Integrated Renewable Hydrogen and Electric Mobility for Grid Flexibility: A Sector-Coupled Framework for Developing Economies

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ABSTRACT

Developing economies face a dual challenge of rapidly increasing transportation demand and the urgent need to decarbonize energy systems. While renewable energy deployment is accelerating globally, the intermittent nature of solar and wind generation presents significant challenges for grid stability and reliability. Simultaneously, transportation sectors remain heavily dependent on fossil fuels, contributing substantially to greenhouse gas emissions. This paper proposes a sector-coupled energy infrastructure framework that integrates renewable hydrogen production, electric mobility systems, and smart grid technologies to enhance grid flexibility and accelerate the transition toward net-zero transportation in developing economies. The framework leverages surplus renewable electricity for hydrogen production through electrolysis while utilising electric vehicles (EVs) as distributed energy storage resources through vehicle-to-grid (V2G) technologies. By coupling power, transportation, and hydrogen sectors, the proposed model addresses renewable energy curtailment, grid balancing, energy security, and transportation decarbonisation simultaneously. The study examines technological pathways, infrastructure requirements, policy mechanisms, and economic considerations for implementation. The proposed framework demonstrates how integrated hydrogen-electric mobility systems may improve renewable energy utilisation, reduce grid congestion, enhance system resilience, and support sustainable economic development through coordinated sector coupling between power, transport, and hydrogen systems. The paper concludes by outlining strategic recommendations for policymakers and stakeholders seeking to establish flexible, low-carbon transportation and energy infrastructures in developing economies.

Keywords: Renewable hydrogen, Electric mobility, Grid flexibility, Net-zero transportation, Developing economies

INTRODUCTION

Global efforts to achieve climate neutrality have increased the need for integrated solutions that simultaneously decarbonise energy and transportation sectors. Transportation accounts for approximately one-quarter of global energy-related CO_2 emissions, with developing economies experiencing rapid growth in vehicle ownership and energy demand. Although many of these regions have abundant renewable resources, particularly solar and wind, they face challenges such as grid instability, infrastructure limitations, and energy access constraints [1] The increasing penetration of renewable energy introduces variability, often leading to curtailment and inefficiencies. Conventional approaches relying on grid expansion or standalone storage solutions are frequently cost-prohibitive. In response, sector coupling has emerged as a promising strategy for enhancing system flexibility by integrating electricity, transport, and hydrogen systems [2]. Renewable hydrogen provides long-duration energy storage, particularly for hard-to-electrify transport sectors, while electric vehicles (EVs) offer short-term flexibility through smart charging and vehicle-to-grid (V2G) capabilities. The integration of these systems enables complementary benefits, combining short-term battery storage with long-term hydrogen storage. Despite growing research, the application of integrated

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sector-coupled systems in developing economies remains limited. This paper addresses this gap by proposing a unified framework that integrates renewable energy generation, hydrogen production and storage, and electric mobility systems with V2G capability. The framework aims to enhance grid flexibility, improve renewable energy utilisation, and support the transition towards net-zero transportation systems [3] While previous studies have investigated renewable hydrogen systems, electric mobility, and vehicle-to-grid (V2G) technologies independently, limited attention has been given to their coordinated integration within a unified framework for developing economies. The novelty of this study lies in the integration of short-duration flexibility provided by EV batteries and long-duration flexibility provided by renewable hydrogen storage within a single sector-coupled architecture. Furthermore, the framework is demonstrated using complementary case studies from Kenya and South Africa, highlighting practical pathways for renewable energy integration, transport decarbonisation, and grid flexibility in developing economy contexts.

RESEARCH METHODOLOGY

This study adopts a conceptual framework methodology to investigate the integration of renewable electricity, hydrogen production, and electric mobility for enhancing grid flexibility in developing economies. Rather than employing numerical optimisation or software-based simulation, the research develops an analytical framework through a comprehensive review of recent literature published between 2020 and 2025 on renewable hydrogen, vehicle-to-grid (V2G) technology, electric mobility, and sector coupling. Based on this review, an integrated sector-coupled architecture linking renewable electricity generation, electrolysis, hydrogen storage, electric vehicle charging, V2G operation, and the electricity grid was developed. Mathematical equations describing the energy flows among these subsystems were formulated using established energy balance relationships reported in the literature to illustrate the interactions between renewable generation, hydrogen production, electricity demand, and EV operation. To demonstrate the practical application of the proposed framework, representative operational scenarios based on publicly available information from Kenya and South Africa were incorporated. The numerical values presented are illustrative and derived from representative renewable generation and electricity demand profiles reported in the literature; they are intended to demonstrate the operation of the proposed framework rather than represent outputs from numerical simulation or optimisation software. The numerical values used in this study are derived from representative ranges reported in recent literature and publicly available data sources. Solar irradiance and renewable generation profiles are based on typical values observed in Sub-Saharan Africa, while electricity demand patterns and electric vehicle charging behaviour are informed by existing studies on developing economies, including Kenya and South Africa. Electrolyser efficiency, hydrogen energy content, and system parameters are selected based on commonly reported values in hydrogen energy research. These assumptions are intended to provide realistic and representative conditions for illustrating the operation of the proposed framework, rather than serving as site-specific or optimised results.

Sector-Coupled Energy System Architecture

The proposed framework integrates renewable power generation, hydrogen production and storage, and electric mobility with vehicle-to-grid (V2G) capability into a unified energy system designed to enhance grid flexibility and support net-zero transportation in developing economies [4].

ISSN 2278-2540 | DOI: 10.51583/IJLTEMAS | Volume XV, Issue VI, June 2026

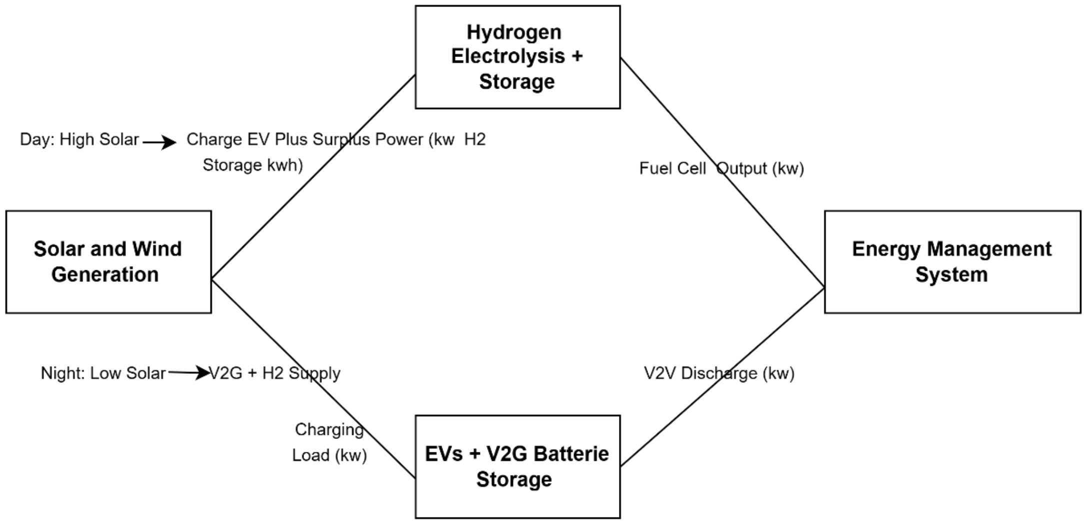

Figure 1. Sector-coupled system architecture

The diagram is a conceptual representation developed by the authors based on established sector coupling principles reported in recent literature, illustrating the main energy flows and system components. The primary interactions include conversion of surplus renewable energy into hydrogen via electrolysis, EV charging from renewable power, vehicle-to-grid (V2G) discharge to support the grid, and electricity generation from stored hydrogen using fuel cells. The combination of short-duration storage (EV batteries) and long-duration storage (hydrogen systems) provides a multi-layered flexibility mechanism capable of addressing both short-term fluctuations and long-term variability. During high renewable generation, excess energy is allocated to EV charging and hydrogen production. During low generation periods, stored energy is supplied through V2G operation and hydrogen fuel cells, supporting demand and reducing reliance on conventional generation. System operation is coordinated by an Energy Management System (EMS), which optimises energy flows between generation, storage, and demand in real time. Overall Energy Balance of the Sector-Coupled System.

Equation (1)

$$P\_RE + P\_V2G + P\_FC = P\_D + P\_EL + P\_EV + P\_loss$$

Where P_RE represents the total renewable power generation (kW), P_V2G is the power supplied from electric vehicles to the grid through vehicle-to-grid operation (kW), and P_FC denotes the fuel cell power output (kW). On the demand side, P_D represents the total electricity demand (kW), P_EL is the power consumed by the electrolyser during hydrogen production (kW), and P_EV denotes the electric vehicle charging demand (kW), while P_loss accounts for system losses (kW). Equation (1) represents the overall energy balance of the proposed sector-coupled system. The total renewable power generated is allocated among grid demand, hydrogen production through electrolysis, EV charging demand, and system losses. The Energy Management System (EMS) continuously regulates these energy flows to maximise renewable energy utilisation while maintaining system stability and reliability. However, implementation requires advanced control strategies and significant infrastructure investment, particularly for hydrogen and V2G systems [5].

Renewable Power Generation (Solar and Wind Systems)

Renewable power generation within the proposed framework is primarily derived from solar and wind energy sources. These resources are widely available in many developing regions and are increasingly deployed due to their low operating costs, environmental sustainability, and scalability [6]. However, their inherent variability necessitates robust energy management and storage strategies. The total renewable power output at any time $t$is expressed as:

ISSN 2278-2540 | DOI: 10.51583/IJLTEMAS | Volume XV, Issue VI, June 2026

Equation (2)

$$P\_RE = P\_PV + P\_Wind$$

Where $P_{RE}(t)$is the total renewable power generation, $P_{solar}(t)$is solar PV output, and $P_{wind}(t)$is wind power output (kW). This equation represents the combined contribution of solar and wind resources, providing a more stable power supply by reducing individual variability.

Solar Power Model

Solar power generation within the system is modelled as a function of solar irradiance and photovoltaic (PV) system efficiency. The output power from the PV system at time $t$is expressed as:

Equation (3)

$$P\_PV = \eta\_PV \times A \times I$$

Where η_PV represents the photovoltaic conversion efficiency (–), A denotes the surface area of the solar panel (m^2), and I represent the solar irradiance incident on the panel (W/m^2). Solar output depends on these parameters, with irradiance variations leading to fluctuating power generation [7]

Wind Power Model

Wind power generation within the proposed system is modelled based on the kinetic energy of moving air, which is converted into mechanical and subsequently electrical energy by the turbine. The instantaneous power output from a wind turbine at time $t$is given by:

Equation (4)

$$P\_Wind = 1/2 \times \rho \times A \times C\_p \times V^3$$

Where ρ represents the air density (kg/m^3), A denotes the swept area of the wind turbine (m^2), C_p is the power coefficient indicating the efficiency of the turbine (–), and V represents the wind speed (m/s).Wind power depends on these parameters, with wind speed variability contributing to intermittent generation [8]

Intermittency and Energy Management

Due to the inherent variability of solar and wind resources, renewable power generation within the system is highly intermittent [9] as a result, there are periods when renewable energy supply exceeds demand and periods when it is insufficient to meet system requirements [10]. Effective energy management strategies are therefore essential to ensure system stability and reliability.

Surplus Generation Condition

A surplus condition occurs when renewable generation exceeds total system demand

Equation (5)

$$P\_RE > P\_D + P\_EV$$

Under surplus conditions, excess energy is allocated by the EMS to battery storage (including EVs), hydrogen production via electrolysis, grid export, or flexible loads to minimise curtailment.

Deficit Generation Condition

A deficit condition arises when renewable generation is insufficient to meet demand:

ISSN 2278-2540 | DOI: 10.51583/IJLTEMAS | Volume XV, Issue VI, June 2026

Equation (6)

$$P\_RE < P\_D + P\_EV$$

Under deficit conditions, the EMS maintains system balance by utilising stored energy from EVs (via V2G) and hydrogen systems (via fuel cells), alongside grid imports or backup generation if required.

Role of Energy Storage and Management

These alternating surplus and deficit conditions highlight the critical importance of Energy Storage Systems (ESS) and intelligent energy management. Short-term storage (EV batteries) provides rapid response for peak demand and load balancing, while long-term storage [11] supports sustained energy supply during extended periods of low renewable generation [12]. The Energy Management System continuously monitors system conditions and dynamically allocates energy flows to optimise performance, minimise curtailment, and ensure reliable operation of the sector-coupled energy system.

Graphical Representation

Below is a 24-hour Representative 24-hour renewable power profile showing solar, wind, and total renewable power:

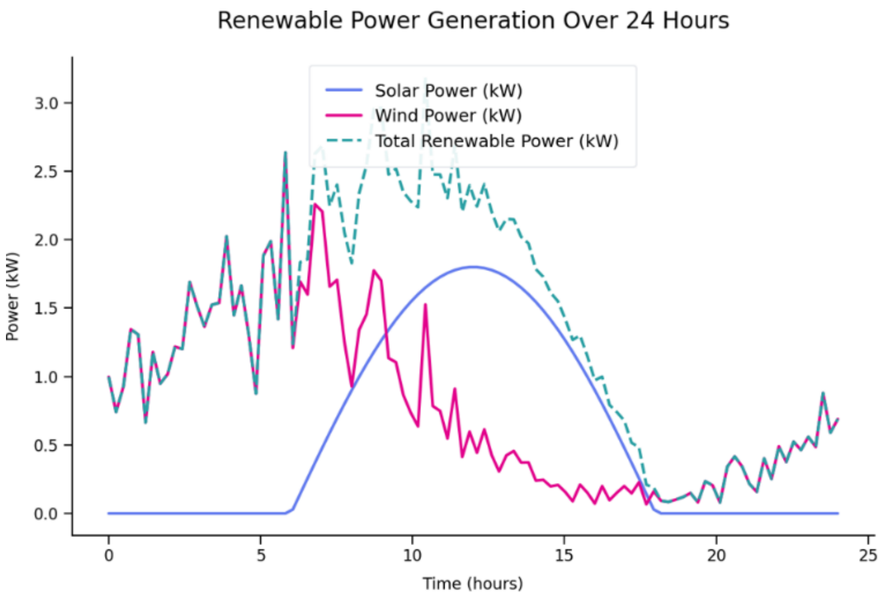

Figure 2. Representative 24-hour renewable power generation profile.

The profile is based on typical solar irradiance and wind generation patterns reported for Sub-Saharan Africa. Power values are representative and used to illustrate daily variability rather than site-specific measurements. The horizontal axis represents time (hours), while the vertical axis represents power output (kW). Solar output follows a typical diurnal pattern, peaking at midday and falling to zero at night, while wind generation remains variable but continuous throughout the day. The combined renewable output highlights the complementary nature of solar and wind resources, resulting in a more stable overall power supply. Periods of surplus generation occur during midday, while deficits arise during evening and low-wind conditions. These variations emphasise the need for energy storage and management strategies, where surplus energy can be stored in EV batteries or converted into hydrogen, and deficits are met through V2G discharge and fuel cell operation. Overall, the results demonstrate that integrating multiple renewable sources and storage technologies improves system stability and supports the effectiveness of the proposed sector-coupled framework.

Hydrogen Production and Storage Subsystem

ISSN 2278-2540 | DOI: 10.51583/IJLTEMAS | Volume XV, Issue VI, June 2026

The hydrogen subsystem provides long-duration energy storage by converting surplus renewable electricity into hydrogen through electrolysis. This process reduces renewable energy curtailment and enables energy to be stored in chemical form for later use, addressing the intermittency of solar and wind resources [13]. Stored hydrogen can be utilised for electricity generation via fuel cells, transportation particularly for heavy-duty applications—and various industrial processes. Within the proposed framework, hydrogen complements short-term storage provided by electric vehicle batteries by offering high-capacity, long-term energy buffering. This integration enhances overall system flexibility and resilience, making hydrogen particularly suitable for large-scale, renewable-based energy systems in developing economies.

Electrolysis Process

The hydrogen production process in the proposed system is based on water electrolysis, an electrochemical reaction that uses electrical energy to split water into hydrogen and oxygen.

The overall electrochemical reaction is expressed as:

$$H_2O(l) \rightarrow H_2(g) + \frac{1}{2}O_2(g)$$

This reaction demonstrates the conversion of electrical energy into chemical energy stored in hydrogen molecules. The hydrogen produced can then be stored and utilised at a later stage.

Hydrogen Production Rate

The rate of hydrogen production during electrolysis is given by:

Equation (7)

$$\dot{m}\_{H2} = (\eta\_{EL} \times P\_{EL}) / LHV\_{H2}$$

Where ṁ_H2 represents the hydrogen production rate (kg/s), η_EL denotes the efficiency of the electrolyser (–), P_EL is the electrical power input to the electrolyser (kW), and LHV_H2 represents the lower heating value of hydrogen (kWh/kg).Hydrogen production depends on electrical input, system efficiency, and hydrogen energy content. Higher efficiency improves conversion performance, while lower efficiency increases energy requirements. During surplus renewable conditions, electricity can be directed to electrolysis to produce hydrogen for long-term storage and utilisation.

Energy Storage Function

Hydrogen storage provides long-duration, high-capacity energy storage, enabling energy to be preserved over extended periods and addressing seasonal variability in renewable generation. Within the proposed framework, hydrogen serves multiple functions, including energy buffering during low-generation periods, fuel supply for transportation (particularly heavy-duty applications), and integration across power, transport, and industrial sectors.

Stored Hydrogen Energy

The amount of energy stored in hydrogen is given by:

Equation (8)

$$E\_{H2} = m\_{H2} \times LHV\_{H2}$$

Where E_H2 represents the stored hydrogen energy (kWh), m_H2 denotes the mass of hydrogen (kg), and LHV_H2 is the lower heating value of hydrogen (kWh/kg).Where E_{H_2} is the total stored hydrogen energy

ISSN 2278-2540 | DOI: 10.51583/IJLTEMAS | Volume XV, Issue VI, June 2026

(kWh), m_{H_2} is the hydrogen mass (kg), and LHV_{H_2} is its lower heating value (kWh/kg). This equation represents the chemical energy stored in hydrogen, which is directly proportional to the hydrogen mass. As storage increases, the system builds a long-term energy reserve.

Fuel Cell Energy Recovery

Stored hydrogen can be reconverted into electricity using a fuel cell during periods when renewable generation is insufficient to satisfy electricity demand. Within the proposed sector-coupled framework, fuel cells provide long-duration backup power by converting the chemical energy stored in hydrogen into electrical energy. This process complements vehicle-to-grid (V2G) systems, which primarily provide short-term grid support, thereby enhancing overall system flexibility and reliability.

System-Level Interpretation

These equations describe the hydrogen energy cycle, where surplus renewable electricity is converted into hydrogen via electrolysis, stored as chemical energy, and reconverted into electricity using fuel cells when required. This process enables energy shifting across time, ensuring efficient utilisation of excess generation and supply during deficit periods. Hydrogen storage complements short-term EV storage by providing long-duration flexibility and enhancing overall system reliability.

Electric Mobility and Vehicle-to-Grid (V2g) Subsystem

Electric vehicles (EVs) play a dual role within the proposed sector-coupled framework, functioning both as transportation assets and as distributed energy storage systems. When aggregated, EV batteries represent a significant flexible resource capable of supporting grid stability through smart charging strategies and bidirectional vehicle-to-grid (V2G) operation. By intelligently controlling charging and discharging cycles, EVs can absorb excess renewable energy during periods of surplus and supply energy back to the grid during peak demand periods. This enhances overall system flexibility and reduces reliance on conventional backup generation.

Role in Energy Management

Within the sector-coupled system, EVs absorb surplus renewable energy during high generation periods and supply energy back to the grid via V2G during deficit conditions. This bidirectional functionality enables EVs to provide peak load reduction, demand response, and short-duration energy storage, thereby enhancing grid flexibility and renewable energy utilisation.

Vehicle-to-Grid Operation

In vehicle-to-grid (V2G) mode, electric vehicles (EVs) operate as distributed energy resources by discharging stored energy from their batteries back into the grid. This process typically occurs during periods of peak electricity demand or low renewable generation, thereby supporting grid stability and reducing peak load stress. Within the sector-coupled framework, V2G supports grid operation during deficit and peak demand periods, while enabling EVs to recharge or remain idle under normal conditions. This bidirectional capability enables EVs to function as short-term energy storage, complementing long-term hydrogen storage, and effectively forming a virtual power plant that responds dynamically to grid conditions.

The integration of EV fleets with renewable generation enables dynamic load balancing and enhances overall system flexibility.

Functional Contributions of EV Integration

ISSN 2278-2540 | DOI: 10.51583/IJLTEMAS | Volume XV, Issue VI, June 2026

The integration of electric vehicles (EVs) within the sector-coupled framework enhances grid flexibility by enabling EV fleets to operate as distributed energy resources. Through vehicle-to-grid (V2G) functionality and smart charging, EVs contribute to peak load reduction, demand response, short-term energy storage, and improved load distribution. The interaction between renewable generation, hydrogen systems, and EVs is coordinated by an Energy Management System (EMS), which dynamically optimises energy flows between generation, storage, and demand. The EMS prioritises renewable energy utilisation, efficient allocation of surplus energy to hydrogen production and EV charging, reliable supply during deficit conditions via V2G and fuel cells, and minimisation of system losses and curtailment. The operation of the proposed Energy Management System (EMS) is governed by the overall energy balance presented in Equation (1). The EMS continuously coordinates renewable generation, hydrogen production, electric vehicle charging, and vehicle-to-grid operation to satisfy electricity demand while minimising renewable energy curtailment and system losses

CASE STUDY: SECTOR-COUPLED ELECTRIC MOBILITY AND RENEWABLE ENERGY INTEGRATION IN KENYA

Kenya's power system is characterised by a high share of renewable energy, accounting for approximately 90% of electricity generation, primarily from geothermal, hydro, and wind sources. This strong renewable base provides a favourable foundation for sector-coupled energy systems. Electricity demand continues to grow, with peak demand occurring during evening hours, creating a mismatch between renewable supply and load. Electric mobility adoption is expanding rapidly, with over 35,000 EVs by 2025, largely driven by electric motorcycles and buses. Within this context, surplus renewable energy generated during daytime can be utilised for EV charging and hydrogen production. During evening peak periods, energy stored in EVs (via V2G) and hydrogen systems (via fuel cells) can be used to balance supply and demand.

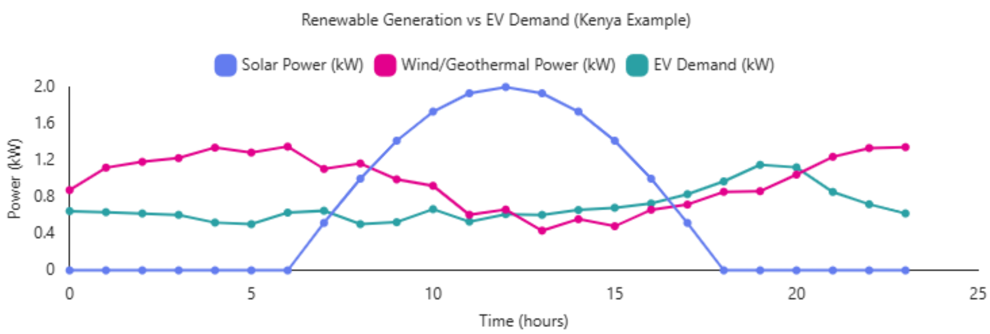

Figure 3. Representative 24-hour renewable power profile for Kenya.

The data presented are based on reported trends in Kenya's energy system, including solar generation patterns, stable geothermal contribution, and typical EV charging demand behaviour. The values are indicative and derived from literature to demonstrate system operation under realistic conditions. The axes represent time (hours) and power (kW), respectively. Solar generation follows a typical diurnal pattern, peaking at midday and falling to zero at night, while wind and geothermal provide a more stable and continuous energy supply. EV demand remains low during early hours and increases during the evening peak, reflecting typical charging behaviour. Kenya's energy system demonstrates a strong foundation for sector coupling, with high renewable penetration supporting transport electrification. Surplus renewable energy can be utilised for EV charging and other flexible loads, while EVs function as distributed energy storage resources. The system already exhibits key elements of sector coupling, including the direct use of renewable electricity for transport and the integration of EV batteries as flexible storage. Although hydrogen infrastructure remains underdeveloped, existing conditions provide a suitable basis for future integration of hydrogen as a long-duration energy storage solution. Key insights from the Kenyan case include the ability of renewable energy to support transport decarbonisation, the role of EVs as flexible loads in reducing curtailment, and the benefits of decentralised systems in improving resilience and energy access. However, challenges such as limited charging infrastructure, grid constraints, and high upfront costs remain. Overall,

ISSN 2278-2540 | DOI: 10.51583/IJLTEMAS | Volume XV, Issue VI, June 2026

the Kenyan case demonstrates the feasibility of integrating renewable energy and electric mobility, while highlighting the potential benefits of incorporating hydrogen systems to further enhance flexibility and support long-term energy balancing

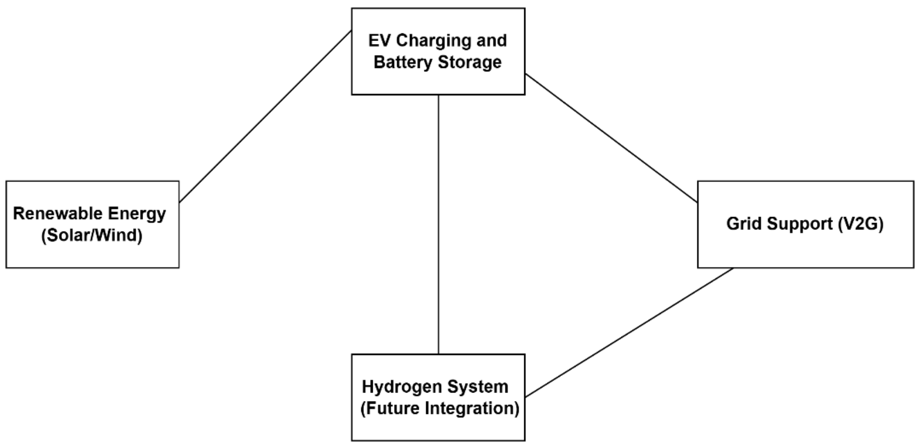

Figure 4. Sector-coupled framework in the Kenyan

This figure is a conceptual illustration based on the proposed framework, highlighting the bidirectional energy flows between renewable generation, electric vehicles, and hydrogen subsystems. It is intended to demonstrate system interactions rather than quantitative results. Showing the interaction between renewable generation, electric mobility, and potential hydrogen integration. Renewable energy, primarily from solar and wind, is used for EV charging, where EVs act as both transport units and distributed storage. Energy can either be used directly for transport or supplied back to the grid through vehicle-to-grid (V2G) operation during peak demand. Surplus renewable energy can also be converted into hydrogen via electrolysis for long-term storage and later use in electricity generation or transport. Overall, the diagram highlights the interconnected and bidirectional energy flows that enhance system flexibility and efficiency.

Electric Mobility Deployment and Grid Interaction

Electric mobility in Kenya has grown rapidly, supported by government initiatives and private-sector innovation. By 2025, EV adoption particularly motorcycles and buses have expanded significantly, supported by battery-swapping and decentralised charging solutions. Kenya’s high renewable energy share enables EV charging using surplus electricity, reducing curtailment. In this context, EVs act not only as transport systems but also as flexible loads and distributed storage, contributing to grid balancing and improved energy utilisation.

Operational Characteristics of the Proposed Framework

The proposed sector-coupled framework operates by coordinating renewable electricity generation, hydrogen production, and electric vehicle (EV) charging, according to variations in renewable energy availability and electricity demand. During periods of high renewable generation, surplus electricity is directed to EV charging and hydrogen production through electrolysis, thereby reducing renewable energy curtailment. During periods of low renewable generation or high electricity demand, stored energy from EV batteries through vehicle-to-grid (V2G) operation and hydrogen fuel cells can be utilised to support grid operation and improve system flexibility. Hydrogen production within the proposed framework is directly related to the availability of surplus renewable electricity. When renewable generation exceeds electricity demand, excess energy is converted into hydrogen through electrolysis for long-term storage. This stored hydrogen can subsequently be used for electricity generation or transport applications during periods of reduced renewable energy availability.Electric vehicles contribute to grid flexibility through controlled charging and vehicle-to-grid (V2G) operation. During periods of surplus renewable generation, EVs absorb excess electricity through smart charging, while during peak demand they can discharge stored energy back to the grid, thereby

ISSN 2278-2540 | DOI: 10.51583/IJLTEMAS | Volume XV, Issue VI, June 2026

improving load balancing and reducing reliance on conventional generation. Although this study does not present quantitative performance evaluation through numerical simulation, the proposed framework is expected to improve renewable energy utilisation, reduce renewable energy curtailment, enhance grid flexibility, and strengthen long-term energy resilience by integrating hydrogen storage with electric mobility. These expected benefits are consistent with findings reported in recent studies on sector-coupled energy systems. The integration of renewable hydrogen and electric mobility provides complementary flexibility across different timescales. Electric vehicles offer rapid, short-duration energy storage and demand response, whereas hydrogen provides high-capacity, long-duration energy storage suitable for extended periods of low renewable generation. Combining these technologies within a sector-coupled framework improves operational flexibility and enhances the resilience of renewable-based energy systems in developing economies.

Renewable Energy Coupling with Transport Systems

Kenya's energy system provides a strong example of implicit sector coupling through the integration of renewable energy and electric mobility, even in the absence of fully developed hydrogen infrastructure. Solar-powered EV charging and battery-swapping systems enable decentralised energy use and reduce reliance on conventional grid infrastructure. These systems allow surplus renewable energy to be redirected to transport applications, improving overall energy utilisation while reducing grid stress. Studies have shown that integrating EVs into solar-based systems can enhance performance by absorbing excess generation and reducing dependence on fossil fuels [14]. This interaction between renewable energy and transport aligns with the proposed sector-coupled framework, where EVs act as flexible demand-side resources. It also highlights the potential for future integration of hydrogen systems to provide long-duration energy storage and further enhance system flexibility.

System Flexibility and Grid Implications

Kenya provides valuable insights into the impact of electric vehicle (EV) adoption on grid performance in developing economies. Uncontrolled EV charging can strain distribution networks and increase peak demand; however, smart charging strategies can mitigate these effects by shifting demand to periods of high renewable generation, thereby improving load balancing and grid stability. Vehicle-to-Grid (V2G) technology further enhances system flexibility by enabling EVs to operate as distributed energy storage units, supplying electricity back to the grid when required. Although V2G deployment in Kenya is still emerging, it aligns closely with the proposed sector-coupled framework, supporting the transition toward a more flexible and decentralised energy system.

Socio-Economic and Environmental Impact

The Kenyan case demonstrates that sector-coupled energy systems can deliver significant socio-economic and environmental benefits. Transport electrification reduces emissions and operating costs while improving energy security by decreasing reliance on imported fuels [15] Additionally, EV adoption supports local economic development through job creation and expansion of related industries [16]. However, challenges remain, including limited charging infrastructure, grid capacity constraints, high upfront costs, and regulatory gaps. Addressing these issues requires integrated planning, targeted investment, and supportive policy frameworks to enable effective sector coupling and long-term sustainability.

Relevance to the Proposed Framework

The Kenyan case study provides strong empirical support for the sector-coupled energy framework proposed in this paper. Table 1 presents a mapping between the key components of the framework and their corresponding real-world implementation in Kenya.

ISSN 2278-2540 | DOI: 10.51583/IJLTEMAS | Volume XV, Issue VI, June 2026

Framework Component	Kenya
Renewable generation	>90% renewable electricity mix
Electric mobility	Rapid EV adoption (buses and motorcycles)
Distributed storage	Battery-swapping systems and EV batteries
Smart energy use	Solar-powered charging infrastructure
Sector coupling	Integration of power and transport sectors

Table 1. Proposed framework components

The information presented in this table is based on publicly available reports and literature sources related to Kenya's energy system and electric mobility development and is intended to provide a qualitative representation of the proposed framework components. The comparison shows that several elements of sector coupling particularly the integration of renewable energy and electric mobility are already being realised in practice. While large-scale hydrogen deployment remains limited, the availability of renewable resources and flexible EV demand provides favourable conditions for future integration of hydrogen systems for long-term energy storage and transport decarbonisation [17]. Overall, the Kenyan case demonstrates the feasibility of the proposed framework and highlights the potential for developing economies to progressively adopt sector-coupled systems.

CASE STUDY: HYDROGEN DEVELOPMENT AND SECTOR COUPLING IN SOUTH AFRICA

South Africa represents a leading hydrogen-focused case in Africa, demonstrating how renewable energy can be integrated with hydrogen production to support decarbonisation and enhance energy system flexibility [18] The country's abundant solar and wind resources, combined with targeted policy initiatives, position it as a key example of sector coupling in a developing economy context. Through its Hydrogen Society Roadmap, South Africa aims to scale green hydrogen production and expand electrolyser capacity, supported by large-scale renewable energy projects, particularly in regions such as the Northern Cape [19]. These developments highlight the country's potential to become a major producer and exporter of green hydrogen. Overall, South Africa illustrates how renewable resource availability, infrastructure investment, and supportive policy frameworks can enable large-scale integration of hydrogen within sector-coupled energy systems [20].

ISSN 2278-2540 | DOI: 10.51583/IJLTEMAS | Volume XV, Issue VI, June 2026

Hydrogen Strategy and Policy Framework

South Africa has established a national strategy through its Hydrogen Society Roadmap, positioning green hydrogen as a key component of its energy transition and economic development plans [21] The strategy focuses on decarbonising hard-to-electrify sectors, developing a global hydrogen export market, improving energy security, and supporting economic growth. To support these goals, the government has identified priority hydrogen development hubs, including Johannesburg, Durban, and Limpopo, based on their proximity to renewable resources and industrial demand [22] South Africa aims to significantly scale hydrogen production, targeting approximately 500,000 tonnes per year by 2030, supported by expanding electrolyser capacity [23] .This policy-driven approach provides a strong foundation for integrating hydrogen into sector-coupled energy systems.

Renewable Hydrogen Production Systems

A key element of South Africa's energy transition is the integration of renewable energy with hydrogen production through electrolysis, enabling the direct conversion of renewable electricity into green hydrogen [24]. For example, pilot projects in the Northern Cape utilise co-located solar photovoltaic (PV) systems to power electrolysers, producing hydrogen without associated carbon emissions [25]. This approach demonstrates the core principle of converting variable renewable energy into storable chemical energy while reducing curtailment. The produced hydrogen can be applied across multiple sectors, including heavy-duty transport, industrial processes, and export markets. Overall, this integrated approach highlights the role of hydrogen as a long-duration energy storage solution and a key enabler of sector coupling, enhancing grid flexibility and supporting decarbonisation [26].

Grid Flexibility and Energy Storage Role

South Africa faces ongoing challenges related to grid instability, driven by supply–demand imbalances and ageing infrastructure. In this context, renewable hydrogen is being explored as a long-duration energy storage solution to enhance system resilience and flexibility [27]. Pilot projects, including those by Eskom, are investigating the integration of hydrogen systems with solar photovoltaic (PV) generation and storage technologies to assess performance under real grid conditions [28]. Hydrogen enhances grid flexibility by storing surplus renewable energy, providing backup power via fuel cells during peak demand, and enabling long-duration and seasonal storage. This aligns with the proposed sector-coupled framework, where hydrogen complements EV-based storage to create a multi-layered flexibility system. Overall, the integration of hydrogen and EV storage improves grid stability, reduces reliance on fossil-fuel backup generation, and supports higher penetration of renewable energy.

Sector Coupling and Transport Applications

South Africa's hydrogen strategy targets hard-to-electrify transport sectors, including heavy-duty freight, industrial transport, and long-distance logistics. The Hydrogen Society Roadmap supports the deployment of hydrogen fuel cell vehicles (FCEVs), such as trucks and buses, for applications requiring high energy density and rapid refuelling [29]. This highlights the complementary roles of battery electric vehicles (BEVs) and FCEVs within a sector-coupled system. BEVs are suitable for short-distance and urban transport, while FCEVs are better suited to heavy-duty and long-range applications. Together, these technologies enable an integrated and flexible transport system, where renewable energy is utilised both directly through EVs and indirectly through hydrogen, supporting decarbonisation and reducing reliance on fossil fuels [30].

Economic and Developmental Impact

The development of a green hydrogen economy in South Africa is expected to deliver significant socio-economic and energy system benefits [31]. Hydrogen expansion can support job creation, industrial development, and international investment, while enabling participation in global export markets. In

ISSN 2278-2540 | DOI: 10.51583/IJLTEMAS | Volume XV, Issue VI, June 2026

addition, hydrogen contributes to energy system resilience by diversifying the energy mix, enhancing energy security, and reducing exposure to fossil fuel price volatility. Overall, the hydrogen economy represents a pathway toward sustainable economic growth and reinforces the role of sector coupling in linking energy production with industrial development and transport decarbonisation.

CHALLENGES AND LIMITATIONS

This study has several limitations that should be acknowledged. The proposed framework is conceptual and analytical rather than simulation-based; therefore, it demonstrates the operational principles of sector coupling without providing optimised system performance or detailed numerical validation. The representative renewable energy generation and electricity demand profiles discussed in this study were derived from published literature and publicly available reports, and actual system performance may vary depending on local climatic conditions, electricity demand characteristics, renewable resource availability, and infrastructure development. Furthermore, comprehensive techno-economic analysis, life-cycle assessment, optimisation of system components, and detailed cost evaluation were beyond the scope of this research. The successful implementation of the proposed framework also depends on several external factors, including supportive government policies, investment in renewable energy and hydrogen infrastructure, the rate of electric vehicle adoption, and the deployment of smart grid technologies, all of which vary considerably across developing economies. These limitations provide opportunities for future research involving detailed simulation, optimisation, and techno-economic assessment to further evaluate the feasibility and scalability of the proposed sector-coupled framework.

Relevance to the Proposed Framework

The South African case study provides strong support for the hydrogen component of the proposed sector-coupled framework, demonstrating how renewable energy can be effectively integrated with hydrogen production, storage, and transport applications in practice. Table 2 presents a comparison between key elements of the framework and their real-world implementation in South Africa.

Framework Component	South Africa
Renewable energy input	Solar-powered electrolysis systems
Hydrogen production	Large-scale and pilot electrolysers
Long-term storage	Hydrogen as seasonal energy storage
Transport integration	Hydrogen for heavy-duty vehicles
Sector coupling	Power → Hydrogen → Transport

Table 2. Sector-coupled framework in relation to South Africa [30]

The data in this table are derived from published studies and policy reports on hydrogen development in South Africa and are intended to illustrate the alignment between the proposed framework and real-world applications rather than provide precise quantitative analysis. The results show that key elements particularly the integration of renewable energy with hydrogen production are already being realised. Solar-powered electrolysis demonstrates how variable renewable energy can be converted into a storable energy carrier, improving flexibility and reducing curtailment. In addition, hydrogen-based applications in heavy transport highlight the extension of sector coupling beyond the power sector. Overall, the South African case confirms the feasibility of the proposed framework and the role of hydrogen in enabling long-duration storage and decarbonisation of hard-to-electrify sectors.

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DISCUSSION AND PRACTICAL IMPLICATIONS

The proposed sector-coupled framework enhances renewable energy utilisation by coordinating renewable generation, hydrogen storage, and electric vehicle (EV) integration within a unified system. Surplus renewable electricity is redirected to hydrogen production and EV charging, reducing curtailment and improving flexibility. EVs, through vehicle-to-grid (V2G) functionality, provide short-term storage and grid support, while hydrogen enables long-duration energy balancing, creating a complementary multi-layered storage system that improves grid stability and supports transport decarbonisation. The Kenya and South Africa case studies demonstrate the practical applicability of this approach, highlighting sector coupling as a viable pathway toward low-carbon energy systems in developing economies. Compared with conventional systems relying on grid expansion or standalone storage, the proposed framework enables improved energy balancing across multiple timescales through the integration of EV batteries and hydrogen storage. However, challenges remain, particularly the high capital cost of hydrogen infrastructure and constraints related to scalability, grid capacity, and regulatory frameworks. These may be mitigated through declining technology costs, improved renewable energy utilisation, and potential revenue streams from V2G services. The modular structure of the framework supports phased implementation, beginning with EV integration and gradually incorporating hydrogen systems. Overall, the framework enhances grid flexibility, energy resilience, and decarbonisation potential, although future work should focus on detailed simulation, optimisation, and techno-economic analysis to validate large-scale deployment.

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