

Development of Hybrid Renewable Energy-Powered Drilling Rig Systems for Sustainable Irrigation in Semi-Arid Regions: A Review with Reference to Nasarawa State, Nigeria

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Abstract: *In semi-arid countries of Sub-Saharan Africa, such as Nasarawa state in Nigeria, low grid electricity access, expensive fuel prices of ground water pumping and unreliable rainfall limits agricultural output. Energy nexus innovations provide opportunities of sustainable irrigation through linking the renewable energy frameworks (solar, wind, hybrid) with the borehole drilling and pumping facilities. The review is a synthesis of theoretical foundations and conceptual frameworks, empirical evidence and efficiency of renewable energy-powered drilling and irrigation systems. Three primary streams are pointed out in the review: A case study will be conducted on the following: (1) climate variability, agricultural demand and groundwater; (2) design of renewable energy system to water abstraction; and (3) techno-economic and environmental discussions of renewable systems against conventional systems. The important conclusions indicate that solar-PV and hybrid systems have the potential to cut operations cost and carbon emission in comparison to diesel pumps (e.g., Solar or Diesel: A Comparison of Costs for Groundwater Fed Irrigation in Sub Saharan Africa Under Two Energy Solutions). Nonetheless, adoption is still impeded by social economic, institutional and power-quality issues (e.g. Adoption of solar powered pumps in agriculture: insights into smallholders in Burkina Faso). There is a lack of research on hybrid solar-wind-battery systems to support drilling rigs, optimisation through GIS/MCDA, and the problem of power-quality in off-grid environments. We put forward an integrated simulation-based design, life-cycle techno-economic and adaptive governance model agenda in Nasarawa State. The review is used as a reference among scholars, policy makers and practitioners interested in duplicative research concerning such agro-ecologies.*

Keywords: renewable energy, irrigation, solar-wind hybrid, techno-economics, drilling rig system.

INTRODUCTION

The national GDP and is the main source of employment to almost three-quarters of the rural population [1]. The sector has potential, but it has been plagued by chronic productivity limits especially in semi-arid areas like the Nasarawa State where the small holder farmers rely on rain fed systems. Unpredictable rain, frequent drought and the long dry season have also increased the food insecurity situation and this has necessitated the need to have stable irrigation mechanisms [2]. The inability to access grid electricity in most of these communities also restricts the power of water abstraction systems, as they have to rely on the use of diesel-powered pumps, which are quite expensive and harmful to the environment. High prices of fuel and lack of good energy infrastructure have led to a sustainability bottleneck in the agricultural value chain. With Nigeria on the path toward the realization of the United Nations Sustainable Development Goals (SDGs), the need to include renewable energy technologies in agricultural water systems is becoming a strategic necessity [3]. This is a critical review of how drilling and irrigation systems run on renewable energy may address these structural challenges in Nasarawa State and other agro-ecological areas.

Groundwater availability is now a vital adaptation approach to variability of rainfalls in semi-arid regions. Nonetheless, borehole construction and irrigation systems are still energy-intensive and out of reach of farmers in the rural regions [4]. Traditional drilling rigs that run on diesel power produce high volumes of carbon dioxide, which pollute the area and lead to global warming. The renewable power systems (solar photovoltaic (PV), wind, and hybrid models) have become cleaner options that can supply the power to both the drilling and pumping operations in a sustainable way [5]. However, the spread of these systems is not quite widespread because of the high cost of initial investment, the absence of technical capacity, and the insufficient policy environment [6]. This review is aimed to explore the technological-economic viability of the integration of renewable energy in the agricultural drilling business in Nigeria with references to their efficiency, cost-effectiveness, and their scalability. Moreover, it examines the way hybrid renewable systems (solar, wind, and battery storage) can address the problem of intermittency with single-source renewables.

Interconnection of energy, water, and agriculture is the core concept of the Water-Energy-Food (WEF) nexus that has become a world-renowned approach to sustainable operations of resources [7]. In this nexus, renewable energy is an enabler technology, which can strengthen the reliability of irrigation and eliminate the reliance on fossil fuels. When it comes to the state of Nasarawa, the implementation of renewable-powered drilling and irrigation will have the power to change the agricultural production level and foster environmental responsibility. Nevertheless, the functioning of the supply and demand of resources, energy efficiency, and socio-economic factors is dynamic, and it is necessary to understand these interdependencies in order to develop effective systems [8]. The paper thus places the interface of renewable energy and irrigation in the context of climate-water-agriculture nexus, basing on the best practices on the same as well as empirical

studies of the region. In this way, it helps address a gap that is paramount in the literature: the role of the systems of drilling powered by renewable sources as part of sustainable irrigation systems.

The solar and hybrid technologies have enhanced significantly the performance and reliability of off-grid water infrastructure [9]. Solar photovoltaic (PV) systems are being incorporated into irrigation systems in most regions of Africa in order to allow year-round farming and to survive drought. However, the existing literature has focused on surface water pumping without paying much attention to the drilling stage involved in exploiting deep aquifers in semi-arid areas. Renewable energy technologies used to borehole drilling be not studied extensively, though it is crucial when it comes to developing groundwater [10]. The gap here requires an outright assessment of system design, efficiency of energy conversion, and cost effectiveness, in relation to the activity of drilling. This review integrates both theoretical modelling and empirical research to evaluate the sustainability and feasibility of renewable-powered drills systems under Nigerian climatic and geological conditions. On the economic front, irrigation systems powered by renewable energies have shown that they have the potential to reduce operational costs in the long run, even though initial investments are significantly high [11]. In the last ten years, the price of solar modules decreased significantly, and it has become possible to apply off-grid solutions in rural locations [12]. Additionally, energy storage technologies have been incorporated that improved reliability and reduced the downtimes of the systems. Nevertheless, the restriction of access to credit, inadequate maintenance facilities, and unreliable policy incentives remain the obstacles to extensive adoption in Nigeria [13]. In order to solve these obstacles, this review highlights the relevance of local manufacturing, capacity-building, and public- private partnerships as an important facilitator of sustainable deployment. The strategies are in line with the national renewable energy policy goals of Nigeria and global climate changes commitments of the Paris Agreement.

Renewable-powered drilling and irrigation systems are of great benefit to the environment in terms of minimizing greenhouse gases and the use of natural resources. Borehole drilling using diesel also pollutes the air and air, and has long-term health and ecological effects [14]. On the other hand, solar and wind systems are non-polluting and do not emit much noise, which helps to increase the quality of air and health in rural areas. In addition to the emissions removal, renewables are also related to the lack of pressure on the ecosystem because groundwater abstraction can be controlled during the design of smart monitoring systems [15]. These merits support the case of mainstreaming renewable energy in agricultural water infrastructure as one of the aspects of low-carbon rural development of Nigeria. But proper integration of the policies and monitoring systems is still needed to establish environmental sustainability and resilience over the long term. Lastly, this review finds the gaps in research and suggests the roadmap of future research and policy interventions. System-level modeling, including the combination of hydrological, energy, and economic parameters to optimize the drilling and irrigation configurations powered by renewable is urgently needed. Besides, the interdisciplinary study needs to explore the behavior of its user adoption, socio-cultural acceptance, and the economic consequences of switching to use of renewable-based systems instead of fossil fuel [16]. The

purpose of this paper is to not only synthesize the existing literature but it will also give concrete policy suggestions to the policymakers, engineers, and development practitioners. The focus on Nasarawa State is a microcosm to draw the general issues in semi-arid regions of Africa. The results are thus placed to impact on the national policy-making as well as the international debate on sustainable energy shift in agriculture.

Conceptual and Theoretical Foundations

Sustainable Agriculture and the Energy-Water-Food Nexus

Sustainability in agriculture Embodied in the sustainability paradigm is the goal of optimizing both productive and environmental processes to ensure current food systems do not preclude future generations from meeting their ecological or social needs [17]. This sustainability model is of particular interest in the semi-arid and off-grid agricultural setting such as found in Nasarawa State, Nigeria, where energy scarcity and water stress are both limiting factors to productivity. The EWF Nexus offers an analytic approach to comprehending the interrelations of the three resource domains and their key dependencies [18]. In this interconnection, irrigation requires predictable energy supplies but the generation of energy is in many cases reliant on water availability – generating circular dependencies that have to be managed collectively. Low-carbon decentralized energy solutions for water abstraction and distribution such as renewable-powered drilling and irrigation systems directly tackle this challenge [19]. By reducing dependence on fossil fuels, renewable technologies help cut greenhouse gas emissions, protect groundwater resources, and strengthen agriculture's ability to cope with climate-related shocks. Integrating these technologies within the Energy-Water-Food (EWF) nexus directly supports several Sustainable Development Goals (SDGs), such as SDG 2 (Zero Hunger), SDG 7 (Affordable and Clean Energy), and SDG 13 (Climate Action).

However, putting the EWF concept into practice in developing countries comes with major challenges, particularly those linked to weak coordination and institutional inefficiencies. In Nigeria, for example, agricultural energy systems often operate independently, with minimal collaboration between energy planners, water authorities, and agricultural departments. This lack of coordination hinders effective resource management and can result in issues like groundwater overuse or energy wastage [20].

Adopting a nexus-based strategy encourages stronger policy coherence across sectors and promotes the integration of clean technologies into agricultural planning. A practical example is the use of solar photovoltaic (PV) systems combined with smart irrigation scheduling tools, which can help balance energy and water use while improving overall crop productivity [21]. Moreover, the nexus framework makes it possible to evaluate trade-offs and potential synergies among sectors, giving policymakers the evidence they need to design more sustainable agricultural systems powered by renewable energy. In this way, the EWF approach serves not only as a guiding concept but also as a valuable decision-making tool for driving systemic and sustainable innovation.

Systems Theory, Innovation Diffusion, and Resilience

Systems Theory serves as a useful framework for examining how renewable energy is integrated into agricultural water systems. It treats agriculture as a complex social and technical arrangement made up of several interdependent parts: the physical elements such as energy and water infrastructure, the social components including farmers, institutions, and markets, and the environmental systems shaped by climate and ecological processes [22]. These parts interact constantly, and their relationships create feedback loops that determine how well the entire system performs and adapts over time.

In the case of irrigation or water pumping systems powered by renewable energy, these feedbacks are reflected in practical ways—for example, how the supply of energy influences irrigation frequency, which then affects soil moisture, crop yield, and local groundwater balance. Designing an efficient system therefore requires understanding where meaningful interventions can have the greatest effect. These leverage points can take many forms, including technical capacity-building for farmers, financial incentives that make renewable technologies more accessible, and policy or governance reforms that support broader systemic improvement [23]. From this perspective, systems thinking encourages policymakers, engineers, and researchers to view agriculture as a network of interrelated elements in which technology, human behavior, and institutional frameworks evolve together to achieve long-term sustainability.

Alongside this, the Innovation Diffusion Theory (IDT) developed by [24] explains how new technologies spread and gain acceptance among users. The rate at which renewable energy technologies are adopted in agriculture largely depends on how potential users perceive them. Farmers tend to weigh the benefits the technology offers, its compatibility with their current farming methods, how difficult it is to operate, whether it can be tested on a small scale, and how visible its outcomes are to others. In many rural parts of Nigeria, however, the spread of such innovations has been relatively slow. This is often due to practical challenges such as limited technical knowledge, poor access to credit, and inadequate maintenance or after-sales support [25]. Nevertheless, evidence from various pilot projects suggests that when farmers are given the chance to observe renewable systems in action—through local demonstrations or hands-on training—they become more open to adopting them. Seeing tangible results, such as reduced fuel costs and improved crop yields, helps to build confidence and encourages wider acceptance of new technologies. When farmers witness outcomes like better yields or reduced spending on diesel fuel, they become more willing to switch to solar irrigation systems [26]. Hence, the Innovation Diffusion Theory provides practical guidance for promoting renewable energy adoption by addressing the social and institutional factors that influence people's willingness to innovate.

Resilience in Renewable-Powered Irrigation Systems

Resilience Theory provides a complementary approach as it focuses on the ability of the system to change and get flexible in times of stress [27]. Within the framework of the irrigation powered by renewable energy, resilience is the measure of how the system can be able to provide water in spite of changes in solar radiations, wind velocity, or ground water levels. This theory describes the

importance of redundancy, diversification, and flexibility in developing an energy system. These principles are reflected in the hybrid renewable designs (that isolate and render solar PV systems and wind energy more efficient due to the battery storage) so that energy can be constant even during unfavorable circumstances [28]. Moreover, using intelligent monitoring solutions will also increase adaptive capacity by making real-time changes in water abstraction rate, guided by environmental feedback. Resilience thus cannot be considered as an aesthetic quality but a process where there is learning and self-organization within the socio-technical systems. To make the resilience more robust, it is essential to invest in hardware and the governance systems, knowledge networks, and the local institutional capacity.

Socio-economic and policy aspects of resilience are also seen in a wider context. The availability of spare parts, maintenance skills and financial reserves can be instrumental in increasing the resilience of farmers who need to be able to continue irrigation in times of energy or climate disruption [29]. Policy frameworks that facilitate decentralized renewable systems, put up local repair centers and microfinance of replacement items can go a long way in improving the outcome of resilience. In addition, community-based ownership models have also been identified to enhance long-term sustainability of the systems as opposed to top-down interventions [30]. Therefore, in renewable-powered agricultural systems, the concept of resilience is multidimensional: The concept of technical resilience, social integration, and institutional flexibility. By incorporating these dimensions, it is possible to make the process of energy transition in the agricultural sector not only fair, but also lasting in the uncertain environment.

Key Concepts and Definitions

A drilling rig system within the agricultural setting is used to include borehole drilling and casing, pumping, and water abstraction system [31]. These systems are normally power-consumptive systems whose power requirement differs depending on the depth of the drilling, hardness of the formation and the water table. The replacement of diesel with renewable-powered rigs presents some of the engineering issues that are uncommon, including the regulation of varying power quality and torque demand. A hybrid renewable energy system would be a combination of solar PV, wind turbines, battery storage and sometimes back up diesel generators that would provide a flexible supply of power that can meet these intermittent loads [32]. The configuration option is determined by availability of resources at the site, parameters of cost and preferred degree of reliability. Levelized Cost of Electricity (LCOE), Net Present cost (NPC), Internal rate of return (IRR), and Payback period are techno-economic parameters that are important in analyzing the performance of the system and its economic viability [33]. Lastly, it is important to keep the power quality, i.e. reduce the variation in voltage, harmonic, and instability, to prevent damaging of drilling motors and ensure a stable operation in an off-grid environment.

All of these theoretical frameworks put up the theoretical structure of the present review. This framework, based on the EWF nexus, Systems Theory, Innovation Diffusion, and Resilience perspectives, enables us to understand comprehensively how drilling and irrigation systems which are powered by renewables will change semi-arid agriculture. The combination of these theories

brings out the fact that technology is not sufficient to bring about sustainability and is supposed to be complemented by social learning, adaptive governance and economic viability. These frameworks can be applied to make a multidimensional assessment of renewable technologies as explained further, as a mean of balancing performance, socio-economic acceptance, and environmental impact. This combination is consistent with the epistemological development of sustainability science, which suggests trans-disciplinary, systems-oriented, investigation of intricate socio-environmental issues [34]. This section therefore gives the theoretical-empirical fit between the theoretical understanding and the empirical evaluation of renewable agricultural systems.

Empirical Review: Renewable Energy-Powered Drilling, Pumping and Irrigation Systems

Solar Photovoltaic Pumping and Irrigation

Sub-Saharan Africa has seen a high level of adoption of solar-powered irrigation systems, which is a major technological and policy change of the fossil fuel dependence to clean energy options. A general survey of solar irrigation technologies conducted by [35] revealed that photovoltaic (PV) water-pumping systems are more cost-effective and reliable in operation than those based on diesel especially in off-grid rural areas. Equally, [36] has conducted the life-cycle economic analysis of solar and diesel-powered irrigation systems and found that solar PV had lower total ownership cost and greater net present value at varying groundwater-fed irrigation sites in sub-Saharan Africa. These results highlight the economical sustainability of the solar energy in the rural farming systems of the long term, even though the initial costs are high. This was further elaborated by [37] in the context of agrivoltaic models which combine solar PV panels with crop farming, noting that a further combination of energy and land use can make it more efficient and resilient. These systems of integrated designs would solve the problem of land-use conflicts and provide dual productivity, which would promote both food and energy security goals. Nevertheless, there is still a relative paucity in the literature with respect to the specific adaption of PV-powered systems when it comes to the drilling rig operations where high torque and short-duration bursts of energy are needed. The gap indicates that a specific study on modeling and hardware optimization is required in order to adjust PV technologies to the changing load patterns of drilling rigs under semi-arid conditions.

System design characteristics including pump efficiency, hydraulic head, solar insolation, as well as battery autonomy are important in determining energy performance of solar irrigation [38]. Research has found out that optimization of a system by correct sizing of modules, MPPT controllers and storage elements considerably improves daily water output and efficiency in the use of energy [39]. Nonetheless, there are still operational issues, such as dust deposition, problems with inverters, and seasonal changes in irradiance usually hamper the performance of the system and reduce the reliability in dry seasons when the demand on irrigation is greatest [40]. In semi-arid regions, such as Nasarawa, where ambient temperatures have the potential to decrease PV performance by up to 15, the hybrid system integration (i.e., solar + wind power or solar + diesel backup) gains more significance. Thus, although solar PV is a potentially viable and economical

approach to sustainable irrigation, system resiliency and flexibility are included in the key factors to the success over time.

Hybrid Renewable Systems and Agricultural Water Use

Current empirical studies have centered on hybrid renewable systems, which are solar PV systems in conjunction with wind and energy storage systems, to enhance energy stability and coverage to use in agriculture as the source of water. The latter was investigated in [41] exploring the case of hybrid solar-wind-battery systems in agricultural pumping in Iraq, and found out that optimal system design can lower the cost of operation up to more than 30 percent without compromising the reliability of water delivery. Other related modeling efforts in other areas of East and West Africa reveal that hybrid systems are superior to standalone PV in the assurance of constant power provision especially in the fluctuating irradiance and day-night wind characteristics [42]. Although this has been achieved, little has been done on the drilling rig-specific energy profiles, which are intermittent, high-load energy requirements when penetrating a borehole and casing. The existing models are mostly aimed at constant irrigation loads as opposed to variable drilling cycles and hence lack empirical evidence on the performance of hybrid systems in drilling. There is need to fill this research gap to come up with renewable-powered borehole systems that will enable them work effectively without having to rely on the grid.

Besides, hybrid systems can facilitate integrated water resource management (IWRM) through the integration of power generation with intelligent monitoring of the abstraction and recharge into the aquifer [43]. Practically, by integrating real time sensor data and renewable system controls it is possible to perform adaptive pumping which can be optimized to match the sustainability goals of groundwater. This method is more applicable in Nasarawa State where over- extraction and seasonal change of recharge are threats to shallow aquifers. Hybrid systems therefore are not just a case of the engineering enhancement but an instrument of instilling strength and sustainability in the concept of agricultural water governance. They however need more advanced operation and maintenance capabilities and technical training on how to use them by the rural users. As a result, the adoption of hybrid technologies in the agricultural sector should strike a balance between the increase in performance and social and institutional preparedness.

Socio-Economic Determinants and Adoption Studies

Empirical literature on adoption points out to the fact that failure of renewable energy technologies in the agricultural practice is not as related to technical performance as it is to social and economic factors. A study carried out in [44] ranked gender, education, size of farm, household income and group membership among the predictors of solar pumps adoption as it concurs with the changes in the diffusion theory of compatibility and relative advantage [45]. Nigeria has evidence-based research founded on field-based research on Adamawa and Katsina States that show that solar-pump interventions contributed to increasing the intensity of the cropping, reducing diesel expenditure, and increasing net earnings of farmers [46]. Nevertheless, the issue of sustainability still persists, such as a lack of appropriate financing systems, insufficient maintenance services, and the lack of spare parts that can easily result in untimely system failures [47]. Such conclusions

stress the importance of the fact that renewable energy shifts in agriculture should be accompanied by institutional and financial innovations including microcredit programmes and ownership models based on cooperatives.

Moreover, socio-cultural forces are also important factors that influence the pattern of adoption. The trust farmers have in the technology suppliers, the approval of the local leadership, and their perceived ease of maintenance are all always associated with the high uptake rates [48]. Systems seen to be complex or foreign, on the other hand, are likely to be rejected, even in circumstances where they are technically more advanced. Therefore, participation design methods, in which the final-users take part in the decision-making, can enhance adoption and long-term maintenance greatly. Notably, policies that aid the adoption of renewable energy in agriculture must not only be gender inclusive but also local capacity-building since women farmers are not always considered in technology trainings but constitute a large percentage of smallholder farmers [49]. Overall, culture and socio-economic preparedness are essential pillars of effective integration of renewable energy in agricultural water systems.

Power Quality, Water-Energy Efficiency, and System Performance

Main determinants of reliability of renewable-powered drilling and irrigation systems are technical performance and power quality (PQ). Research has determined that the main factors that cause performance decline in off-grid renewable pumping systems are voltage variations, harmonic distortions, and failure of inverters [50]. Due to poor PQ, the overheating of motor and shortened life of pumps and inefficiencies may counter the environmental advantages of renewables. In the case of drilling rigs, where motor loads are dynamic and torque is high, it is even more important to maintain PQ. According to [51], voltage and current distortions could be prevented by the proper size of inverters and filters, which enhanced the efficiency of converting energy to up to 12 percent. In addition, harmonics that are caused by variable frequency drives (VFDs) have to be managed carefully by modeling the system and choosing the components. These results indicate the relevance of PQ consideration in renewable system design and simulation particularly when it comes to mechanical drilling activities.

In a broader systems view, the perspective of high water-energy efficiency consists of a set of trade-offs, which include, but are not limited to, optimizing water output per kWh, reducing equipment degradation, and reducing storage losses [52]. The development of simulation software (MATLAB/Simulink, and RET Screen) enables the PQ dynamic and energy flow modeling and optimization via optimization of the system configuration at any renewable system scale [53]. Experimental analyses indicate that the use of smart controllers and energy control algorithms can dynamically adjust the energy used by the drilling and irrigation processes in order to produce greater system efficiency. However, it is still difficult to translate these technical innovations into the field conditions because of the lack of knowledge and skills in maintenance and insufficient access to diagnostic means. Consequently, to enhance PQ and performance, technological perfection and capacity building of rural technical ecosystems is necessary.

Technology and Design Review: Drilling Rig Systems Powered by Renewables

Use of renewable energy in drilling rig systems has emerged to be a paradigm shift in ensuring sustainable drilling of ground water in semi-arid farming areas. Water demand, energy needs of irrigation and drilling are core knowledge to the design of a system. Water demand can only be correctly estimated by taking into account the following factors: crop type, evapotranspiration, soil properties, and climatic variables, which can be modeled with the help of such tools as FAO CROPWAT or AquaCrop [54]. Nonetheless, the energy profiles of the drilling (high torque and periodic peaks) are quite different to continuous irrigation pumping loads [45]. Crop water demand and drilling motor energy have not been studied as a simulation framework, which is an area of research gaps in energy optimization and groundwater sustainability models [46]. In the case of Nasarawa State, this kind of integrated modelling is necessary due to the heterogeneous nature of the aquifer as well as the seasonal rate of recharge of the ground water.

The multidisciplinary approach to designing hybrid systems of renewable systems that combine energy engineering, hydrology, and the science of agriculture is required when designing hybrid systems of drilling and irrigation. The standard system is the solar photovoltaic (PV) arrays, wind turbines, battery power storage, and optional diesel or grid backup [27]. The process of designing starts with site-specific resource analysis, which involves meteorological analysis to calculate the distribution of solar irradiance and wind speed (to satisfy the power requirements of the drilling rig), and optimal component sizing [38]. Complex design software like the HOMER Pro and MATLAB/Simulink have been used to optimize system designs in various conditions of load and climatic conditions. It is worth noting that PV-based systems have proven to be cost effective, particularly in areas where there is a problem with the logistics of diesel fuel. However, in the case of drilling rigs with high transient power requirements, hybrid systems with PV-battery systems or PV-diesel systems are more reliable [29].

The expected basis of renewable energy decision in agricultural use is constituted of the techno-economic and environmental assessment. Measures like Levelized Cost of Electricity (LCOE), Net Present Cost (NPC) and Internal Rate of Return (IRR) are used in assessing the viability of the system. According to some studies conducted within the ECOWAS countries, PV-based irrigation is cheaper and has a higher IRR than diesel-powered ones [60]. As an example, a study in Egypt discovered that PV pumping systems without a battery could achieve water pumping at a low cost of 0.015 USD/m³ which was much better than the diesel pumping cost at 0.073 USD/m³ [21]. In a similar way, hybrid solar-wind systems lower carbon emission by more than 60 percent in contrast to fossil-based solutions [22]. In the case of drilling rigs in Nigeria, techno-economic feasibility is anchored on optimization of component size and consideration of seasonal changes in energy, depth of drilling, and operational cycle. Environmental co-benefits are decreased greenhouse gas emissions, less spillage of oil, and management of ground water abstraction in sustainable manner.

Geographic Information System (GIS) and Multi-Criteria Decision Analysis (MCDA) have become a vital instrument in the spatial planning and optimization of the renewable powered drilling and irrigation systems. Resource mapping with GIS makes it possible to visualize solar

irradiance, wind potential, depth of the aquifer, and land-use constraints, and MCDA makes it possible to implement frameworks to use optimal locations based on a variety of criteria, such as energy potential, accessibility, and agricultural suitability [43]. Research in Kenya and Burkina Faso has shown that the combination of GIS and MCDA can be used to increase the system placement efficiency by more than 40 percent compared to random siting methods [34]. Nevertheless, the use of such spatial tools in drilling rig systems is not extensive, which suggests that there is a potential of methodological innovation. The implementation of such methods in Nasarawa State would help determine areas where the synergy between solar and wind is the best, the groundwater potential can be utilized, and the number of environmental conflicts is the minimal.

The merging of renewable energy engineering, hydrological modeling and spatial analytics, therefore, characterizes the new paradigm of sustainable ground water drilling and irrigation. A combination of a sophisticated level of simulation, techno-economic optimization, and GIS-based decision support makes sure that the system of renewable-powered drilling can be regarded not only as technically possible but also as green and cost-effective. Such systems in Nigeria will only be successful under the conditions of developing adaptive management systems that would involve the incorporation of local knowledge, policy incentives, and real-time monitoring technologies. Finally, drilling rigs that run on renewable energies can eventually change water access and agricultural productivity in sub-Saharan Africa to support climate-resilient rural economies and achieve the Sustainable Development Goals (SDGs 2, 7, and 13) [25].

Gaps, Challenges and Research Agenda

Gaps Identified

Solar-wind-battery drilling rigs: Much of the literature deals with irrigation pumping; little has been researched on drilling rig (borehole drilling).

Synthesized simulation models: There is no literature that integrates the crop-water demand, drilling energy load, sizing of hybrid renewable systems, hydraulics (EPANET) and techno-economic modelling.

GIS/MCDA driven site-specific resource mapping: Potential not used in semi-arid Nigeria drilling-rig.

The quality of power and system reliability: The literature to deal with off-grid PQ in drawdown is limited, motor start-up loading, inverter harmonics in drilling/pumping systems.

Socio-economic inclusivity, gender and governance studies: In the majority of studies of technology, land tenure, access to finance, role of females, cooperatives, and maintenance ecosystems are overlooked. Lifecycle and environmental analyses: Although CO₂ savings and LCOE are calculated by many studies, not many are fully life-cycle assessment and few

incorporate the thinking of the circular-economy (waste-to-energy, biomass, agrivoltaics) to the context of drilling rigs.

Key Challenges

High investment requirements and lack of finance to the small-scale adoption.

Rural maintenance, logistics and human capacity of spare-parts. Over-depletion of groundwater and sustainability of aquifers with the face of augmented abstraction under the influence of simple renewables. Fragments of institutions, a poor policy system and poor coordination of stakeholders. Technical incompatibility: pump-motor power, power to store, loss of PV/Wind in dusty locations, Intermittent loads to drill and irrigate.

Research Agenda and Recommendations.

Create built in modelling infrastructure (simulates drilling + abstraction + irrigation loads with a hybrid renewable supply) with hydraulics (e.g., EPANET), energy simulation (MATLAB/Simulink), techno-economic analysis (RETScreen) and GIS/MCDA siting.

Field pilot test to semi-arid regions such as Nasarawa State to test modelled performance, maintenance requirement and services models.

Quality and reliability of study power of off-grid drilling systems such as inverter design, motor startup harmonics, and battery management.

Examples of solutions to the circular economy: agrivoltaics (siting drilling rigs on PV farms and crops), biomass energy in exercises, built-in waste-to-energy on agricultural systems.

Smallholder-based (micro-finance, cooperatives, PPPs, service-contracting) and women and social equity-based commodity finance and systems of commodity governance.

Make groundwater sustainable with the enshrinement of abstraction limits, monitoring, regulatory framework, and linking with drilling powered by renewable energy sources.

Relevance to Nasarawa State, Nigeria

Nasarawa State has a good location in relation to hybrid renewable drilling systems because the solar irradiance (5-5.5 kWh/m²/day), moderate winds and large agricultural potential are favorable. The irrigation requirement, risk related to water scarcity and limitations of energy accessibility combine to make it an ideal location to use in this study. Through the insights of the review, the researchers and practitioners of Nasarawa State can come up with context-sensitive systems integrating solar-wind hybrids, GIS-based site selection over 13 LGAs and techno-economic modelling at the smallholder level of viability.

CONCLUSION

The review has integrated the current literature about renewable energy used in drilling and irrigating systems, has specified main theoretical frameworks, has reviewed empirical research

and outlined technological design challenges, gaps and a research program. Although solar and hybrid renewable systems portend high potential to revolutionize irrigation and drilling processes in semi-arid areas, the issue of power-quality, adoption, financing and groundwater sustainability have to be addressed. The future of sustainable irrigation to the agro-ecologies including Nasarawa State is through integrated systems approach to energy, water and agriculture coupled with stakeholder-based governance and inclusive finance.

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