESS plays a significant role in optimizing the grid network or operations, therefore enhancing the transition to a more sustainable energy future [14] [3] [64]. However, the integration of HESS into the grid has challenges and impacts [72] [73] [74]. Therefore, to comprehensively depict the impacts of HESS integration, a SWOT analysis was conducted, as shown in Table 1, highlighting the strengths, weaknesses, threats, and opportunities of ESS integration.

Table 1. Impacts of grid integration of HESS using SWOT analysis [75] [76] [77] [78].

Strength	Weaknesses	Opportunities	Threats
Grid Stability and Reliability	Higher initial costs	Environmental benefits	Regulatory challenges
Peak shaving and Load shifting.	Technological advancements	Market growth	Competition from other technologies

Renewable Energy Integration	Maintenance and life span	Technology advancement and job opportunities	Market volatility
Sector Coupling	Complexity in integration	Policy support	Threat to the government
Energy Storage and Grid Balancing	Technological advancements	Global market potential	Competition from other technologies
Decarbonization Potential	Technical complexity	Environmental benefits and technological advancements	Regulatory challenges

Strengths

- Grid Stability and reliability: This refers to constant power supply from the grid despite fluctuations in demand and supply. HESS enhances grid stability and reliability by balancing the power demand and supply. HESS stores excess energy during low demand periods and drops in generation thus providing a reliable backup.
- Peak shaving and load shifting: Integrating HESS reduces peak demand, thus lowering energy costs. This helps in managing energy demand more efficiently and economically. The load shifting process flattens the energy curve leading to a more efficient balanced grid operation.
- Renewable energy integration: HESS enhances the use and adoption of other renewable energy sources by storing the excess energy from these sources and dispatching it when needed.
- Decarbonization potential: The use of HESS as an energy carrier significantly reduces greenhouse gas emissions which harm the environment supporting global climate goals.
- Sector coupling: HESS integration facilitates the interconnection of various energy sectors (electricity, heating, transportation), hence promoting a more efficient energy system.

Weaknesses

- Higher initial costs: The excessive cost of installing HESS technology presents a barrier to its widespread adoption. The costs include infrastructure costs, technology to be used, and operational and maintenance costs. The integration of HESS is a capital-intensive process.

- Technological advancement: The integration of HESS is still ongoing research. Some of the HESS may not offer the best optimal efficiency and short lifespan. In developing countries, HESS technologies are still in the developmental stage.
- Maintenance and life span: The HESS systems require regular maintenance during their operation leading to higher maintenance costs. Regular performance monitoring is also required. The life span is also finite.
- Complexity in integration: Integrating HESS into the existing grid may be complex. Advanced technology may be needed to integrate HESS into the existing grid infrastructure. Regular upgrades and grid management techniques should be employed.
- Limited Infrastructure: The current infrastructure for hydrogen production and distribution is underdeveloped, which requires more research, significant upgrades and more investments.

Opportunities

- Environmental benefits: HESS contributes to the sustainable development goals by reducing greenhouse gas emissions. Adoption of HESS through renewable energy sources will reduce the reliance on fossil fuels thus helping in combatting climate change.
- Market growth: The significant growth in the use of renewable energy technologies enhances larger markets for HESS. This growth represents market penetration for HESS technologies.
- Policy support: The adoption of renewable energy sources funded by the government enhances HESS technologies. Regulatory support for renewable energy will drive the use of HESS.
- Technology advancement and job opportunities: Ongoing research will lead to more efficient, cost-effective and durable HESS technologies. This will also create employment opportunities.

Threats

- Regulatory challenges: Unfavorable government regulations and inconsistent policies can hinder the adoption and integration of HESS.
- Public Perception and Acceptance: Concerns about safety, environmental impact, and the maturity of hydrogen technologies may hinder public acceptance and adoption
- Competition from other technologies: Ongoing research on advancements in grid integration management, energy management and other alternative technologies can reduce the competitiveness of the HESS.
- Threat to the government: As HESSs are integrated into the grid, they become potential targets for cyber-attacks. Integration of HESS into the grid by private companies may also pose a risk power threat to the government.
- Market Volatility: Fluctuations in energy prices and market dynamics can impact on the economic viability of these HESS projects

The SWOT analysis on the impacts of integrating HESS systems highlights a complex landscape of strengths, weaknesses, opportunities, and threats. From the analysis, the strengths of HESS, particularly in enhancing grid stability and reliability and facilitating renewable energy integration, position the HESS technologies as pivotal in the transition to a more sustainable energy future[73] [3]. However, other aspects, like the high initial costs and ongoing maintenance requirements, cause significant challenges that must be addressed through strategic planning, innovative financing models, and technological advancements [2] [76] [64]. Nevertheless, opportunities, for example, peak shaving, load shifting, and supportive policy frameworks, further underscore the potential benefits of HESS, while threats like cybersecurity risks and environmental disposal issues necessitate robust mitigation strategies supported by recent studies [79] [80] [77]. To summarize the analysis, by leveraging the strengths and opportunities while effectively addressing the weaknesses and threats, stakeholders can enhance the adoption and integration of HESS, contributing to a more resilient and sustainable energy grid. Addressing weaknesses and threats is essential for overcoming barriers to implementation and realizing the full potential of hydrogen technologies in the energy landscape.

Mitigation strategies for grid-integration of HESS

To address the impacts associated with the grid-integration of HESS technologies, various mitigation strategies can be employed. A breakdown of potential approaches to mitigate the identified strengths, weaknesses, opportunities, and threats is shown in Figure 3.

The hydrogen value chain remains largely underdeveloped: green hydrogen production, storage, transport, and distribution infrastructure demand coordinated, large-scale investments that are often beyond the financial capacity of individual countries. External risks exacerbate these internal weaknesses. Policy instability, regulatory fragmentation, and unclear fiscal regimes increase perceived investment risks and slow project development. Market volatility affects revenue predictability and undermines business cases, while competing technological innovations and evolving grid management methods can divert investor interest from HESS. Public concerns about safety and environmental impacts of new hydrogen systems may also limit social acceptance. Therefore, SSA hydrogen programmes need to focus on three interconnected areas: tailored de-risking finance instruments and long-term offtake agreements to close capital gaps; prioritised public investment, regional cooperation, and targeted R&D to establish resilient hydrogen production and logistics infrastructure; and clear, stable regulatory frameworks, standardised contracts, and fiscal guarantees that reduce governance risks and safeguard project viability against market fluctuations. HESS can only turn from promising potential to practical, scalable impact across Sub-Saharan Africa through an integrated approach that links finance, infrastructure, and policy stability.

Various mitigation strategies can be employed to address the impacts associated with the grid integration of HESS technologies. Figure 3 shows the potential approaches to mitigate the identified strengths, weaknesses, opportunities, and threats.

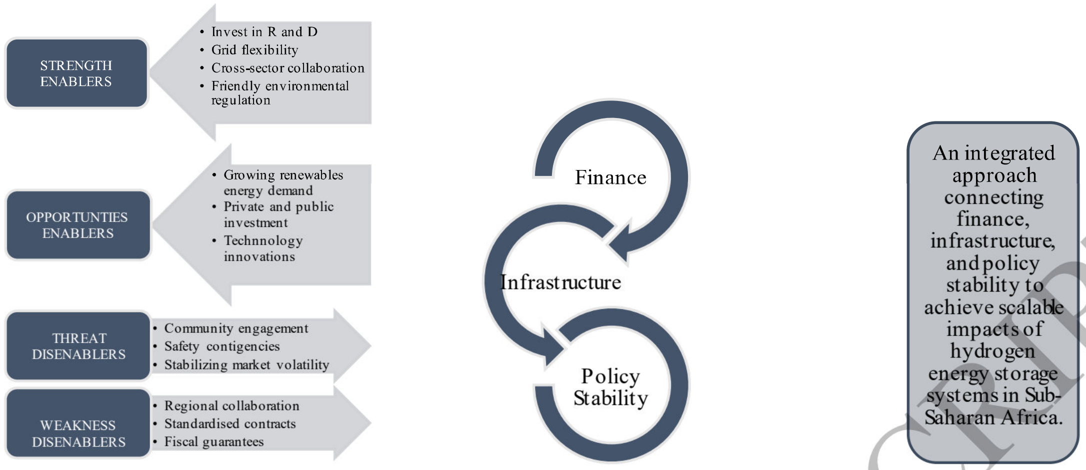


Figure 3. Mitigating Impacts of Grid Integration of HESS.

If the integration or adoption of HESS grows, the cost is also expected to decrease [4] . This will lead to economies of scale, thus reducing costs per unit and making HESS accessibility more economically viable. Improvements in manufacturing processes and technology will also reduce the costs. Innovative financing models like leases and power purchase agreements will enhance the purchase of HESS systems. Continuing to invest in more research and development in ESS adoption or integration will show cost-effective and efficient solutions. Innovation should also apply to improve production techniques and the life span of the systems. Favorable regulatory policies will make the environment conducive to operation hence more adoption of HESS technologies. Government support in terms of tax reductions, subsidies and incentives can make these systems affordable. Introducing policies that promote renewable energy integration favors the deployment of HESS. Effective life cycle management for the HESS system from production installation to decommissioning. The application of predictive maintenance during operation is also a viable solution.

Mitigating these impacts in HESS adoption involves a combination of government support, financial incentives, research and development with technological advancements and strategic planning. Therefore, by addressing the weaknesses and threats by employing the discussed mitigation strategies, the adoption and integration of HESS into the grid can be significantly enhanced, leading to a more stable, reliable, and sustainable energy system. By implementing these strategies, stakeholders can enhance the viability and effectiveness of HESS in contributing to a sustainable energy future.

Hydrogen programs, policies and plans in Sub-Saharan Africa

The integration of HESS into power grids in Africa is a promising area of development, leveraging the continent's abundant renewable energy resources [81] [82] [83]. Several case studies and initiatives highlight the potential and challenges of this integration [14] [70]. Hence, this section provides a comprehensive overview of renewable energy and hydrogen initiatives across various Sub-Saharan African nations due to their unique and complementary hydrogen initiatives, highlighting the region's commitment to sustainable energy development. Specific case studies illustrate different approaches, such as South Africa's Hydrogen South Africa (HySA) program, which focuses on green hydrogen and fuel cell technologies, and the Eskom battery energy storage system for grid stability. Other countries' strategies are detailed, including Cameroon’s Kribi Gas Power Plant integrating photovoltaic-electrolysis, Djibouti’s wind-to-hydrogen project utilizing high-wind sites, and Kenya's Vision 2030 for increasing renewables. Additionally, the section outlines the policy frameworks and strategic plans of nations like Nigeria, Tanzania, Rwanda, Zimbabwe, Ethiopia, and Namibia, emphasizing goals such as diversifying the energy mix, reducing fossil fuel reliance, and enhancing energy access often through public-private partnerships (PPPs).

South Africa

South Africa leads in national hydrogen strategy and innovation through the HySA program (supported by the Department of Science & Technology) focusing on green hydrogen, fuel cells, and storage technologies. The HySA Systems project is part of South Africa’s broader effort to develop and use hydrogen energy and fuel cell technologies [84].It’s based at the Cape Peninsula University of Technology and aims to create real, working systems that use hydrogen as a clean energy source. A long-term (15-year) Hydrogen and Fuel Cell Technologies Research; Development, and Innovation strategy was officially launched in September 2008 by the Department of Science and Technology in South Africa [84] [85] . This project is aimed at developing South African intellectual property, knowledge, human resources, prototypes, products, components, and processes to support South African participation in the nascent but rapidly developing international platforms in hydrogen and fuel cell technologies [86] . The HySA program is based upon the beneficiation of the country's large Platinum Group Metal resources.

The project is focusing on developing hydrogen and fuels cell systems including prototypes and the final products [87]. The key technologies involved include high temperature proton-exchange membrane (PEM) fuel cells, metal hydrides used for hydrogen storage and finally the hydrogen fuel cell power modules. The project is on small and medium-scale hydrogen production with storage systems on the plant. In summary, the HySA systems project is on track for the implementation of a fuel cell industry in South Africa. From 2013 onwards, a large emphasis has been on implementing and advancing R&D vehicular system integration, and broadening systems engineering activities to improve HySA technology maturity and commercialization.

South Africa's approach to hydrogen is a foundation laid by its two key renewable energy policy instruments: the Integrated Resource Plan (IRP) and the Renewable Energy Independent Power Producer Procurement Program [88]. The IRP is a strategic blueprint outlining South Africa's electricity demand and the planned energy mix. The IRP 2019 sets out the country’s strategy for diversifying its energy portfolio and reducing its reliance on coal-fired power stations, which currently dominate the energy mix [89]. The program has also contributed to job creation, socio-economic development, and the empowerment of historically disadvantaged communities.

Morever, South Africa’s energy landscape has been significantly impacted by the Eskom battery energy storage system project, a groundbreaking initiative aimed at enhancing the stability and reliability of the national grid. Eskom, the state-owned electricity utility, has embarked on deploying large-scale battery storage systems as part of its strategy to integrate renewable energy sources and mitigate the challenges of intermittent power supply. The Eskom BESS project, initiated in 2019, involves the installation of battery storage systems across various locations in South Africa, with a total capacity of 1,440 MWh. These batteries store excess energy generated from renewable sources, such as wind and solar, and release it during peak demand periods or when renewable generation is low. This not only stabilizes the grid but also enhances the utilization of renewable energy, reducing reliance on coal-fired power plants.

South Africa’s energy landscape has been significantly impacted by the Eskom BESS project, a groundbreaking initiative aimed at enhancing the stability and reliability of the national grid [90] . Eskom, the state-owned electricity utility, has embarked on deploying large-scale battery storage systems as part of its strategy to integrate renewable energy sources and mitigate the challenges of intermittent power supply [90]. The Eskom BESS project, initiated in 2019, involves the installation of battery storage systems across various locations in South Africa, with a total capacity of 1,440 MWh. These batteries store excess energy generated from renewable sources, such as wind and solar, and release it during peak demand periods or when renewable generation is low. This not only stabilizes the grid but also enhances the utilization of renewable energy, reducing reliance on coal-fired power plants.

The Eskom BESS project has delivered numerous benefits, significantly improving grid reliability and flexibility. Through the storage and dispatching of renewable energy, the system helps balance supply and demand, reducing load shedding and power outages [91]. This improved stability supports economic activities and ensures a more consistent power supply for businesses and households [92]. Furthermore, the project contributes to South Africa's environmental goals by facilitating greater integration of renewable energy and reducing carbon emissions.

The Eskom BESS project has faced several challenges, offering valuable insights into similar initiatives. High upfront costs and the need for substantial investment have been significant hurdles [93]. To address this, Eskom has sought funding from international donors and financial institutions, highlighting the importance of financial support for large-scale energy projects to ensure the longevity and efficiency of battery systems, which require ongoing research and development.

Cameroon

Cameroon's 216 MW Kribi Gas Power Plant, operational since 2013, integrates photovoltaic electrolysis with conventional gas operations and has demonstrated promising outcomes, including ~76.2% power-to-hydrogen efficiency and notable emissions reductions [94]. The Kribi Gas Power Plant is a critical part of Cameroon's national energy infrastructure. Located near the coastal town of Kribi, it was commissioned in 2013 to diversify the country's energy mix and reduce overreliance on hydropower [95]. Operating mainly on natural gas, it serves as a reliable backup during dry seasons when water levels are low, ensuring grid stability across the country. The aim of the project is to increase electricity generation capacity and address the serious power shortage blocking the country's development [96]. Integrates hydrogen production via water electrolysis powered by photovoltaic electricity and gas power plants [95]. This project aims to reduce environmental impacts and improve energy storage efficiency. The system generates hydrogen through water electrolysis using electricity from a photovoltaic plant and the gas power plant. The study evaluates the technical, financial, and environmental viability of a hybrid hydrogen-natural gas fuel system. Results show that the power-to-hydrogen process achieves an efficiency of 76.2%, making it the most efficient option among the assessed power-to-fuel pathways

Djibouti

Djibouti, with its high-wind sites (Nagad, Bara Wein) averaging over 7 m/s, hosts advanced techno-economic studies using alkaline and PEM electrolyzers that reveal competitive green hydrogen production costs of approximately US $1.79–3.38 per kilogram [97] .Utilizing wind energy to produce green hydrogen using alkaline and PEM electrolyzers, the Nordex turbine with alkaline electrolyzer provides affordable electricity production and significant carbon dioxide emission reductions. The results of the proposed wind energy system showed that Nagad and Bara Wein are suitable for green hydrogen production using Nordex N90 compared to the De Wind D6 and Vestas wind turbines. With monthly average velocities above 7 m/s, the sites are adequately classified as having potential for wind energy development

Kenya

Kenya has established itself as a regional leader in renewable energy through its comprehensive policy framework aimed at fostering sustainable energy development. The cornerstone of Kenya’s energy strategy is encapsulated in its National Energy Policy, which outlines the country’s vision for the energy sector. The National Energy Policy emphasizes the diversification of energy sources to include more renewable options such as geothermal, wind, solar, and biomass. The policy's objectives include ensuring adequate, reliable, and cost-effective supply of energy, protecting the environment, and promoting renewable energy sources [98]. The policy also prioritizes rural electrification and the development of off-grid and mini-grid systems to enhance energy access in remote areas.

In alignment with the National Energy Policy, Kenya's Vision 2030 sets ambitious targets for the energy sector. Vision 2030 is a long-term development blueprint aimed at transforming Kenya into a newly industrializing, middle-income country, providing a high quality of life to all its citizens [99]. Under this vision, the government aims to increase the proportion of renewable energy in the national energy mix to 70% by 2030, with significant investments in geothermal and wind energy projects. The policy has already borne fruit, with Kenya being one of the largest producers of geothermal energy in the world [99].

Kenya’s Green Hydrogen Strategy seeks to harness abundant geothermal, solar, wind and hydro resources to build a domestic green-hydrogen industry that supports industrialisation, fertiliser production, energy storage and export opportunities. The roadmap prioritises phased pilots, policy and regulatory frameworks, certification and standards, financing mechanisms (Development Finance Institutions and concessional support) and public–private partnerships to mobilise multi-GW electrolyser capacity sited near renewable resource zones and industrial clusters.

Studies have modelled cost trajectories and identified use cases (ammonia/methanol for export; domestic fertiliser and power balancing), while emphasising grid integration, water management, and localisation of supply chains [100] [101] . Other implementation risks relate to bankability, certification, and equitable value capture, recommending strong local content rules, transparent procurement, and staged commercialisation to avoid extractive outcomes and maximise socio-economic benefits [102].

Zimbabwe

The Zimbabwe’ NREP was instituted in 2011 to advance the development and application of renewable energy resources in Zimbabwe. The policy seeks to enhance renewable energy production capability, diminish dependence on fossil fuels, and foster sustainable economic development [103]. The primary aims encompass augmenting the proportion of renewable energy within Zimbabwe's energy portfolio, fostering sustainable economic development, diminishing greenhouse gas emissions, generating employment opportunities, and bolstering energy security. The NREP recognizes renewable energy technologies with considerable development potential, such as solar, wind, hydro, biomass, and geothermal. The strategy establishes a framework for renewable energy initiatives, encompassing incentives, restrictions, and finance mechanisms. The NREP is an essential initiative for Zimbabwe's transition to a sustainable and resilient energy future, tackling issues such as energy poverty, climate change, and economic development. The degree of energy storage integration within Zimbabwe's renewable energy sector is not clearly defined, necessitating further investigation to evaluate the present status of energy storage integration in this domain [104].

Zimbabwe can explore green hydrogen as a route to enhance electricity access, decarbonise industry, and provide seasonal storage, supported by pilot projects and private-sector initiatives such as HDF Energy's proposed MiddleSabi Renewstable plant in Chipinge [105]. Policy and technical assessments reveal opportunities from abundant solar and biomass resources but also highlight significant constraints: chronic generation shortfalls, ageing hydro and thermal assets, limited grid resilience, water availability issues, and weak regulatory frameworks[106]. Mkaratigwa's work in [107] emphasizes social acceptance, the potential for local innovation, and the need for supportive public policies to turn pilots into sustainable local benefits. Evaluating project potential and feasibility by Inter Africa Power prioritises power-to-power demonstrations to supply rural electrification and stabilise supply while testing water, financing, and supply chain risks [105] . Hence, achieving a national impact from hydrogen storage implementation depends on a clear hydrogen policy, strong environmental and water safeguards, binding local content and skills requirements, staged financing with concessional support, and transparency in procurement.

Nigeria

In 2022, Nigeria initiated its Energy Transition Plan (ETP) to enhance the sustainability and resilience of the nation's energy system. The plan's objectives encompass promoting economic development, enhancing access to renewable energy, and reducing greenhouse gas emissions. Attaining a higher percentage of renewable energy, reducing reliance on fossil fuels, enhancing energy efficiency, promoting sustainable development, and creating employment opportunities are essential objectives. The approach fundamentally depends on the integration of energy storage, which can enhance system stability and flexibility. The significance of energy storage for system resilience and the benefits of clean energy will increase as Nigeria's renewable energy potential advances. The ETP represents a significant advancement in the pursuit of a more secure and environmentally sustainable energy future.

Based on the ETP, Nigeria will have to develop an export-and domestic-focused green-hydrogen strategy that leverages abundant solar, wind, biomass and existing oil- and gas infrastructure to lower costs and speed deployment .National efforts should emphasise integrated, coastal projects combining multi-GW renewables, electrolysis and conversion to transportable derivatives (ammonia, methanol) sited near ports and industrial clusters to tap international offtake markets and existing logistics [108]. Also, financing models need to centre on blended public–

private finance, concessional debt and long-term PPAs to de-risk bankable projects, while policy work should codify a Green Hydrogen Strategy, certification and safety standards. Key priorities should focus on areas not limited to enforcing local content and skills development, strengthening environmental and water safeguards, and building regulatory capacity to ensure transparent procurement and equitable benefit sharing. Findings from analyses caution that without strong governance and domestic value-capture measures, projects risk reproducing extractive patterns despite potential for industrialisation and decarbonisation [109].

Rwanda

Rwanda has taken a proactive stance towards renewable energy development through its comprehensive National Energy Policy and Strategy. The National Energy Policy, first formulated in 2008 and subsequently revised, provides a robust framework aimed at increasing energy access, enhancing energy security, and promoting the use of renewable energy sources [110].

The National Energy Strategy outlines specific targets and action plans for achieving the policy objectives. One of the key components of the strategy is the promotion of off-grid renewable energy solutions, such as solar home systems and mini-grids, to accelerate rural electrification [111] . The government has established the Rwanda Development Board to facilitate investment in renewable energy and provide one-stop services for investors. Furthermore, the Rwanda Utilities Regulatory Authority (RURA) oversees the regulation of energy markets and ensures compliance with standards.

To incentivize renewable energy investments, Rwanda offers several fiscal and non-fiscal incentives. These include tax exemptions on renewable energy equipment, subsidies for rural electrification projects, and favorable feed-in tariffs for independent power producers (IPPs) [111]. Additionally, the government has launched initiatives such as the Rwanda Renewable Energy Fund (REF) to provide financial support to renewable energy projects and enhance access to affordable financing.

Rwanda's energy policy promotes hydrogen pilots and a 10 MW demonstration to test production, storage and grid integration while expanding renewables to supply electrolysers [112] Policy emphasises private-sector participation, feasibility studies and phased scaling aligned with industrialisation and clean-energy goals [113]. As a landlocked country, Rwanda faces higher export logistics costs, dependence on transit neighbours and ports, added conversion needs (ammonia/LOHC), and risks that export ambitions divert scarce water, grid capacity and finance from domestic priorities.

Tanzania

Tanzania has made significant strides in reforming its energy sector through the Energy Policy of Tanzania and the Electricity Supply Industry Reform Strategy and Roadmap. The Energy Policy, first introduced in 2003 and revised in 2015, provides a framework for sustainable energy development and emphasizes the diversification of energy sources to include more renewables [114] .

The Electricity Supply Industry Reform Strategy and Roadmap (2014-2025) outlines a comprehensive plan for restructuring the electricity sector to enhance efficiency, reliability, and access. The roadmap sets clear targets for increasing renewable energy capacity and reducing dependence on fossil fuels [115]. Key elements of the roadmap include the unbundling of the state-owned utility, Tanzania Electric Supply Company (TANESCO), and the promotion of private sector participation in power generation and distribution.

Tanzania offers various incentives to attract investments in renewable energy, including tax holidays, import duty exemptions on renewable energy equipment, and guaranteed market access for IPPs through power purchase agreements [116]. Additionally, the government has established the Rural Energy Agency to spearhead rural electrification projects and provide financial support to renewable energy initiatives.

Although no concrete policies are in place, Tanzania could develop green hydrogen by utilising its abundant renewable resources, such as solar, wind, geothermal, biomass, and mini-hydro, and its strategic location on the Indian Ocean to serve regional and export markets. National planning can focus on diversifying the power mix and expanding near-term generation capacity to support electrolytic production, with opportunities connected to the Eastern and Southern African power pools for cross-border trade. Cooperation with the state utility TANESCO's central role, increasing industrial demand, and planned additions from solar, wind, and geothermal sources underpin the project's feasibility, while priorities should include attracting investment, building transmission and manufacturing capacity, and aligning hydrogen development with agricultural and industrial decarbonization goals.

Zambia

Zambia's energy system is dominated by hydropower, which supplies over 80% of electricity generation. While historically reliable, this dependence has exposed the grid to climate-induced variability and drought-related disruptions. Recent modelling using the PyPSA-Earth-Zambia framework explores twelve low-carbon scenarios that integrate solar, wind, biomass and battery storage to reduce hydrological risk, improve grid stability and expand access by 2030 [117]. These renewable-dominant pathways offer long-term cost and environmental benefits, though they require upfront investment and institutional reform [118].

Zambia's energy policy is evolving to support this transition. The government has introduced net-metering, power wheeling, and open access reforms to liberalize the electricity market and attract private investment. These measures aim to improve grid flexibility, reduce costs, and enable decentralized renewable deployment. However, policy implementation remains uneven, and further regulatory clarity is needed to support bankable projects and long-term planning.

Complementing this transition, Zambia is exploring green hydrogen as a strategic industrial and energy solution. A German-led training week in 2025 catalyzed interest in hydrogen applications for fertiliser production, mining, and food processing, highlighting its potential to reduce import dependence and enhance energy security [117].With targeted financing, technical capacity building, and robust safeguards, Zambia could position itself as a regional leader in low-carbon development while advancing Sustainable Development Goals 7 and 13.

Ethiopia

Ethiopia's Growth and Transformation Plan (GTP) is a strategic framework aimed at accelerating economic growth and development, with a strong emphasis on the energy sector. The GTP, which spans multiple phases (GTP I from 2010-2015 and GTP II from 2015-2020), prioritizes the expansion of renewable energy capacity to meet the growing energy demand and support industrialization efforts [119].

Public-private partnerships (PPPs) play a significant role in achieving GTP's ambitious energy targets. The Ethiopian government has actively sought private sector participation in the development of large-scale renewable energy projects, particularly in hydro, wind, and solar power. For instance, the Corbetti Geothermal Project, one of the largest geothermal projects in Africa, is being developed through a PPP involving the Ethiopian government and private investors such as Reykjavik Geothermal and African Renewable Energy Fund [120].

The Ethiopian Electric Power company, a state-owned enterprise, collaborates with private partners to implement PPP projects under the GTP framework. These partnerships are facilitated by favorable policies and regulatory reforms, including the establishment of the Public-Private Partnership (PPP) Directorate General within the Ministry of Finance to streamline PPP processes and enhance transparency [121].

Ethiopia is positioning itself to develop green hydrogen by leveraging abundant hydropower alongside expanding wind, solar and geothermal capacity to supply electrolysis and support export-oriented projects. The government aims to scale generation through new hydropower dams and renewables while a cross-ministerial taskforce is finalising green-hydrogen policy, trade rules and project documents to attract investors and fiscal incentives for electrolytic production (reported policy revision) [122]. Early activity includes international developer interest, licences and power purchase arrangements that could underpin large renewable plants whose output feeds electrolysers or the domestic grid. Financing strategies emphasise long-term PPAs, public-private partnerships and foreign direct investment to de-risk capital-intensive builds. The key risks are water availability and competing uses, transmission constraints, and regulatory clarity; equitable outcomes will require enforceable local-content rules, transparent procurement and phased projects prioritising Ethiopian socio-economic value.

Namibia

Namibia's National Renewable Energy Policy, adopted in 2017, sets a clear framework for the promotion and development of renewable energy sources through PPPs. The policy aims to diversify the energy mix, enhance energy security, and reduce greenhouse gas emissions by increasing the share of renewables in the national energy portfolio [123]. The policy outlines specific strategies to foster PPPs, including the creation of an enabling environment for private sector participation and the provision of financial incentives. The Namibian government collaborates with private investors to develop large-scale renewable energy projects, such as solar and wind farms. For instance, the Omburu Solar PV Plant, a 4.5 MW solar power project, was developed through a PPP involving NamPower, the national utility, and InnoSun Energy Holdings, a private company. Additionally, the National Renewable Energy Policy encourages the development of smaller, community-based renewable energy projects through PPPs. The policy provides guidelines for the establishment of cooperative schemes where local communities and private investors jointly develop and manage renewable energy installations. These initiatives not only increase energy access but also promote local economic.

Namibia is pursuing an export-oriented green hydrogen strategy that leverages exceptional solar and wind resources to produce green hydrogen and its derivatives (notably ammonia) for European and regional markets, guided by national planning and flagship concessions. The government has established institutional structures, identified hydrogen hubs, and accelerated large integrated projects that combine multi-GW renewables, desalination, grid upgrades, and electrolyzers to enable scale and long-term offtake agreements [124] .Financing involves blended de-risking, public-private partnerships, and concessional finance, with the state open to equity participation to attract international capital. Anticipated benefits include export revenues, infrastructure development, and employment, but scholarly and civil society analyses highlight significant risks: freshwater demand and brine disposal, biodiversity and land-use impacts, limited local value-chain capture, governance transparency gaps, and potential neo-colonial dynamics in commodity-scale exports, [125] [126] . Achieving equitable development relies on stronger safeguards, commitments to local content and skills, clear procurement and consenting procedures, and phased, socially embedded project designs that prioritise Namibian benefit over rapid scale alone.

Ghana

Ghana's energy landscape is dominated by thermal generation with growing but still limited renewable penetration; recent analyses show renewable capacity remains below national targets and that integrating variable solar and wind requires investment in storage, grid flexibility and institutional reform [127] [128]. Policy pathways under the National Energy Transition Framework and Renewable Energy Master Plan, therefore, prioritise scaling utility-scale solar, offshore/near-shore wind and grid reinforcement while exploring low-carbon baseload options to stabilise supply [127]

Against this backdrop, Ghana’s hydrogen plan is deliberately phased and coastal-focused, aiming to co-locate multi-GW renewables, electrolysers and conversion plants near Tema and Takoradi to supply domestic industry and export markets. Studies highlight a near-term preference for derivatives (ammonia, methanol) to reduce shipping and storage costs and leverage existing port and petrochemical clusters [129] [130].The strategy emphasises pilots to prove techno-economic models, strong certification and lifecycle emissions accounting for “low-carbon” claims, and financing packages using blended public–private capital and concessional debt to de-risk first movers [131].

Key governance priorities should include strong environmental and water safeguards, transparent procurement, enforceable local content and skills development measures, and institutional capacity for certification and safety standards. Otherwise, projects risk perpetuating extractive export dynamics and failing to deliver widespread domestic industrialisation benefits could emerge, [132] [130]. Therefore, success depends on sequencing: starting with shore-based pilots that secure domestic offtakes and demonstrate environmental safeguards, then expanding to scaled coastal export facilities integrated with strengthened grid and water management, guided by Ghana’s broader renewable transition planning, [128] [127].

The successful integration of renewable energy sources in Sub-Saharan Africa depends heavily on implementing robust and supportive policies. These policies establish the foundation for renewable energy development and foster a favourable environment for investments, technology transfer, and capacity building. The case studies demonstrate the flexibility and potential of HESS technologies in addressing Africa's energy challenges. They also emphasise several advantages of incorporating HESS technologies into African energy systems. Incorporating HESS technologies into African power grids presents a clear roadmap, with many projects suggesting the potential for sustainable energy solutions. While each initiative has distinct characteristics, they collectively underscore the importance of customised approaches, investment, and supportive policies to promote the growth of green hydrogen technologies across the continent [4].

Cost-Benefit Analysis

The successful integration of renewable energy sources in SSA Africa is heavily dependent on the implementation of robust and supportive policies. These policies not only set the stage for renewable energy development but also create an enabling environment for investments, technology transfer, and capacity building.

Integrating ESS in SSA countries presents substantial prospects for improving energy security, decreasing dependence on fossil resources, and fostering sustainable development. Nevertheless, the choice to allocate funds towards HESS necessitates a meticulous assessment of the corresponding expenses and advantages. Capital expenditures, operating expenses, and expenses related to integrating the energy storage system into the power grid are significant elements that affect the cost-benefit analysis of energy storage system integration in these countries.

The integration of HESS offers several advantages, such as increased grid stability, improved integration of renewable energy sources, less dependence on fossil fuels, and economic benefits. HESS can enhance the stability of power grids by offering frequency regulation, voltage management, and peak shaving capabilities. This helps to minimize the occurrence of blackouts and brownouts. Additionally, it can store surplus energy generated from renewable sources, thereby expediting the shift towards a low-carbon energy future. To evaluate the practicality of integrating HESS in SSA nations, thus, this section deals with a thorough cost-benefit analysis of ten selected SSA. These selected encompass countries from the different regions that constitute SSA and whose energy system data are available and extracted for analysis in this section. This analysis encompasses the different energy technologies presence as in Table 2, shares in the electricity mix in Table 3, and Figure 4, the electricity generation and utilization capacity as in Table 4, with a SWOT highlight on the feasibility of HESS integration from the perspective of policy and regulatory factors in Table 5. The rationale for the choice of countries in further analysis of environmental and cost benefits of HESS integration is established from the same Table 5 in order to help make well-informed decisions regarding the best way to use HESS technology for sustainable energy development in the region through the analysis following the inputs from Table 6 to 7, and discussion on the costs and environmental benefits in terms of CO_2 emission reduction and abatement, as in Tables 8, 9, and 10.

Table 2. Energy technology presence in selected SSA.

Countries	Wind	Hydropower	Nuclear	Geothermal	Biomass	Solar	Natural gas	Oil	Coal	Refs
Zambia	-	✓	-	-	-	✓	-	✓	✓	[133] [134] [135]
Namibia	-	✓	-	-	✓	-	-	✓	✓	[136] [137] [138]
South Africa	✓	✓	✓	-	-	✓	-	✓	✓	[139] [140] [89] [141]
Tanzania		✓	-	-	-	✓	✓	-	-	[142] [143]
Kenya	✓	✓	-	✓	-	✓	-	-	-	[144] [145]
Zimbabwe	-	✓	-	-	✓	-	-	✓	✓	[146] [147] [148]
Nigeria	-	✓	-	-	✓	✓	✓	✓	✓	[149] [150] [151]
Ghana	-	✓	-	-	-	-	✓	✓	-	[152] [153] [154]
Rwanda	-	✓	-	-	✓	-	-	✓	✓	[155] [156] [157]
Ethiopia	✓	✓	-	✓	✓	✓	-	-	-	[158]

Table 3. Shares (in Percentage) of the energy technology in electricity mix, generation capacity, and average annual CO_2 emissions presence in selected SSA

Countries	**Generation Capacity (MW)**	**CO_2 Emissions ($MtCO_{2eq.}$)**	**Projected Generation Capacity (MW) By 2030**
Zambia	2800	6	**2523.** No new plans for infrastructure, except that the current renewables are expected to grow by 15%
Namibia	600	4	No defined target
South Africa	49400	392	**58100.** Plan to increase RE capacity to 8.7MW
Tanzania	1605.86	16	**10000**
Kenya	3321	17	**5000.** Increasing RE capacity
Zimbabwe	2800	9	**3378.** Increasing RE capacity
Nigeria	6024	101	**49000.** Both centralized and decentralized estimated growth capacity including RE
Ghana	5134	21	**6455.13.** Increasing the RE value (only 42.5) in 2015 to 1,363.63
Rwanda	332.6	1	**412.6.** Adding 80 to the existing capacity
Ethiopia	5200	13	**22200.** Adding 17000 to the existing capacity

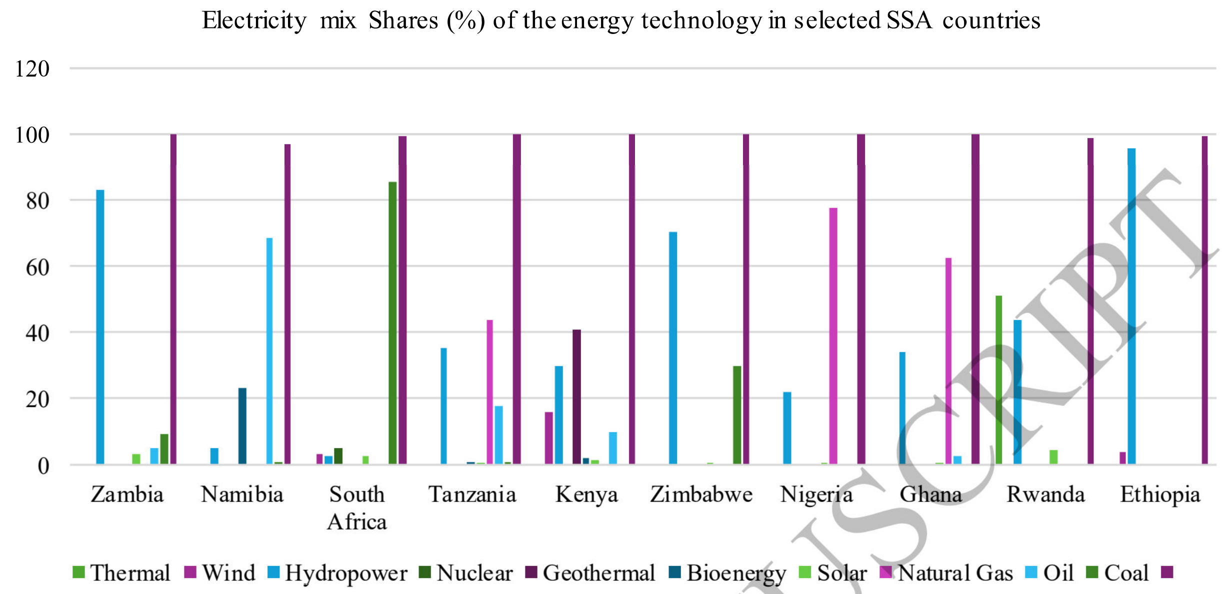
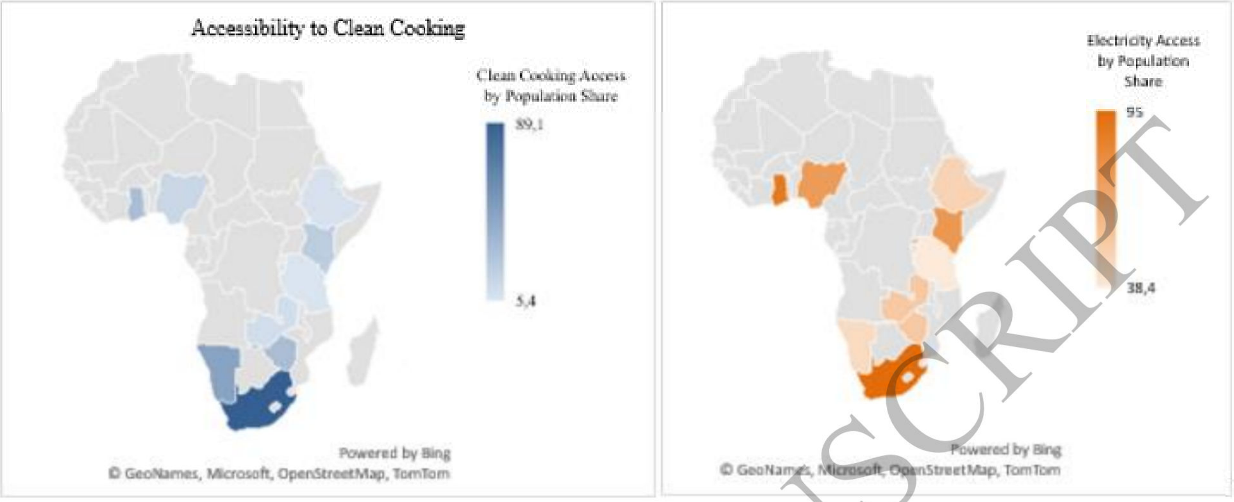


Figure 4. Shares (in %) of the energy technology in the electricity mix in the selected SSA.

Table 4. Generation as per Utilisation capacity (0.85 factor)

Countries	**Thermal**	**Wind**	**Hydropower**	**Nuclear**	**Geothermal**	**Bioenergy**	**Solar**	**Natural Gas**	**Oil**	**Coal**	**Total (MW)**
Zambia	0	0	1859.2	0	0	0	67.2	0	112	201.6	2240
Namibia	0	0	23.52	0	0	110.4	0	0	329.28	3.84	467.04
South Africa	**0**	**1343.68**	**1106.56**	**2015.52**	**0**	**0**	**1067.04**	**0**	**0**	**33868.64**	**39401.44**
Tanzania	0	0	457.348928	0	0	10.277504	7.708128	563.978032	231.24384	14.131568	1284.688
Kenya	**0**	**425.088**	**789.0696**	**0**	**1081.3176**	**53.136**	**34.5384**	**0**	**270.9936**	**0**	**2654.1432**
Zimbabwe	0	0	1570,24	0	0	0	4,48	0	0	665,28	2240
Nigeria	0	0	1060.224	0	0	0	9.6384	3749.3376	0	0	4819.2
Ghana	**0**	**0**	**1400.5552**	**0**	**0**	**0**	**24.6432**	**2571.1072**	**110.8944**	**0**	**4107.2**
Rwanda	51	0	116.80912	0	0	0	11.17536	0	0	0	263.68528
Ethiopia	0	149.76	3997.76	0	0	0	0	0	0	0	4147.52



2022-Clean cooking [159]

2022-Electricity Access) [160]

Figure 5. Electricity access and clean cooking access by selected SSA.

Table 5: Selected SSA and their SWOTs towards HESS integration

Countries	Strength	Weakness	Opportunities	Threats	Remarks on ESS Integration
Zambia		High electricity/fuel importation No definite set targets Electricity access less than 50%	Resources and reserves for new development	Inadequate installed capacity	Low expectations on diversification into ESS
Namibia		High electricity/fuel importation No definite set targets Electricity access less than 50%	Resources and reserves for new development	Inadequate installed capacity	Low expectations on diversification into HESS
South Africa	Excess electricity for HESS Enabling systems and high investments	High dominance of coal in the current mix	Large energy resources and reserves for new development	Less political will for rapid RE integration	Ongoing diversification into HESS with diversity in RE options

Tanzania	Set targets for RE	High electricity/fuel importation Electricity access less than 50%		Inadequate installed capacity	Low expectations on diversification into HESS
Kenya	Firm supporting policies Set targets for RE		Large energy resources and reserves for new development An active plan for HESS to expand the current grid capability	Inadequate installed capacity	Ongoing diversification into HESS with diversity in RE options
Zimbabwe	Set targets for RE	High electricity/fuel importation		Inadequate installed capacity	Low expectations on diversification into HESS
Nigeria	Set targets	Lack of firm policy implementation Less political will for rapid RE integration	Large energy resources and reserves for new development	Inadequate installed capacity Unstable policies	Low expectations on diversification into HESS
Ghana	Excess electricity for ESS Set targets for RE		Large energy resources and reserves for new development		Ongoing diversification into ESS with diversity in RE options
Rwanda	Firm supporting policies Set targets for RE	High electricity/fuel importation		Inadequate installed capacity	Low expectations on diversification into HESS
Ethiopia	Excess electricity for HESS Supporting policies	Electricity access less than 50%	Large energy resources and reserves for new development	Increased demand owing to continued economic development and population growth Inadequate installed capacity	Low expectations on diversification into ESS

The selection of Kenya, South Africa, and Ghana among SSA countries is motivated by their comparatively better RE landscapes, stronger implementation frameworks, and higher levels of electricity and clean-cooking access. As shown in Tables 3 and 4, these three countries exhibit greater renewable-energy potential across multiple sources, including solar PV, wind, geothermal, hydro, and biomass relative to many other SSA states. This is consistent with broader regional assessments indicating that Kenya, South Africa, and Ghana are among the few SSA countries with diverse and scalable RE portfolios [20] [29] [33].

Figure 5 further demonstrates that the three countries maintain higher shares of electricity access and clean-cooking adoption, which are critical indicators of system readiness for integrating new hydrogen-production pathways without destabilizing national grids. For instance, Kenya leads in geothermal development and non-hydro RE penetration; South Africa possesses the most advanced utility-scale renewable infrastructure in SSA; and Ghana has achieved over 80% electricity access and maintains stable grid performance.

These quantitative patterns align with the qualitative implementation strategies previously reviewed in Section 4, which highlight active national programs such as Kenya's Renewable Energy Auction Scheme, South Africa's REIPPPP, and Ghana's Strategic National Energy Plan. As summarized in Table 5 (SWOT analysis), all three countries exhibit high preparedness, institutional capacity, and policy coherence, while also benefiting from RE diversity that mitigates the risk of system bottlenecks.

Collectively, these strengths justify the focus on Kenya, South Africa, and Ghana as practical early adopters for hydrogen production in SSA. Because these countries have relatively lower grid vulnerability, stronger RE expansion pathways, and more robust enabling environments, hydrogen generation can be deployed with minimal adverse impacts on grid stability compared to other SSA countries that face more severe infrastructural deficits. Therefore, the subsequent cost–benefit and decarbonization analysis will assess their hydrogen-driven energy-storage potential, aimed at accelerating sustainable energy transitions across the region.

While the use of ESS is often seen as a good option for achieving grid stability as well as the availability of energy for use at any time, the use of different energy technologies in storage has different environmental implications. For instance, table 7 depicts the different CO_2 emissions from each of the technologies in hydrogen production. Therefore, this section compares the feasibility of the CO_2 emissions reduction potentials from the three SSA countries, should part of their annual energy production be shared for use in hydrogen production. To estimate these emission values, CO_2 emissions are determined by the relation in equation (1) and (2):

$$CO_2 = [\, CO_{2(technology\, specific\, per\, unit\, H2)} * P_{H2}] \tag{1}$$

$$CO_{2(Reduction)} = [CO_{2(ref)} - CO_{2(technology\, specific\, per\, unit\, H2)}]/CO_{2(ref)} \tag{2}$$

$$CO_{2(Cost\ of\ Removal)} = c_{(removal\, cost\, for\, a\, unit)} * [\, CO_{2(technology\, specific)} * P_{hydrogen}] \tag{3}$$

The P_h is the annual hydrogen (kg/year.H_2) from selected countries obtained from the scenarios in Table A1, and the $CO_{2\ (technology\ specific)}$ as in Table 7. In addition, the reduction potential of $CO_{2\ (reduction)}$ emissions is estimated based on equation (2), and the $CO_{2\ (ref)}$ is the reference system (in this case, the main energy technology of the selected Country). If various energy technologies generate power with specified CO_2 emission levels utilised, as shown in Table 7, the CO_2 emissions are expressed in tons per annum.

Table 6. Life cycle CO_2 emissions and from Hydrogen production using different energy technologies

Energy Technology	High (gCO_2 e/kWh)	Mean (gCO_2 e/kWh)	Low (gCO_2 e/kWh)	Emissions (kg CO_2/kg H_2) (excluding emissions from H_2 system manufacturing and disposal) Per unit of H_2	Ref
Wind	124	6	26	0	[66]
Hydropower	237	2	26	0	[66]
Nuclear	130	2	29	0	[66]
Geothermal		37		0	[67]
Biomass	101	10	45	0	[66]
Solar PV	731	13	85	0	[66]
Natural gas	891	362	499	10-14 (12*)	[66]
Oil	935	547	733	12-15 (13.5*)	[66]
Lignite (Coal)	1372	790	1054	23-27 (25*)	[66]

* Mean

Table 7. Generation capacity for sample countries for ESS integration

Countries	Generation Capacity (MW)	Operational Capacity (MW) (0.85 utilisation)	Peak Demand (MW) (0.95 utilisation)	Additional Demands at Peak (MW)
South Africa	49400	39401,44	46930	7410
Ghana	5134	4107,2	4877,3	770,1
Kenya	3321	2654,14	3154.95	166.1

Table 8. Outcome of HESS integration in South Africa, Ghana, and Kenya

Energy Technology	CO_2 (From H_2 production) ($MtCO_{2eq.}$) South Africa	CO_{2ref} ($MtCO_{2eq.}$) South Africa	$CO_{2\,reduction}$ ($MtCO_{2eq.}$) South Africa	CO_2 (From H_2 production) ($MtCO_{2eq.}$) Ghana	CO_{2ref} ($MtCO_{2eq.}$) Ghana	$CO_{2\,reduction}$ ($MtCO_{2eq.}$) Ghana	CO_2 (From H_2 production) ($MtCO_{2eq.}$) Kenya	CO_{2ref} ($MtCO_{2eq.}$) Kenya	$CO_{2\,reduction}$ ($MtCO_{2eq.}$) Kenya
Wind	**0**	**0.79**	**-0.79**	**0**	**0.081**	**-0.081**	**0**	**0.0174**	**-0.0174**
Hydropower	**0**	**0.26**	**-0.26**	**0**	**0.027**	**-0.027**	**0**	**0.0058**	**-0.0058**
Nuclear	**0**	**0.26**	**-0.26**	**0**	**0.027**	**-0.027**	**0**	**0.0058**	**-0.0058**
Geothermal	**0**	**4.80**	**-4.80**	**0**	**0.500**	**-0.500**	**0**	**0.1073**	**-0.1073**
Bioenergy	**0**	**1.30**	**-1.30**	**0**	**0.135**	**-0.135**	**0**	**0.0029**	**-0.0029**
Solar	**0**	**1.69**	**-1.69**	**0**	**0.176**	**-0.176**	**0**	**0.0377**	**-0.0377**
Natural Gas	**1.56**	**46.95**	**45.39**	**0.162**	**4.887**	**4.725**	**0.0348**	**1.0498**	**1.015**
Oil	**1.75**	**70.95**	**69.2**	**0.183**	**7.385**	**7.202**	**0.0392**	**1.5863**	**1.5471**
Coal	**3.24**	**102.46**	**99.22**	**0.338**	**10.665**	**10.327**	**0.0725**	**2.291**	**2.2185**

Note - The negative sign implies **CO_2** emission savings.

Note - (At 1MW Electrolyser = 15 - 20 tons H_2)

For South Africa, $P_{hydrogen}$ (P_{H2}) = Additional Peak (7410 MW = 0.1112 – 0.1482 **Mtons H_2**) * Mean = 0.1297 **Mtons H_2**

For Ghana, $P_{hydrogen}$ (P_{H2}) = Additional Peak (770.1 MW = 0.0116 – 0.0154 **Mtons H_2**) * Mean = 0.0135 **Mtons H_2**

For Kenya, $P_{hydrogen}$ (P_{H2}) = Additional Peak (166.5 MW = 0.0025 – 0.0033 **Mtons H_2**) * Mean = 0.0029 **Mtons H_2**

Table 9. CO_2 reduction based on comparison across the different energy technologies.

Energy Technology	CO_2 Abated (From H_2 production) ($MtCO_{2eq.}$) South Africa	CO_{2ref} Abated ($MtCO_{2eq.}$) South Africa	CO_2 Abated (From H_2 production) ($MtCO_{2eq.}$) Ghana	CO_{2ref} Abated ($MtCO_{2eq.}$) Ghana	CO_2 Abated (From H_2 production) ($MtCO_{2eq.}$) Kenya	CO_{2ref} Abated ($MtCO_{2eq.}$) Kenya
Wind	3.24	101.67	0.162	4.806	0	0.0899
Hydropower	3.24	102.2	0.162	4.86	0	0.1653
Nuclear	3.24	102.2	0.162	4.86	0	0.1653
Geothermal	3.24	97.66	0.162	4.387	0	**0.1073**
Bioenergy	3.24	101.16	0.162	4.752	0	**-0.1363**
Solar	3.24	100.77	0.162	4.711	0	**-0.145**
Natural Gas	1.68	55.51	**-0.162**	**-4.887**	**-0.0348**	**-1.1571**
Oil	1.49	31.51	**-0.345**	**-12.272**	**-0.0392**	**-1.6936**
Coal	**-3.24**	**-102.46**	**-0.5**	**-15.552**	**-0.0725**	**-2.983**

Note - The reference values for South Africa (Coal, 3.24 and 102.46), Ghana (Natural gas, 0.162 and 4.887), and Kenya (Geothermal, 0 and 0.1073) $MtCO_{2\ eq.}$, respectively.

Note - The negative sign implies **CO_2** debt (i.e., CO_2 yet to be abated).

Table 10. Towards meeting the peak demand through H_2 - main drivers (in red) of the additional CO_2 emissions and debt (in $USD). Assuming 1 ton CO_2 removal = $USD 30.

Energy Technology	Cost of CO_2 Abated (From H_2 production) ($MtCO_{2eq.}$) South Africa	Cost of CO_{2ref} Abated ($MtCO_{2eq.}$) South Africa	Cost of CO_2 Abated (From H_2 production) ($MtCO_{2eq.}$) Ghana	Cost of CO_{2ref} Abated ($MtCO_{2eq.}$) Ghana	Cost of CO_2 Abated (From H_2 production) ($MtCO_{2eq.}$) Kenya	Cost of CO_{2ref} Abated ($MtCO_{2eq.}$) Kenya
Wind	97.2	3050.1	4.86	144.18	0	2.697
Hydropower	97.2	3066	4.86	145.8	0	4.959
Nuclear	97.2	3066	4.86	145.8	0	4.959
Geothermal	97.2	2929.8	4.86	131.61	0	-3.219
Bioenergy	97.2	3034.8	4.86	142.56	0	4.089
Solar	97.2	3023.1	4.86	141.33	0	4.35
Natural Gas	50.4	1665.3	-4.86	-146.61	-1.044	-34.713
Oil	44.7	945.3	-10.35	-368.16	-1.176	-50.808
Coal	-97.2	-3073.8	-15	-466.56	-2.175	-89.49

The results presented in Table 10 demonstrate that wind, hydropower, nuclear, geothermal, bioenergy, and solar energy sources have a significant impact on reducing CO_2 emissions when used as electricity drivers for hydrogen production in South Africa, Ghana, and Kenya. In fact, the emissions reduction is close to zero when compared to the usage of coal, oil, and natural gas. Consequently, the utilisation of geothermal energy in Kenya or the complete absence of attempts to utilise wind, hydropower, nuclear, geothermal, bioenergy, and solar energy would be sufficient to eliminate all CO_2 from the environment.

South Africa, whose primary energy technology is coal, and Ghana, whose principal energy technology is natural gas, would need to allocate investment towards renewable hydrogen to avoid emitting more CO_2, considering the viability of the situation. The potential for reducing CO_2 emissions from the nine energy technologies is illustrated in Table 9, while the expense of removing these emissions is shown in Table 11. These tables highlight the main factor driving emissions in future hydrogen generation required to meet peak demand.

The increasing use of renewable energy sources is being considered as a viable option for generating hydrogen, with the aim of reducing the environmental effects caused by fossil fuels. This transformation provides several benefits, including reduced greenhouse gas emissions and improved sustainability [1] . However, various challenges need to be addressed to harness renewable energy sources properly [4] [161]. These challenges involve the need to achieve 100% energy and clean cooking access in SSA, as shown in Figure 5, which no country has achieved yet. This is necessary to ensure continuous electricity production from renewable sources and to address the variability associated with solar and wind energy by utilising hydrogen and meeting peak energy demand.

The upfront costs related to the installation of solar panels, wind turbines, and energy storage technologies are quite expensive [162] [163]. Nevertheless, in addition to the negative environmental impact, the potential expenses associated with reducing CO_2 emissions in the future could make investing in an ESS system a reasonable alternative at present [162].

Moreover, system optimisation is essential to guarantee optimal functioning, considering variations in the availability of renewable energy resources among the various countries in SSA. To ensure the extensive acceptance of renewable electricity in SSA, it is crucial to address the developmental obstacles in addition to the technological and cost-related concerns associated with it.

South Africa, Ghana, and Kenya offer distinct yet complementary pathways for renewable-driven HESS, requiring careful, critical evaluation for cost optimisation and other co-benefits. Meaningful carbon reduction as depicted in Figure 6, is achievable only when technical design (optimal production site selection, electrolyser efficiency, capacity factor increment), market arrangements (volatility stability, minimizing life cycle production cost, risk management and trade-offs), and policy instruments (electricity price reduction) work together cohesively. The main optimisation challenge would involve balancing the minimisation of levelised cost of hydrogen (LCOH) with maximising avoided CO_2 emissions compared to a credible fossil baseline. Practically, this entails prioritising very low-carbon electricity sources, high electrolyser utilisation, and reduced system integration penalties such as transmission losses, desalination energy, and balance-of-plant costs. Shifting electrolysis feedstock from coal or gas to near-zero emission sources would result in significant CO_2 avoidance. This also offers a modest per-kg carbon savings when carbon is priced at typical policy levels. However, these savings may not automatically lead to a low LCOH unless electricity prices and capacity factors are carefully considered.

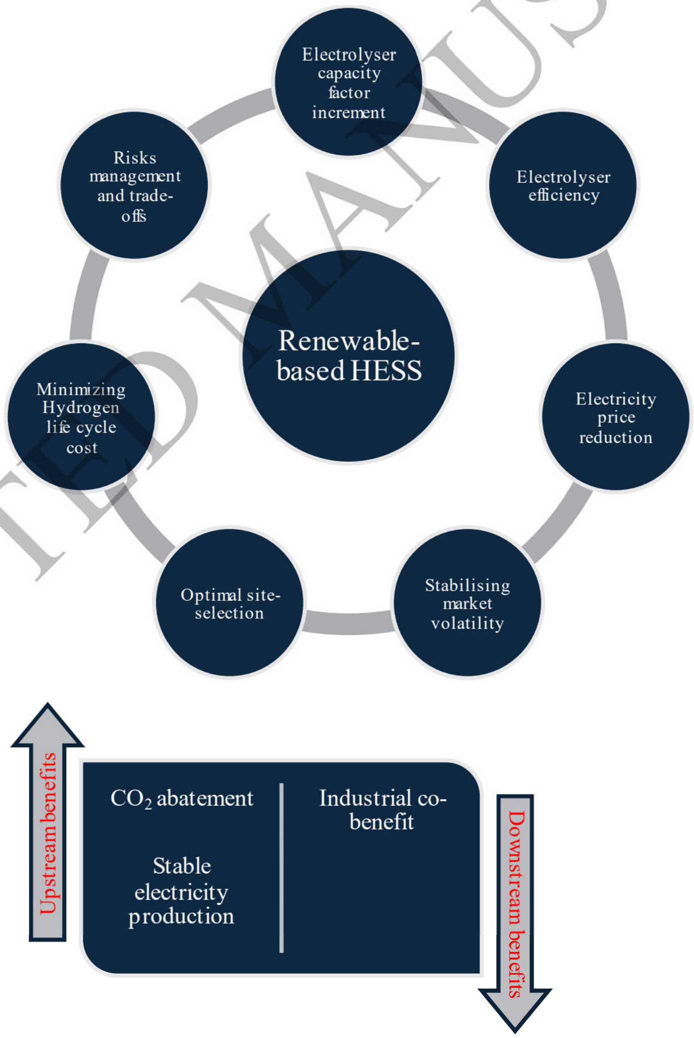


Figure 6. Towards a renewable-based hydrogen energy storage system in SSA.

Critically, electricity prices will likely be the main factor influencing LCOH. With typical electrolysis energy consumption of approximately 50 kWh per kilogram of H_2, a variation of $0.01/kWh in the electricity tariff could result in about $0.50 per kilogram on LCOH. Consequently, projects that depend on high retail grid tariffs or costly desalination energy face inherent competitiveness issues; this is particularly significant for coastal export projects that require seawater treatment for electrolysis. Equally vital is the electrolyser capacity factor: the annualised CAPEX per kilogram decreases significantly as utilisation increases. Policy and procurement should, therefore, focus on mechanisms that improve utilisation, secure stable domestic offtakes (such as for fertiliser or mining processes, especially in the SADC region where South Africa is a key player), implement price signals to leverage curtailed renewable energy, and develop market products that reward flexibility, rather than constructing electrolysers that remain idle waiting for favourable export prices.

Furthermore, site selection matters in terms of both cost and carbon. Kenya's geothermal endowment offers a distinctive advantage: high capacity factor, firm, low-carbon power that can produce hydrogen with very low operational CO_2 intensity and comparatively stable wholesale prices, reducing both LCOH and lifecycle emissions. Ghana and South Africa should prioritise integrated clusters where large wind/solar farms are paired with hydro or battery balancing to firm output; co-location with ports and industrial clusters reduces transport and logistics costs for ammonia/methanol conversion and supports domestic value capture. Notwithstanding, co-location often raises resource competition issues; water use for electrolysis and desalination competes with municipal and ecological needs, so project designs must internalise water-energy trade-offs and include water-treatment energy explicitly in cost models.

Another important consideration is stabilising the decisive market and policy instruments. For instance, internalising carbon via carbon pricing, procurement scoring, or tradable certificates, improves the bankability of low-carbon siting by monetising avoided emissions; but at typical mid-range carbon prices, this effect is additive rather than transformative. Blended finance, concessional debt and long-term offtake guarantees remain necessary to lower the weighted average cost of capital and bring LCOH into internationally competitive bands. Equally, transparent local-content rules and enforceable environmental safeguards are required to ensure projects deliver domestic industrialisation and do not replicate extractive export models.

There are other significant risks and trade-offs, such as export-first strategies and hydrogen infrastructure project sequencing. Export-first strategies can lock in low local utilisation and weaken domestic industrial linkages; heavy reliance on costly desalination or grid backup undermines carbon credentials and raises LCOH; weak regulatory frameworks can discourage private investment. To manage these risks, project sequencing should start with domestic-focused pilots that demonstrate technology, secure offtakes, ensure environmental safeguards, and optimise water use, then expand to export-oriented clusters using lessons learned.

Therefore, HESS can provide sustainable, cost-effective CO_2 abatement and industrial co-benefits in South Africa, Ghana, and Kenya, but only when low-cost, low-carbon electricity is prioritised, utilisation is maximised through market design, carbon is meaningfully internalised, and integration penalties are fully included in financial models.

Conclusion and Outlook

Integrating HESS in SSA countries presents substantial prospects for improving energy security, decreasing dependence on fossil resources, and fostering sustainable development. However, challenges include achieving 100% energy and clean cooking access in SSA poses a threat, and which most of the SSA countries have not yet achieved. Despite the upfront costs, investing in an HESS system is a reasonable alternative due to potential future CO_2 emissions reduction costs.

In this study, the significance of using hydrogen storage in decarbonising electricity grids of three promising SSA countries is evaluated as well as assessing the opportunities and implications of increasing integration of renewable energies. The study focuses on energy storage systems to improve system efficiency reliability and to cater for the peak load demands since renewable energies are naturally variable.

Some of the key takeaways from the study are:

i. Generally, HESS improves grid reliability, flexibility and stability by regulating the voltage and frequency deviations, reducing the loss of power supply probability, reduce operational and maintenance costs, hence exhibiting better economic performance.

ii. Their typical applications include load shifting, price arbitrage, and provision of black start capability, among others.

iii. Providing detailed information like cycling limitations, fast ramp rates, etc., in the market structure increases the chances of HESS to participate in electricity (capacity, ancillary services, and wholesale) markets.

iv. Various renewable energy and storage policies that enable conducive environments for renewable energy investments and technology transfer for different Sub-Saharan African nations are discussed. These include Public-Private Partnerships, which enable the private sector to aid the governments in diversifying the energy mix and reducing greenhouse gas emissions by developing large-scale renewable energy projects.

v. According to the energy technologies analysed, coal, oil and hydropower are common in SSA countries, and wind, hydropower, nuclear, geothermal, bioenergy, and solar energy sources are seen to reduce CO_2 emissions effectively.

vi. Compared to other SSA countries, South Africa generates much electricity, around 49 400MW, followed by Nigeria generating around 6 024MW. Hence, these two countries contribute more in terms of CO_2 emissions. South Africa and Ghana depend largely on coal and natural gas, respectively. Hence rapid integration of renewable energies and HESS technologies is recommended to reduce CO_2 emissions significantly.

vii. Kenya, Nigeria, South Africa and Zimbabwe have plans to increase their renewable energy generation capacity, with South Africa aiming for 8.7MW renewable energy generation capacity by 2030.

viii. In terms of integrating HESS technologies, Ghana, Kenya, and South Africa are the only countries with ongoing diversification into HESS, whilst others exhibit low expectations due to less political will for the integration, ineffective policy implementation, and lack of sufficient capital, technical skills and technology among other reasons.

This study suggests that the capital expenditures necessary for the installation and integration of renewable energy and energy storage technologies may be more cost-effective and surpass the costs associated with the long-term reduction of CO_2 emissions. Consequently, it is advisable to adopt ESS technologies to meet peak electrical demand with renewable energy and to provide access to nearly 100% clean cooking across the SSA region. This study is preliminary and did not include the dynamic electricity needs across different sectors in future years; yet it provides a foundation for future research that should rectify these constraints. Such research could improve the planning and use of clean electricity in Sub-Saharan Africa across many sectors and aid in achieving emission reduction goals.

By 2050, hydrogen development is expected to gain greater acceptance in the transportation, residential, and commercial sectors, thereby decreasing the daily marginal costs of hydrogen and energy generation. Hence, it is imperative to focus on the hourly generation of energy and hydrogen on a daily average or seasonal basis, employing a long-term multi-sectoral energy planning model to assess the energy mix in various SSA nations, a region with considerable renewable potential while conforming to stringent emission reduction objectives. This will enhance the planning of investments that yield higher returns for installed capacity and optimum emissions reduction strategies. Implementing stringent emissions reduction techniques, such as increasing hydrogen fuel cell capacity, would have simultaneously enhanced power supply capacity.

Author Contributions

Conceptualization, **A.N.C, H.K, and J.A**; procedures, **A.N.C, and D.C.M.**; formal analysis, **J.A**; investigation, **A.N.C, D.C.M, H.K, and J.A**; writing (original draft preparation), **A.N.C, D.C.M, H.K, and J.A**; writing (review and editing), **D.C.M, J.A, and O.O**; project administration, **A.N.C, J.A, and O.O**. All authors have agreed to the submission of the manuscript.

Declaration of competing interest

The authors of this article declare that they have no relationships or financial conflicts of interest that could influence this study.

Data availability statement

Data sharing is not applicable to this paper, as all data used have been properly referenced.

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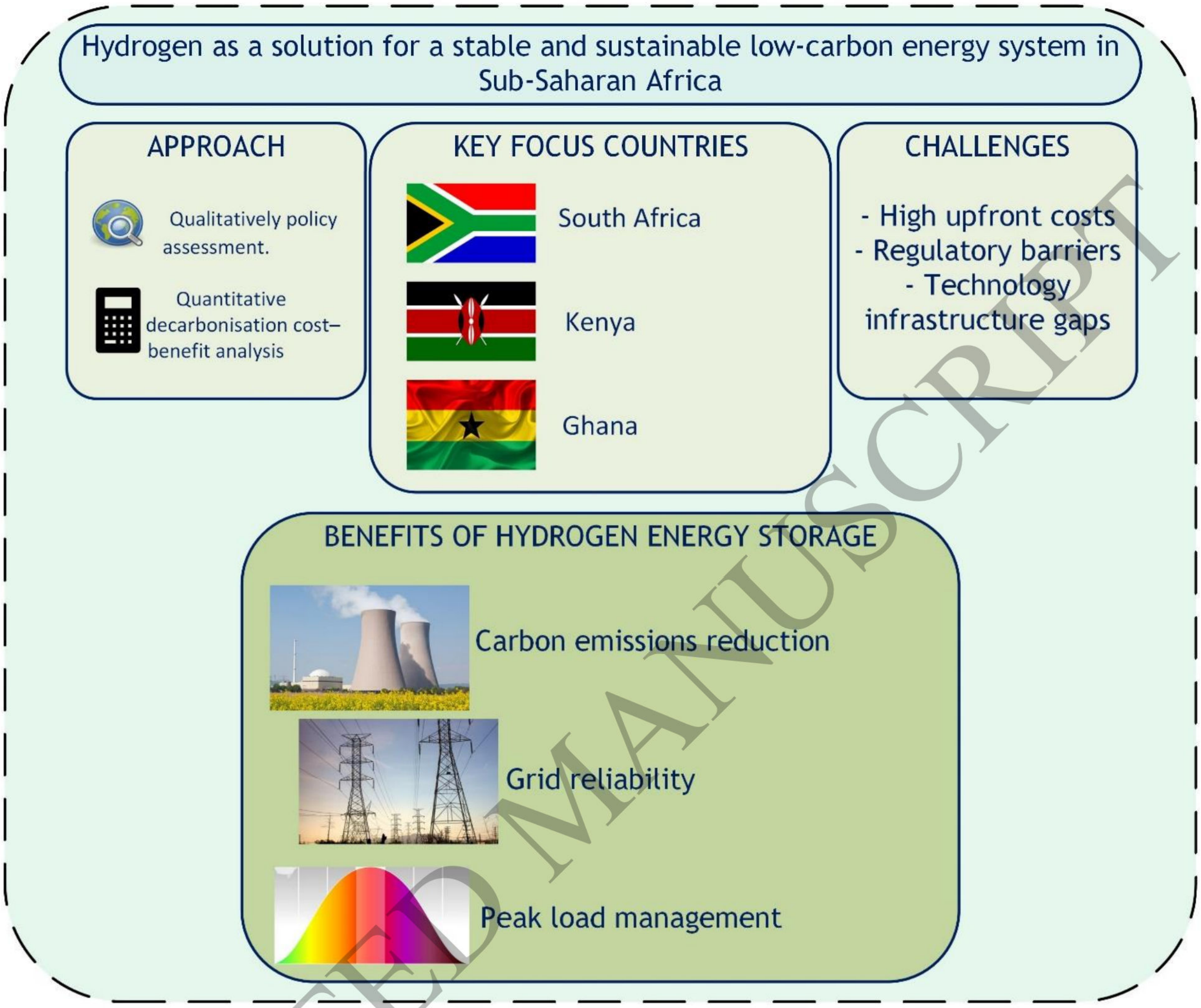

Hydrogen as a solution for a stable and sustainable low-carbon energy system in Sub-Saharan Africa

APPROACH

Qualitatively policy assessment.

Quantitative decarbonisation cost–benefit analysis

KEY FOCUS COUNTRIES

South Africa

Kenya

Ghana

CHALLENGES

- High upfront costs
- Regulatory barriers
- Technology infrastructure gaps

BENEFITS OF HYDROGEN ENERGY STORAGE

Carbon emissions reduction

Grid reliability

Peak load management

Graphical Abstract
165x139 mm (DPI)