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Development and Evaluation of Techno-Economic Renewable Energy Viability Index (TEREVI) for Sustainable Distributed Hybrid Mini-Grid Power Generation in Sub-Saharan Africa

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Abstract

Empirically, all notable past and existing renewable energy mini-grid projects in Sub-Saharan Africa have not been commercially sustainable, thus necessitating financial propping by government grants and external funding from donor agencies, else outright run-to-comatose after a few years of operation. A techno-economic evaluation of the proven and probable renewable energy resources cum technologies based on potentials in South-West Nigeria was carried out as a case study using a Multi-Criteria Decision Method (MCDM) based on an Analytical Hierarchical Program (AHP) scheme from which a comprehensive Techno-Economic Renewable Energy Viability Index (TEREVI) was developed. A hypothetical 100 kW mini-grid power plant powered by 1 or more of the 8 2R renewable energy sources was designed. A technical feasibility analysis, followed by HOMER and MATLAB simulation, was carried out. The TEREVI was calculated and used for the Mutative Genetic Algorithm (MGA) scheme for each hybrid configuration. The TEREVI shows a mean of 0.756914 and a standard deviation of 0.075644 with Solar Photovoltaic, Solar–Thermal, Small Hydro, Bioenergy, and Offshore Wind technologies having above mean values and overall best ranking respectively for off-grid power generation and hybridization. The overall results proved that the TEREVI energy model is a comprehensive technique for local and global application in techno-economically assessing, selecting, sizing, planning, designing, and optimizing off-grid power systems based on existing renewable energy resources and local variables for self-sustainable commercial mini-grids in Sub-Saharan Africa.

Keywords: TEREVI, techno-economic renewable energy, sustainable mini-grid, Sub-Saharan Africa, hybrid energy system, southwest Nigeria.

Introduction

Inadequate and epileptic electric power supply like in most of Sub-Saharan Africa is Nigeria's biggest challenge in meeting the Social Development Goal (SDG7) given a paltry per capita power generation of 20W based on an average baseline power output of 4000MW compared to peers like South Africa, 951W; Brazil, 801W; Egypt, 541W; China, 1264W; Malaysia; Indonesia 1200MW; Pakistan; Russia, 1528W; and so on. Even at that supply is only available less than 40% of the time for the less than 65% of the population connected to the national grid (Akpan, 2023; USAID, 2021; USAID, 2022; ITA, 2023; Mordor Intelligence,2023; IRENA, 2022; CEP, 2021; Worldometer,2023).

Equally troublesome is the weak 5,000Km transmission system (Ademola et al, 2021) with an actual wheeling capacity of just 7,500MW and a prohibitive line loss of over 30% tailings on an equally poor distribution system occasioned by obsolete, substandard, and low - end components besides the intractable problems of energy theft, weak bill collection and shoddy accounting structure, administrative inefficiencies, technical lapses, and poor political will (The Cable, 2022; Okwori, 2011).

A metaphor of the troubling power sector is frequent grid collapse as a result of which there have been over 222 incidents between 2010 and 2022, primarily due to the lack of a redundancy (N–1) configuration. This has led concerned experts and international institutions to lend their voices in favor of unbundling the national grid, as well as massive investment in renewable energy-driven micro- and off–grid power systems, as medium- and long-term solutions. This is especially imperative for the unconnected rural, peri-urban, and stranded settlements, which will, in addition to numerous direct and indirect benefits, bring about the stemming of rural – urban migration, enhanced socioeconomic advancement of communities, and attraction of opportunities and amenities such as roads, schools, healthcare centers, and agro – allied industries (Tajudeen, 2022).

However, the development of non - hydro renewable energy in Nigeria has been disappointingly poor and most real efforts have been from individual and private sector initiatives, while in the same breath, the highly commendable 25million Solar Home Initiative by the Rural Electrification Agency (REA) is yet to gain traction or yield a tangible success let alone contribute to the national grid (Osinachi-Nwandem, 2024; Eghobamien et al, 2021).

Despite spirited efforts and passionate drives by some private and public decision makers at various levels and locations on off – grid renewable energy driven power generation, there has not been any tangible sustainable success recorded due to inadequate techno – economic analysis arising from the lack of a comprehensive tool for evaluation like the Techno – Economic Renewable Energy Viability Index (TEREVI) so developed in this research to thoroughly address every key risk element. The TEREVI will help to optimize, design, plan, accurately cost, and effectively operate and maintain renewable mini-grid power plants sustainably throughout their lifecycle.

Due to the geolocational peculiarity of renewable energies, the TEREVI for this study is developed as a globally applicable model with high sensitivity to local constraints using Southwest Nigeria as a case study for local adaptation. Hence, the candidate energy sources are limited to those available in South–Western Nigeria. South – Western Nigeria is the country's most industrialized geopolitical zone and Africa's 5th largest economy with a Gross Domestic Product (GDP) of about $200billion and endowed with large swaths of arable land, variegated tropical forests, and a long coastal stretch as well as generous renewable energy potentials, numerous inland water bodies and mineral resources among other things. Hence, a proven template like the TEREVI being developed and adapted for South–West Nigeria will serve as a model and catalyst for renewable energy and microgrid development across Nigeria, Sub-Saharan Africa, and the world at large (Eludoyin et al, 2023; Eghobamien et al, 2021).

1.0. Literature Review

Owing to the challenges arising from the lack of a comprehensive, suitable indicator to effectively model and ease the design, development, planning, data acquisition, investment, governance, and policy decision-making in renewable energy generation technologies, several studies by corporate and academic researchers and groups as well as international energy, finance, professional, and scientific institutions have geared efforts towards evolving a workable renewable energy index (Hashim, 2021; Zhang & Leng, 2023; IRENA, 2024).

Zhang and Leng (2023) and Dirmitas (2013) used Analytical Hierarchy Process (AHP) based Multi–Criteria Decision Making (MDCN) methodology integrated with Game Theory in analyzing renewable energy-generating sources for the selection of the best- power options from a list of indicators factoring technical adaptability, social acceptability, environmental impact, and economics for renewable energy planning in Turkey based on wind, solar, hydro and geothermal energy resources using pair – to – pair comparison to determine criteria weights.

Fuller (2005) analyzed and evaluated the sustainability of renewable energy generation based on a list of four impact factors using Futurity Principles, Environmental Principles, Equity Principles, and Participation Principles, drawing inferences from the Rio Declaration 2003 and various United Nations energy transition and climate change policies in a practical sense.

Warren et al (2019) reviewed Ernst and Young's Global Energy and utility biennial Renewable Energy Country Attractiveness Index (RECAI) based on five pillars; each with its dataset inspired by energy transition and climate change ideals which include: Macroeconomics fundamentals, energy development is imperative, imperative, especially with resource data history and availability, enabling business environment policy framework, existing or supporting components of renewable energy project delivery success, and technology which it conducts with a periodic (biennial) list of top 40 RECAI countries since inception in 2003.

Afgan et al (2000) as well as Afgan and Begic (2007), used MCDM to analyze and evaluate energy generating sources based on various indicators and weighing system, while Wang et al (2006) factored technical, economic, social and environmental indicators for evaluating the sustainable energy generation models.

Jaganmohan (2021) in his RECAI ranked countries based on renewable energy attractiveness on a bi-annual basis with scores ranging from 0 to 100. 100 is the assumed score of the highest-ranked country, wherein its respective score is used as a benchmark for ranking the rest countries as a percentage ratio to the given dataset of variables.

Cristobal (2011), Kahraman et al (2009), Kaya and Kahraman (2010), and Ornut et al (2008) used various MCDM AHP tools such as fuzzy VIKTOR for the determination of renewable energy projects, Axiomatic Design (AD) and AHP for optimizing renewable energy options in fuzzy systems, fuzzy AHP and VIKTOR model for energy system planning, and Analytical Network Process (ANP) to resolve energy resource selection, respectively.

The EY's specific technology ranking is a weighted average across the various candidate technologies under consideration. Ernst & Young (EY) weighs each dataset, parameter, and pillar based on its perceived importance, relevance, or influence in enhancing investment and development planning and decisions with respect to historical and projected investments.

A key determinant of each technology's application of scores is due to market biases and differential favor towards certain technologies compared to others. Some markets tend to be technology-biased and more favorable to some than others.

Hashim (2021), researched and developed the Renewable Energy Index (REI) based on three factors' data evaluation, namely: quantitative renewable energy production, consumption of renewable energy, and electricity production from renewable sources for economic analysis which reveals the REI range for 142 countries to be zero to 69.5 with a mean of 23.1; with non – oil countries typically ranking better than oil-producing ones.

Standard and Poor's Dow Jones Index (S&P DJI), TSX Renewable Clean Energy Technology index in 2022 has criteria drawn from codes generated in collaborative alignment with Revere Business Industry Classification System (RBICS L6) designed to push investors toward businesses whose economic activities promote innovation, sustainable development, climate-friendly activities, waste reuse, and ecological conservation. The list of businesses is sieved based on the criteria drawn by Sustainalytics, a globally renowned institute in the environment, sustainability, and governance research. S&P Global Clean Energy 3.5% Decrement Index is designed as a performance measure of the S&P Global Clean Energy Index, discounting the annual fixed fee of 3.5%.

The S&PDJI uses its Pure–Play Analysis scheme for screening candidate businesses by which the process a company must earn at least 50% of its revenue from any one or more of: renewable energy, production, and distribution; renewable energy, manufacturing, and technologies; energy efficiency; waste reduction and water management; Low Impact materials and Products (e.g. organic foods). In furtherance, a company earning 100% of its revenue from, say, solar sales will be accorded Pure–Play status in the energy theme, while the one that earns 40% of its revenue from solar cells and a further 45% from water purification equipment would qualify for inclusion in the S&P/TSX Renewable Energy and Clean Technology Index.

The NASDAQ OMX Green Technology Sector Index, which is published every June since 2016, uses a system of datasets as criteria to track the green performance of its listed securities on sectoral basis similar to the S&P 500 DJI TSX Renewable Clean Energy Technology Index with various groupings and subsets covering various generation source and storage technologies.

World Economic Forum (WEF) in its Energy Transition Index 2021 review uses 39 indicators to derive the score and ranking of 115 listed countries, which are published annually since 2011 as a mark of energy transition efforts by nations of the world or as a sign of progress in renewable energy development and associated Clean Development Mechanisms (CDM) in line with Intergovernmental Panel on Climate Change (IPCC) resolutions

Akinyele D. (2018) highlighted the challenges and potentials for microgrids in achieving a smart, flexible, affordable, and reliable electrical grid for distributed power generation in Nigeria for remote and rural locations in a paper titled *Challenges of Microgrids in Remote Communities*. Soyoye O. (2016) carried out a study on the sustainability of microgrids in comparison to main grids in providing electricity to rural and semi-urban settlements in African countries, as elucidated in his research titled *Microgrids for Sustainable Electricity Supply in African Countries.*

Similarly, Orovwode et al (2014) wrote a paper based on their research on the ability of microgrids to enhance cost-effective and efficient transmission and distribution of electrical energy in Nigeria. Bernd and his team in 2014 revealed the challenges and benefits in advancing renewable energy projects and research using GIS-based technologies. This exposes a major gap in the need for accurate and reliable, easy-to-acquire data on selected geographical areas.

Berthieau, P. et al (2016) worked on *Electrification Modeling for Nigeria* under the EU-Africa Renewable Energy Research Using Surveys and Energy Potentials as Critical Factors for Analysis and Integration for Grid and Standalone Applications. For this, he and his team labored through the processes of seeking information via surveys, which further highlights the importance of a geospatial system that a renewable and hybrid energy project could key into and save time, cost, and expensive design errors leading to inefficient project installations.

Hoyer-Klick (2023) and his team researched and mapped energy potentials based on earth coordinates as a means of optimizing energy production and comparative synergies for power generation ease in varying locations.

Diemuodeke, E.O. et al (2016), carried out an Assessment of Hybrid Renewable Energy Systems for some Coastline Communities in Nigeria based on multicriteria analysis. In his incisive research, he gives some insights on techno-economic issues and factors for suitable renewable energy considerations with reference to the Niger-Delta region of Nigeria as an opportunity for more sustainable energy generation.

Okundamiya et al (2014) throw light on some intricate matters and suggestions of renewable energy choices for projects, especially in telecom infrastructure. Sambo (2009), revealed the progress of some renewable energy projects, such as wind, solar, biogas, and small hydro in some Nigerian rural settlements as a veritable means of providing off-grid power. Vasileiou and Vigiona (2017), in their study, brought to bear the technical feasibility and economic viability of fully utilizing and hybridizing marine energy options using Greece as a case study.

The Renewable Energy Master Plan of Nigeria (2006) highlights the tentative targets and strategies of achieving a significant proportion of renewable energy in the national power mix but says nothing about efficient utilization and synergy of sources based on hybrid power systems as a driver for renewable energy penetration. Trotti (2018) examined the various impacts of power supply failures on businesses, health facilities, social life, and productivity while hinting at the need for energy supply resilience. An estimated \$100 billion is lost annually in the United States owing to power supply failures, and another \$25 billion to power supply quality problems/corrections, even though power failures in the U.S. rarely last beyond a few hours. IEA 2018 Report recommends a global 12-year investment of \$13 trillion up to 2030 if power demand increases are met with generation and transmission/distribution to get 50% of the budget

Virtually all indices so far developed by various studies and research works together with existing indices relating to renewable energy tend to focus on finance and a few on technology, governance, or sustainability, thus leaving out critical real world problems associated with energy generating technologies especially of stochastic sources like most renewable energies present such as energy generation quality and harmonic emission issues, capacity optimization, generation uncertainties and technical risks, transmission and distribution issues, material quality, environmental impact on installation and investment, social constraints, sustainability and so on.

Matter–of–factly, none of the indices, both of the renewable or related energy index, is techno–economic or captures the critical components of technical feasibility, economic viability, energy quality, cleanness, storability, sustainability, market availability, technology growth, and enabling environment. Hence, the Techno – Economic Renewable Energy Viability Index (TEREVI) to be developed in this study will provide technical, economic, sustainability, and environmental insights on cost – effective high-performance renewable energy generation projects using key data leveraging on experiential and global best practice technological knowledge for the prediction, projection, prioritization, planning, and preparation of renewable and hybrid energy project and operational variables such as technical, economic, commercial, ESG(Environmental, Social, and Governance) etc. factors or outcomes.

Furthermore, renewable energy research efforts in South–West Nigeria have been based on very limited and non–evenly distributed data sizes with virtually only 1 to 3 stations for the entire region, which, to a large extent, are not very, if at all, representative of the real–world scenarios. Hence, in this study, more adept efforts are made by increasing the number of stations to 25 data collection points based on average monthly and hourly values for given heights Above Sea Level (ASL), thereby providing much higher accuracy and more specific information of the best-fit geolocations for prospective projects and installations.

2.0. Methodology

The process of developing this Techno-Economic Renewable Energy Viability Index involves seven (7) distinct steps carefully followed through using the international best practices, research and development standards, operating procedures concerning the peculiarities and realistic constraints obtainable in the tropical environment of Southwest Nigeria.

The TEREVI to be developed in this study is based on the RETES criterion acronyms:

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R = Energy Resource Availability

E = Economic Viability

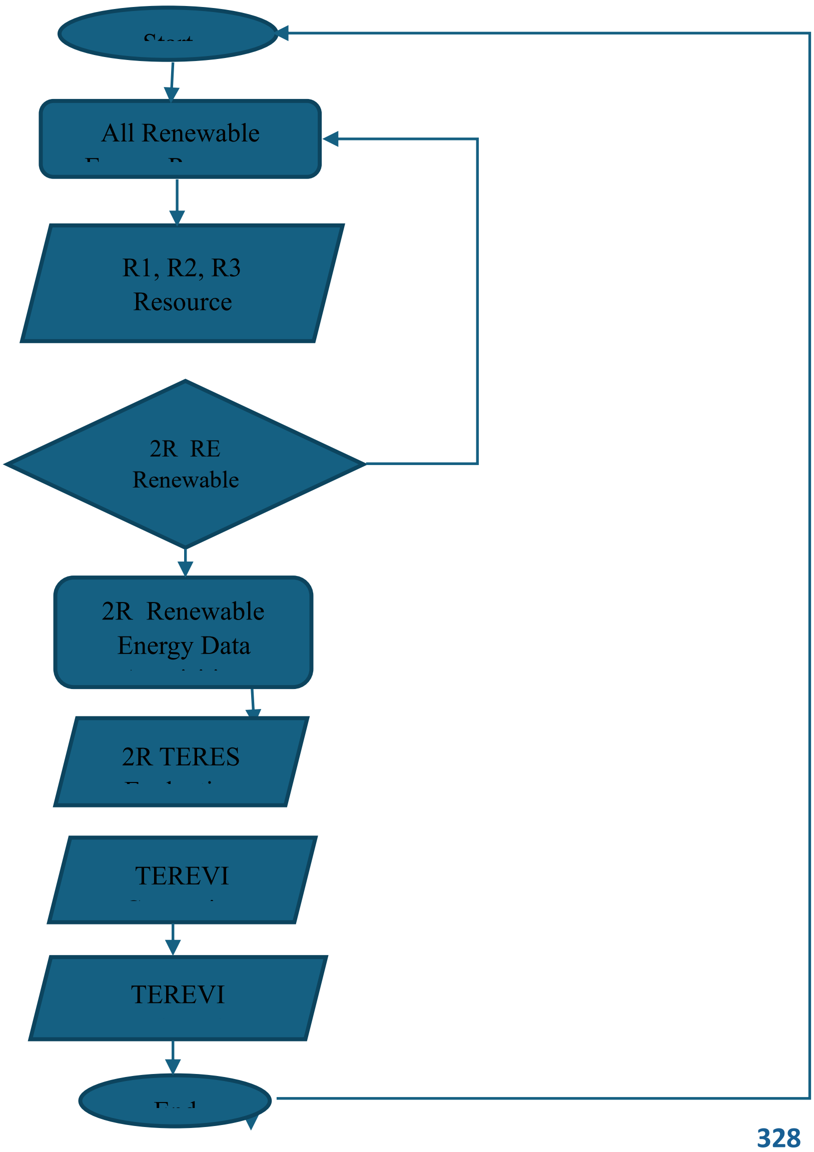
T = Technical Capacity

E = Environmental and Social Impact, including Enabling Business market conditions

S = Sustainability and security of power generation, growth, expansivity, and business continuity in at least a 50-year period

As highlighted in Figure 1.0, the process of developing the TEREVI based on the RETES criteria is via a seven–stage flow sequence viz:

I. Identification of all possible renewable energy resources available in the geopolitical South – West of Nigeria
II. R1, R2, and R3 Classification of identified renewable energy resources
III. 2R Renewable Energy Resource Screening and Selection
IV. 2R Renewable Energy Data Acquisition
V. RETES Evaluation
VI. TEREVI Development
VII. TEREVI Analysis, Simulation, Test and Conclusion



Development

of

Techno – Economic Renewable Energy Viability Index (TEREVI) Process Flow

Figure 3.1

2.1. Step 1: Identification of Available Renewable Energy Sources

The list of available renewable energy resources in South–West Nigeria is compiled based on the availability of natural power generation potential in terms of existing proven(R1), probable(R2), and possible(R3) renewable energy technologies/resources by its geophysical location and meteorology as a tropical coastal area in Sub-Saharan Africa situated at Longitude 30◦E to 70◦E and Latitude 4◦N to 9◦N (Oni and Odekunle, 2016) with diverse vegetation and dual season.

Hence, the broad list of renewable energy resources identified irrespective of potential in the Southwest Nigeria geopolitical zone includes:

I. Solar PV

II. Solar CSP

III. Wind

IV. Offshore Wind

V. Micro Hydro

VI. Biomass

VII. Wave

VIII. Tidal

IX. Hydrogen

X. Geothermal

XI. Ocean Thermal Energy Conversion (OTEC)

XII. Blue Energy Resources

2.2. Step 2: Classification of Renewable Energy Sources

Considering that the available energy resources greatly vary in prospects and potential for practicable investment and development for technical and economic feasibility, it is necessary to streamline the broad list of renewable energy resources by categorizing them into three (3) distinct groups based on qualitative and quantitative potentials, technical feasibility, economic viability and (direct or relative) precedence in using R1, R2, and R3 renewable energy resources for this study.

R1 (or Proven): Are low-hanging fruit renewable energy resources that are plentifully available, affordable, comparatively cheap, sustainable, and of simple proven technologies with components and competence cost–effectively within reach in a given environment, and can be easily developed with existing neighborhood precedence as evidence. R1 is the first point of renewable energy entry into the regional power mix.

R2 (Probable): Are medium-hanging fruit renewable energy resources that are plentifully available, whose conversion technologies are clean, comparatively cheap, with high capacity factors, sustainable, and of great prospect, but with relatively high CAPEX, considerable development time, and challenging technologies. R2 is usually the medium- and long-term energy prospect.

R3 (Possible): Are high-hanging fruits among renewable energy resources. Their availability is very limited, with technology considered underdeveloped or economically impracticable for the time being and therefore subject to long-term research and development, thus treated at best as experimental projects.

R or 1R refers to R1 energy resources, and 2R refers to the sum of R1 and R2 energy resources, while 3R refers to the total R1, R2, and R3 renewable energy resources available in the region under consideration for this study.

Based on available data from the National Renewable Energy Laboratory (NREL), National Aeronautics and Space Agency (NASA) – Langley, Organization for Economic Cooperation and Development (OECD), United State Energy Information Agency (EIA), World Bank and Nuclear Energy Agency (NEA), Nigerian Navy Hydrography Office, Nigerian Institute for Oceanography and Marine Research(NIOMR), Nigerian

Meteorological Agency (NIMET) as well as various research, data collection, energy, and finance groups among other authorities and studies by researchers in consideration of the Southwest Nigeria scenario, the existing renewable energy resources are group thus:

Renewable Energy Potential Classification for South-West Nigeria

R1 – Proven	**R2 – Probable**	**R3 – Possible**
Solar PV	Solar CSP	Hydrogen
Wind	Offshore Wind	Geothermal
Biomass	Wave	OTEC
Micro Hydro	Tidal	Blue Energy Technology

Table 3.1.

From the data collected, solar energy technologies and resources are generally available with 37.5% capacity factor, affordable, technically simple, and doable with at least 9 hours of daily sunlight, fair clearness index, warm climate, and moderate average temperatures in all parts of the region all year round given its tropical location.

Aside from this, several utility-scale solar PV projects have been recorded in the region and other parts of Nigeria, with a 25 million Home Solar project ongoing across the country by the Rural Electrification Agency (REA).

Wind energy resources in the mainland and even coastal areas of the Southwest are generally within 1 – 4 on the Beaufort Scale, with a few locations within 3 – 6. However, the data acquired shows that at least 25% of the region's land mass is technically viable for wind energy conversion for power generation, while the offshore areas, which are on the Atlantic Ocean, present much higher prospects of having well above 3.5m/s wind speed thresholds with much higher Beaufort Scale ranking.

Biomass in various forms is plentifully available in the region like in other parts of Nigeria and is traditionally the main source of energy in the country and still accounts for over 50% of all energy consumption except for power generation where it is still wasted away in terms of landfill gas, biogas from humen, plants and animal wastes or remains as well as combustible municipal solid wastes (MSW). This presents great opportunities for mini-grids, especially for rural and agro-allied electrification. MSW generation in Southwest Nigeria is currently in excess of 7.5MMT per annum, with landfill gas production potential of over 1 billion normal cubic meter (NM^3).

Micro Hydropower in this study refers to hydroelectricity generation below 100MW. South–West Nigeria with a high precipitation rate of up to 3000mm has a long rainy season with a number of high lands, dams, springs, and modifiable streams that will enable both reservoirs and run–of—river micro hydropower generation, especially for rural areas which are easily integrable with Fadama projects for which the region stand a great opportunity to generate up to 500MW or more from various sites combined.

With the glistening pace being recorded in offshore energy technologies, including wave and tidal, and given the high capacity factors, the durability and reliability of these systems, coupled with proximity to higher population densities. Given that over 60% of the global population is concentrated in coastal areas, wave, tidal, and offshore wind together present a great opportunity for medium and long-term baseload power solution for South – West Nigeria since the region is endowed with a coastal stretch of 360Km (Agunbiade et al, 2010; Akomeni et al, 2016) in addition to having fair to promising tidal heights and wave return periods coupled with the advance in lagoon tidal farms based on dataset obtained during this study.

Climate change and energy transition are the primary drivers of hydrogen energy. However, the fact that over 90% of hydrogen globally is produced from natural gas defeats the techno-economic sense aside from the fact that the cost of energy consumed in its production from green sources is hardly justifiable except for energy storage in times of excess power generation not minding the safety issues, storage and transportation difficulties as well as uncertainties surrounding large scale utilization. Hence, hydrogen energy is herein classified as an R3 renewable energy source.

Ocean Thermal Energy Conversion (OTEC), which takes advantage of temperature differentials in the ocean, and Blue Energy Technologies, which takes advantage of the flow gradient between brown waters (freshwater) and blue waters (marine waters) are still very much in their technological infancy and are hardly technical satisfactory with very slow and blurred research and development progress. Hence, these energy sources will be grouped under R3.

As a renewable energy source, geothermal energy is energy derived from the conduction of solar radiation on Earth's surface through high conductivity aquifers as well as the heat from the Earth's core to the aquifers. Geothermal energy sources are viable for power generation only in locations with 20 to 30°C/km geothermal gradient in the uppermost 10 km of the Earth's crust (Kruger,2006).

Geothermal energy potentials do exist in Nigeria to a very limited extent, and then the few known reservoirs like the 37◦C Ikogosi Hot Spring are low enthalpy liquid-dominated reservoirs (LDR), much less than 90◦C which, although useful for other heating solutions, are not suitable for power generation even with enhanced technologies.

South–West Nigeria has a very low geothermal gradient of 1.4◦C/100m – 4.7◦C/100m (Babalola, 1984; Eyinla et al, 2016; Kwaya and Kurowska, 2018) aside from the fact that it lies outside the Pacific Rim of Fire. Hence, geothermal energy is not with the current reserve quality in Nigeria, and the best generation technology obtainable considered for viability in South–West Nigeria and is herein classified as an R3 renewable energy source.

Considering the current realities and techno-economic exigencies for pragmatic energy development in the region, only 2R energy resources shall be considered in this study. All information on offshore energy resources, including wind, waves, and tidal for South–West Nigeria is based on conditions in the Bight (Bay) of Benin within the southwest stretch of the Gulf of Guinea (GoG). The GoG is in this study is defined based on the International Hydrographic Organization (IHO) 2002 convention as the B – Line drawing from Cape Lopez in the Republic of Gabon coast at latitude 0°37′S and longitude 8°43′E to Cape Palmas in Liberia to latitude 0°01′S and longitude 6°32′E) wherein the Bight of Benin extends by 640Km west of South – West Nigeria to Cape of St. Paul in Gabon eastwards to the Nun River Estuary of Bight of Bonny (previously Bight of Biafra) with varying northerly breadths up to 300Km.

Offshore energy resources are strategic in the sense that they are integral to the emerging global blue economy revolution, predictable, reliable, and have short energy transmission distances given that about 40% of the world population is based within 100Km of the coast (EarthData, 2022) and in a similar pattern, over 50% of the population in South-West Nigeria reside within 100Km of a coast even though only 2 of the 6 southwestern Nigerian States are coastal.

The various energy sources for this study in tables and charts or models can be acronymed as follows:

SPV = Solar Photovoltaic

STE = Solar Thermal Energy

WDL = Landed Wind Turbine

WDO = Offshore Wind Turbine

HYD = Hydro Power

BIO = Biomass Energy

WVE = Wave Energy

TDE = Tidal Energy

2.3. Step 4: 2R Renewable Energy Data Acquisition

Data gathering for this study is based on quantitative and qualitative primary and secondary processes including satellite geospatial information system (GIS) using Geo-spatial data acquisition techniques such as LiDAR(Light Detection And Ranging), HOMER(Hybrid Optimization for Microgrid Energy Renewable), Oblique Imagery, High-Resolution Aerial Photogrammetry and ground penetrating data as well as manual and digital recordings at earth-based stations and credible secondary sources where necessary, available and applicable for accurate information gathering on various renewable and natural energy potentials.

Sources of data used directly, indirectly, comparatively, and projectively include the Nigerian Institute for Oceanography and Marine Research (NIOMR), National Aeronautics and Space Agency (NASA) Langley Research Center (LaRC) Data Access Viewer, Nigerian Meteorological Agency (NIMET), Nigerian Navy Hydrography Office(NNHO), Nigerian Institute for Oceanography and Marine Research (NIOMR), HOMER Software real-time geospatial data search, Energy Sector Management Assistance Program (ESMAP) of the World Bank, U. S. Energy Information Agency (EIA), International Energy Agency (IEA), Organization for Economic Cooperation and Development (OECD), Nuclear Energy Agency World Energy Forum (WEF) and World Energy Outlook (WEO) among other sources.

To ensure high data integrity, high accuracy, and more reflective resource values, an unprecedently large number of evenly distributed geospatial data collection sites were used with a total of twenty-six (26) including the GoG (Bight of Benin) offshore area with minimum of three (3) towns in each of six (6) states in the South – West geopolitical zone of Nigeria namely Lagos(Badagry, Victoria Island, Lekki, Epe, and Ikeja); Ogun(Abeokuta, Obafemi Owode and Shagamu/Ijebu Ode); Oyo(Igboho, Ise Eyin, Igbo Ora, and Ibadan); Osun(Ikire, Osogbo, Ilesha, and Ila Orangun); Ondo(Akoko, Owo, Ondo Town, Akure, and Okitipupa) and Ekiti(Ijero, Ado Ekiti and Ise).

a. Technical Feasibility: Technical viability is based on energy resources, technical competence, technological maturity, operability, interoperability, reliability, predictability, scalability, conversion efficiency, capacity factor, generation, flexibility, innovation, complexity, transportability, maintainability, and safety with respect to South–West Nigeria's geographical location.

To determine the technical feasibility, a survey was conducted by a team of 55 energy and power engineers, researchers, and other practicing experts in renewable energy and power with knowledge of the physical geography, and climate as well as the general environment of South – West Nigeria's geopolitical zone across various sectors including regulatory, research and development, project management, academic, consulting and investment to assess the various energy sources against the listed criteria based on weighted five point scale. The respective weights are assigned based purely on the comparative criticality level of each criterion for others on a 0 – 10 scale for each of the technical sub-criteria selected as follows.

i. **Technical Competence**: refers to guaranteed availability or competent technical human capacity or ability to train and develop relevant manpower within an acceptably planned timeframe from construction to operation

ii. **Interoperability**: describes how well the energy generation technology synergizes with other technologies or fits with ancillary units, services, and equipment already existing or that may be installed in the same site.

iii. **Reliability** is a measure of the technology's ability to meet operational requirements and load demand without failing.

iv. **Predictability**: it is a measure of the ability to accurately determine, plan, and project future output in advance based on data histories, models, and simulation tools.

v. **Scalability**: it is the ability to size the plant to suitable capacities for demand, cost, space, and availability of resources without prejudice to safety and efficiency.

vi. **Conversion Efficiency**: is the ratio of exergy to input energy as a percentage. The higher the exergy, the higher the efficiency.

vii. **Generation flexibility**: it is the dispatchability and ability of an energy generation source to adjust the output to meet reserve demands or peak values without operation problems or difficulties.

viii. **Innovation** refers to the rate of advance taking place for a given generation of technology. Innovation is a sign of greater learning rates, cost savings, and technological advantage in the future for a given generation source.

ix. **Technical Complexity**: It is a measure of the ease of understanding and operating a technology. The higher the simplicity of a technology, the less the complexity and the better and the more ubiquitous or cheaper it gets.

x. **Transportability**: it is a measure of the ease of transporting the energy generated by a given technology from the site of production to the market.

xi. **Maintainability**: it is a measure of the ease of maintaining a given technology concerning cost-effectiveness, interchangeability of parts, simplicity, and material integrity as well as favourable failure rate (FR), Mean Time To Repair (MTTR), and Mean Time Between Failures (MTBF)

xii. **Safety**: refers to the ability of a generation technology to, proper handling, operate safely concerning people and the environment as well as other units and equipment around it, with a high degree of integrity.

b. Resource Availability: Resource Availability level in this study is defined based on the quantitative and qualitative availability of energy resources above the minimum amount necessary for electric power generation, either naturally or by technological enhancement.

It is important to know that the availability of resources does not necessarily mean it is adequate for power generation. This is because fewer energy resources are needed to do mechanical work than for conversion to electrical energy (power generation). For example, a minimum average windspeed of 3.5m/s is needed for wind energy conversion for power generation, while lesser values of windspeeds can be applied for windmills and other uses of wind energy resources. In much the same manner, a minimum of 2000 kWh/m2/annum of direct normal irradiation (DNI) is required for solar–thermal power generation for a given site (ESTELA, 2022). Resource Availability is also considered in this study based on geographical spread across the area under study, which becomes more key as the landmass and population density increase. This is aptly termed in this study as the ubiquity of energy resources.

Resource availability is also judged in the study by applicability based on the fact that the availability of energy resources does not necessarily guarantee exploitability, especially for geographical conditions, terrain, and excessive availability, which may be beyond the cut – off values. For example, an area rife with too high wind speed values that are often at the threshold of turbine cut–out is a poor site for wind power generation, notwithstanding. Hence, the sub-criteria for Resource Availability are defined thus:

I. **Energy resource potential** (Quantitative energy value): is the volume of a given energy resource with respect to the minimum amount necessary for commercial power generation fit for mini – grid deployment. Every renewable energy resource has a minimum volume required for power generation, which determines the suitability or feasibility of its generation in a given geographical location or site. For this study, the renewable energy resource potential value with respect to the required minimum for power generation is taken as the quantitative measure of energy resources.

II. **Capacity Factor** (Qualitative value): It is defined by the capacity factor, predictability, and stability of an energy resource in order to guarantee the quality and reliability of output. A challenge of VRE is harmonic emission, which is a key factor in considering the volume of a specific renewable energy resource required to permanently shut down a given nameplate capacity of a fossil fuel source. In this study, the capacity factor of the energy generation sources for the given location is taken as the qualitative value of the energy source with respect to the average drop in output below the average output per annum.

III. **Ubiquity**: ubiquity is a measure of the availability of the sources per unit area of a given geographical location. For example, being that solar energy is available throughout Southwest Nigeria, the ubiquity is going to be 100% of the maximum possible value allocated to ubiquity as a sub–criterion. Moreover, if the energy source has a large potential whose capacity per square meter is equal to or greater than that of solar energy for a given geographical location, the ubiquity can also be said to be 100% of the maximum possible value allocated to ubiquity as a sub-criterion. For example, a 100kW micro hydro potential site per 10,000 m^2 of the geographical area, or 100 homes, can be considered to have a ubiquity of 100% of the maximum possible value assigned to ubiquity as a sub-criterion. Hence, a lesser value will be calculated based on their relative percentage or fraction of the maximum possible value assigned to ubiquity as a sub–criterion.

c. Environment

Environment in this study is defined based on the adaptability of the energy generation sources for commercial scale mini – grid deployment as per market potential, ease of doing business (EODB), rating of the political jurisdiction in whose purview the proposed energy generating site is geo – located and sociocultural disposition of the community towards the project or technology or something similar concerning precedence, records, trends and perception management. In determining the environmental score, the market potential value based on Motor Intelligence 2022 – 2027 Market Report on Nigeria generated makes up 70% in proportion by being multiplied by 0.7 while the EODB makes up a fraction of 30% by being multiplied by 0.3.

I. Environment's Ease of Doing Business (EODB): the World Bank scores and ranks countries on ease of doing business on a scale of 1 – 190 which is the count of candidate economies based on governance and regulatory best practices using a list of 41 component indicators for 10 criteria or business topics namely: Starting Business; Construction Permits; Getting Electricity; Registering Property; Getting Credit; Protecting Minority Investors; Paying Taxes; Trading Across Borders; Enforcing Contracts; and Resolving Insolvency. The calculation is based on a linear transformation formulation given by (Worse – Y)/(Worse–Best, which the highest-scoring country is ranked the best while the lowest-scoring country is ranked the worst (World Bank Group, 2019).

On Getting Electricity as a component indicator, the World Bank Group sets a normalizing standard of 18 days, which implies that countries with less time for new businesses to get electricity have a score of 100% while countries with a higher number of days for new businesses to get electricity are scored accordingly. However, the ease of doing business is not the same for all kinds of business in just the same way that the ease of developing and marketing power generation plants is not the same for all sources because it depends on the required permits, capital expenditure, techno-economic complexities, legal and regulatory hurdles and other things that may be needed. As such, the EODB for each energy generation source is determined perceptively by a team of expert judgments based on the World Bank EODB score expressed as a fraction. Given that the EODB score itself is very comprehensive and a mean of several metrics, the Environmental EODB for a given energy source may be higher or lower than the World Bank value by a given number of 5th percentile deviation. Based on the 2021 EODB Report, Nigeria has a score of 56.9% or 0.56, which ranks 131 of the 190 economies listed.

II. Market Potential: Market potential is a measure of the ratio of energy supply to market demand in the given environment. The higher the ratio of energy demand to the total available energy supply in a given environment, the higher the market potential and investment prospect for power generation.

According to the Motor Intelligence 2022 Market Report, Nigeria's electricity power sector has a projected Cumulative Annual Growth Rate of 13% between 2022 and 2027, with thermal stations expected to be the dominant generation source, with residential areas accounting for 43% of demand. Nigeria's renewable energy generation was 2,153MW in 2020, which the government plans to expand on with the Naija Solar Power Project initiative of the same year, with a target of 5 million connections to off-grid communities.

With a current baseline generation of 4,000MW and a conservative electricity demand of 100,000MW, Nigeria's electricity market potential is 96% (0.96) with a market factor of 25. This represents a strong business prospect for businesses considering an estimated population of over 200 million with a national plan aiming for Top 20 Economies by 2030, of which Southwest Nigeria is the fastest growing region industrially, commercially, and infrastructurally.

The market potential of various energy sources is not the same for a given environment, considering cost, ethical values, environmental and sociocultural issues, market proximity and transmission, storage, and so on. Hence, the market potential scores for the various energy sources are determined based on the general market potential value, considering how they are produced and the kind of market they are likely to serve based on proximity, cost, and convenience.

d. **Sustainability:** Sustainability is the ability of the power generation system to meet present, present-designed, and desired needs without jeopardizing the ability to meet future energy or alternate needs or use of the same site, as well as the reuse of decommissioned equipment or components in a circular economic structure.

Sustainability of energy resources is critical in direct proportion to economic, environmental, and social life in order to balance energy production with other factors (Yilmaz, 2006). Hence, sustainability is directly proportional to renewability, socioeconomic impact, and environmental impact (air, water, land, plants, and animals) on a scale of (0 – 1). 1 = zero environmental impact or extremely positive socioeconomic impact, 0.7 = very good. 0.5 = well. 0.4 = marginal impact. 0.3 = more negative than positive = negative. 0 = very negative impact or no project option.

For this study, the sustainability of an energy generation source is determined by 4 component indicators, namely: environmental impact, social impact, renewability, and reusability, which help to cover ecological protection, social issues, and circular economic considerations as well as maintenance and disposal-friendly system design. Given the Environmental Impact, I_E, Social Impact I_S, Reusability R_U, and Renewability R_N, the Sustainability of energy source is given thus:

$$S = I_E R_N \, R_U I_S \qquad \text{………3.1}$$

i. **Renewability**: based on the fact that not all energy sources are renewable and that not all renewable energy sources are renewable to the same extent or ease in terms of quality, quantity, and time, the renewability of an energy generation source is in this study is determined by the degree or rate of renewal within a given timeframe.

A higher score means an energy generation technology is more easily renewable or has a higher renewal rate than another of a lower score, and vis a vis. Some energy sources like solar, wind, wave, and tidal are daily renewable, while some like biomass, hydro, and geothermal are not, but quarterly, bi-annually, annually, or multi–annually renewable depending on climatic conditions, species, terrains, and edaphic conditions for a given geographical location.

Energy Renewability Index (ERI) is therefore calculated by the ratio of the number of renewal cycles per given period to that of an ideally renewable generation technology, which in this study is counted as the number of full renewal cycles per year by the following equation:

$$ERI = \frac{1}{N} \qquad \text{.................3.2}$$

N is the number of full renewals in a year for a given site's geographical location. For example, energy sources like wind, solar, wave, and tidal that are daily renewable have an ideal energy renewability index, which means their N is 1. N for wind, solar, wave, and tidal and hydro for all locations is 1, given that they are fully renewable within a year, while N for a given biomass says a tree that takes 7 years to grow to full maturity for biomass cultivation is 7 which makes the ERI to be 0.14. However, trees vary a great deal in terms of gestation period. Hence, type, species, soil, and climate conditions, as well as nourishment, determine the ERI for various wood-based biomass sources.

ii. **Reusability**: The reusability of an energy source is a measure of the ratio of the reusable volume of its material of manufacture and ancillary components to the total volume of the material of the installation based on circular economic principles. This includes repurposing for the same and different uses or alternate services.

The reusability or recyclability of materials vary a great deal between various power generation modules, with some being 100% and most being economically almost zero to recycle or reuse in one way or the other which could be tempting for abandonment instead of incurring high reuse or disposal costs, making it serious future environmental concerns as can be seen in many onshore and offshore infrastructures abandoned at end of life especially in weak regulatory environments. The Recyclability or Reusability volume V_{RU}, and total material volume as V_M, are related to Reusability as follows:

$$R_U = \frac{V_{RU}}{V_M} \qquad \text{.................3.3}$$

Hence, no electricity-generating technology is made of exactly 100% recyclable materials or entirely reusable. in this study, it becomes necessary to use the recyclability or reusability rate as the value of the recyclability index of each energy generation source.

Solar PV and solar–thermal modules have a recyclability rate in the region of 90% (0.9) and 94.7% (0.97), respectively, depending on the material technology and design, as well as accessories and ancillary components (Dual Solar, 2020, and We Recycle Solar, 2021).

Onshore and offshore wind turbines have an average recyclability rate of 85% (0.85) and 82% (0.82), respectively (Catapult, 2021), depending on the material, design and ancillary components and accessories. Offshore wind turbines have less in recyclability rate values compared to onshore wind energy systems due to the mooring system and fixed platform construction, and anchoring materials, as well as other component materials.

Based on metallurgical and material as well as component design assessments, hydro turbine, wave, tidal, and biomass power have fair recyclability rates of 90% (0.9), 90(0.9), 85% (0.85), and 95% (0.95) respectively depending on material, mooring system, design and volume of special construction works that are practically unrecoverable at end of life.

iii. **Relative Environmental Impact**: Environmental Impact is determined in this study based on the degree of non – negative impact on the environment rather than on the degree of negative impact on the environment in terms of Greenhouse Gas (GHG) emission levels, water stress, safety of flora and fauna, sanctity of the eco system and environmental health hazards among other possible impact.

Moreover, the environmental impact defined in this study is the percentage of greenhouse gas (GHG) savings or the volume of greenhouse gas emissions saved by the renewable energy source compared to its equivalent (nearest or cheapest) fossil fuel alternative for the project. The volume of GHG is the total emission involved in the development, operation, and disposal of the renewable energy generating source.

For example, if a 1MW wind turbine generates 270MTCO$_2$E during production and another 45MTCO$_2$E throughout its operation, and a further 2.5MTCO$_2$E for disposal, compared to a total of 1800MTCO$_2$E by a natural gas-fired 1MW gas turbine from construction to operation and disposal, then sustainability is computed as follows:

S = (270 + 45 + 2.5)/1800 = 317.5/1800 = 0.82 or 82%

For this study, the relative environmental impact (REI) is calculated based on the relative values concerning the worst-case energy generation source, based on the following equation, given the Energy Source Impact I_E and Worse Energy Source Impact I_M

$$REI = 1 - \frac{I_E}{I_M} \qquad \text{……3.4}$$

According to the National Renewable Energy Research Laboratory (NREL) 2012 Report, the lifetime emission per KWH for solar PV is 40g, while solar thermal has a lifetime carbon footprint of 90g/KWH (Lenzen, 1999), which represents the fair average considering estimates by various sources. However, sizes, design, and material selection also play serious roles in the carbon footprint valuation of energy generation plants.

Wave and tidal energy generation plants have lifetime carbon emission values of 32g/KWH and 22g/KWh, respectively, compared to natural gas, the cleanest of fossil fuels which emits 441g/KWh (EIA, 2022) while biomass power generation averages 230g/KWh (Smooth, 2023) and wind turbine averages 9.5g/KWH (Helman, 2020; Wang and Sun, 2011). In this case, biomass at 230g/KWH has the worst REI in the list of renewable energy generation technologies under consideration for this study, being that it has the highest carbon to power ratio as stated.

iv. **Socioeconomic Development Impact**: The relative socioeconomic development impact (SEDI) of an energy generation source is, for this study, determined by the ratio of the positive impact on socioeconomic development of host communities and societies at large to that of the best energy generation source.

SEDI in this study includes employment creation, rural infrastructure development, rural–urban connectivity, sociocultural advancement, gender parity, access to education, clean energy, and healthcare, among others. The Energy Source Socioeconomic Impact I_{SE} and I_{BSE}

$$SEDI = \frac{I_{SE}}{I_{BSE}} \qquad \text{…………3.5}$$

Given the pivotal importance of employment creation in the socioeconomic advancement of communities, the average job creation rate across the value chain from construction to decommissioning per MW capacity of each generation technology is, in this study, taken as the metric for SEDI determination for greater simplicity, transparency, and objectivity.

The volume of direct and indirect jobs created per given energy generation capacity varies with technology, location, social factors, manpower, capacity, tools, and materials. Hence, values are in these studies based on conservative empirical data obtained from recent real-time projects within sub-Saharan Africa, where South-West Nigeria is located. For example, security and ventilation for batteries are fundamental for the majority of locations, while in some countries neither security nor ventilation is a cost or labour factor.

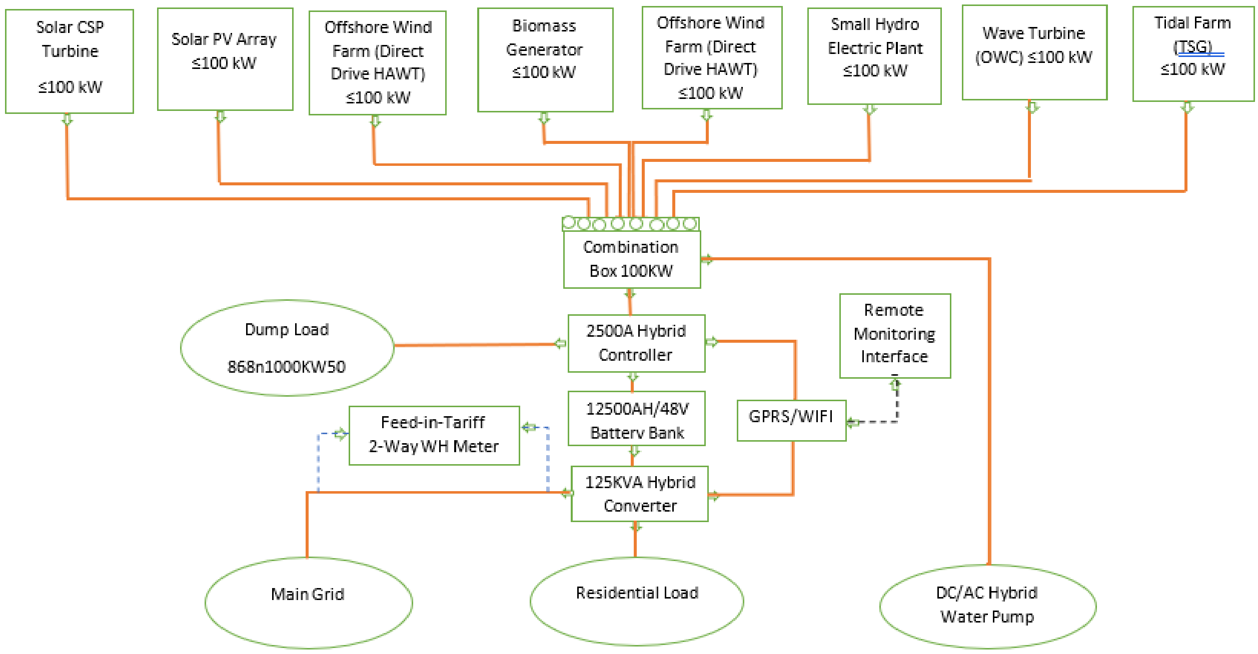
Conservatively, solar PV electric power generation plant on average create 30 jobs (19 direct and 11 indirect employment) throughout its 25years lifetime from construction to decommission excluding procurement and regulatory services from data obtained from local solar PV companies with roughly similar values for solar - thermal except that solar – thermal requires more of the total number of operational roles. Data obtained from telecoms companies, solar installation companies, and engineering consultancies actively engaged in the sector.

Every MW of an onshore wind turbine employs 26 people (19 direct and 7 indirect) from construction to decommission while the value estimated for offshore is 28. Biomass produces 37 direct and indirect jobs per MW on average across its variants of biogas, landfill gas, dedicated energy crops, and wood-based combustion, while reservoir small hydroelectric power creates a total of 41 direct and indirect jobs. Wave and tidal energy based on existing plant data creates roughly the same amount of direct and direct jobs which are put at 23 and 25 per MW, respectively.

The SEDI index is better envisaged in effect by virtue of the high unemployment and dependency rate in Sub Saharan Africa, especially with respect to women and youth in rural and peri – urban areas where mini – grid projects are primarily targeted. Thus, job creation has strong positive correlations with socioeconomic empowerment, crime reduction, education, human development index, ecological protection, and all possible factors pertaining to sustainability, especially with respect to renewable energy and power development projects.

Since all four measures, that is, REI, Recyclability, ERI, and SEDI, have equal priority in the determination of sustainability based on the literatures of SDG, World Bank, UNFCC and expert analysis, there is no hierarchical criteria weighed in the formulation of sustainability index for this study.

Step 5/6: Hypothetical Hybrid Mini-Grid Power Plant



Step 7: Development of Techno – Economic Renewable Energy Viability Index (TEREVI)

Given the TEREVI weights of 0.25, 0.25. 0.25. 0.125. and 0.125 for the respective cardinal criterion Technical, Economics, Energy Resources, Sustainability, and Market Condition (or Business Environment), the relation is given thus:

$$TEREVI = \frac{0.25T+0.25E+.25R+0.125S+).125M}{IPV} \qquad ....3.6$$

3.0. Results

Table 4.1 shows the annual probable renewable energy potentials. Tables 4.2, 4.3, 4.4, and 4.8 show the various criteria assessment results. Tables. 4.5. 4.6. and 4.7 shows the TEREVI and cost of energy results while Table 4.9 shows the TEREVI hybridization averaging. The Techno-Economic Levelized Cost of Energy (TELCOE) is obtained based on studies by Okwori et al (2025)

S/N	Renewable Energy Resources	AVERAGE Potential (MWh/yr.)
1	Solar (PV + CSP)	135,502,198.5
2	Onshore Wind	2,276,644,673.1456
3	Offshore Wind	1,886,924,786,356.8
4	Biomass	3,097,889,859.319
5	Micro Hydro	6,622,560,000
6	Wave	1,269,898,875
7	Tidal	1,893,751,171.875
8	Total	1,902,221,033,134.64

Table 4.1: 2R renewable energy potential for South-West Nigeria

Scale: 1 -5	Energy Potential	Capacity Factor	Ubiquity	Total	Resource Score
Weight	10	10	5		
Ideal Plant	50	50	25	125	1

SPV	50	25	25	100	0.8
STE	50	25	25	100	0.8
WDL	17.5	20	8.75	36.25	0.29
WDO	40	30	8.25	68.25	0.546
HYD	25	35	12.5	72.5	0.58
BIO	50	32.5	12.5	95	0.76
WVE	12.5	30	8.25	50.75	0.406
TDE	10	30	8.25	48.25	0.386
0.80 – 1.00 = Excellent; 0.6 – 0.79 = Very Good; 0. 4 – 0.59 = Okay; 0.30 – 0.49 = Marginal, 0 – 0.29 = Weak 4.0 – 0.5 = Excellent, 3.0 – 3.99 = Very Good, 2 – 2.99 = Good 1.0 – 1.99 = Okay, 0 – 0.99 = Weak					

Table 4.2: 2R renewable energy resources potential assessment

5 – Point Scale	Weight (10)	Ideal Plant	SPV	STE	WDL	WDO	HYD	BIO	WVE	TDE
Competence	10	50	50	45	50	45	50	50	40	40
Interoperability	5	25	25	25	20	20	20	25	25	25
Maintainability	10	50	50	45	45	40	40	40	40	40
Reliability	5	25	25	25	22.5	25	25	20	25	25
Predictivity	3	15	13.5	13.5	13.5	13.5	13.5	15	13.5	13.5
Scalability	3	15	15	12	15	9	12	15	12	12
Efficiency	5	25	7.5	17.5	10	17.5	22.5	10	17.5	17.5
Flexibility	5	25	0	25	0	0	25	25	0	0
Innovation	3	15	12	12	9	9	12	12	9	9
Complexity	7	35	35	28	28.5	24.5	28	31.5	24.5	24.5
Safety	10	50	45	35	35	40	40	35	40	40
Transportation	2	10	10	10	9	8	8	10	8	8
Power/Space	5	25	5	15	17.5	17.5	22.5	15	22.5	22.5
TOTAL	73	365	293	308	275	269	318.5	303.5	277	277
Technical Score		1	0.803	0.844	0.753	0.737	0.873	0.832	0.759	0.759
SPV = Solar Photovoltaic, STE = Solar Thermal Energy, WDL = Landed Wind Turbine, WDO = Offshore Wind Turbine HYD = Hydro Power, BIO = Biomass Energy, WVE = Wave Energy, TDE = Tidal Energy										

Table 4.3: 2R renewable energy Technical Feasibility assessment results

Energy Sources	General Market Potential	Market Potential	Market Potential X 0.7	General EODB	EOD	EODB X 0.3	Environment Score
Ideal Plant	0.96	1.00	0.70	0.569	1.00	0.30	1.00
SPV	0.96	0.96	0.672	0.569	0.654	0.196	0.868
STE	0.96	0.91	0.638	0.569	0.569	0.171	0.809
WDL	0.96	0.864	0.605	0.569	0.569	0.171	0.776
WDO	0.96	0.816	0.571	0.569	0.484	0.145	0.716
HYD	0.96	0.864	0.605	0.569	0.569	0.171	0.776
BIO	0.96	0.91	0.638	0.569	0.569	0.171	0.809
WVE	0.96	0.768	0.538	0.569	0.484	0.145	0.683
TDE	0.96	0.768	0.538	0.569	0.484	0.145	0.683

Table 4.4: 2R Renewable energy enabling environment assessment

	Carbon Emission g/KWh	REI	Recyclability Index	ERI	SEDI	SEDI Index
SPV	40	0.826	0.900	1.00	30	0.734
STE	90	0.609	0.947	1.00	30	0.734
WDL	11	0.952	0.85	1.00	26	0.634
WDO	11	0.952	0.820	1.00	28	0.683
HYD	11	0,952	0.900	1.00	41	1.000
BIO	230	0	0.950	0.14	37	0.902
WVE	32	0.861	0.900	1.00	23	0.561
TDE	22	0.096	0.85	1.00	25	0.601

Table 4.5: 2R Socioeconomic Development Impact assessment of 2R renewable energies

South – West Nigeria TEREVI for Best Available Sources						
Technology	T	E	R	S	M	TEREVI
Ideal Plant	1	1	1	1	1	1
SPV	0.803	0.934144527	0.8	0.865	0.868	0.850911132
STE	0.803	0.923363586	0.8	0.8225	0.809	0.835528397
WDL	0.803	0.900714361	0.29	0.859	0.776	0.70280359
WDO	0.803	0.911249151	0.546	0.86375	0.716	0.762531038
HYD	0.803	0.926410462	0.58	0.963	0.776	0.794727616
BIO	0.803	0.950858024	0.76	0.498	0.809	0.791839506
WVE	0.803	0.688694095	0.406	0.8305	0.683	0.663611024
TDE	0.803	0.764565515	0.386	0.63675	0.683	0.653360129

1st - Solar PV 2nd – Solar Thermal 3rd - Small Reservoir Hydro 4th – Biomass 5th – Wind Offshore 6th – Wind Onshore 7th – Wave Power 8th – Tidal Power

Table 4.5: TEREVI for the 2R renewable energy resources

S/N	Configuration	Simulink Opt COE($/KWH)	LCOE ($/KWH)
1	A – Solar Photovoltaic Power (SPV)	0.0137782	0.01886428
2	B – Solar Thermal Power (STE)	---------	0.021518265
3	C – Hydro Electric Power (HDE)	0.02316	0.027878615
4	D – Biomass Power (BIO)	0.01862	0.024920091
5	E – Offshore Wind Power (WDO)	0.0199044	0.021081431
6	F – Onshore Wind Power (WDL)	0.012298	0.014077099
7	G – Wave Power (WVE)	0.09t11	0.082307404
8	H – Tidal Power (TDE)	0.091201	0.062248695

Table 4.6: HOMER and MATLAB Simulink simulation results of energy generation cost

S/N	Configuration	TEREVI	HOMER COE($/KWH)	TELCOE ($/KWH)
1	A – Solar Photovoltaic Power (SPV)	0.850911	0.016911431	0.019633
2	B – Solar Thermal Power (STE)	0.835528	-----------	0.022847
3	C – Hydro Electric Power (HDE)	0.794728	0.022069123	0.0296
4	D – Biomass Power (BIO)	0.79184	0.020200729	0.026459
5	E – Offshore Wind Power (WDO)	0.762531	0.019963033	0.021939
6	F – Onshore Wind Power (WDL)	0.702804	0.013362281	0.014651
7	G – Wave Power (WVE)	0.663611	0.094003211	0.092809
8	H – Tidal Power (TDE)	0.65336	0.096153237	0.07019

Table 4.7: TEREVI values for 2R renewable energy resources in Southwest Nigeria

Technology	REI	Recyclability Index	ERI	SEDI Index	Total	Sustainability Index
Ideal Plant	1	1	1	1	4	1
SPV	0.826	0.9	1	0.734	3.46	0.865
STE	0.609	0.947	1	0.734	3.29	0.8225

WDL	0.952	0.85	1	0.634	3.436	0.859
WDO	0.952	0.82	1	0.683	3.455	0.86375
HYD	0.952	0.9	1	1	3.852	0.963
BIO	0	0.95	0.14	0.902	1.992	0.498
WVE	0.861	0.9	1	0.561	3.322	0.8305
TDE	0.096	0.85	1	0.601	2.547	0.63675

Table 4.8: Renewable energy sustainability assessment

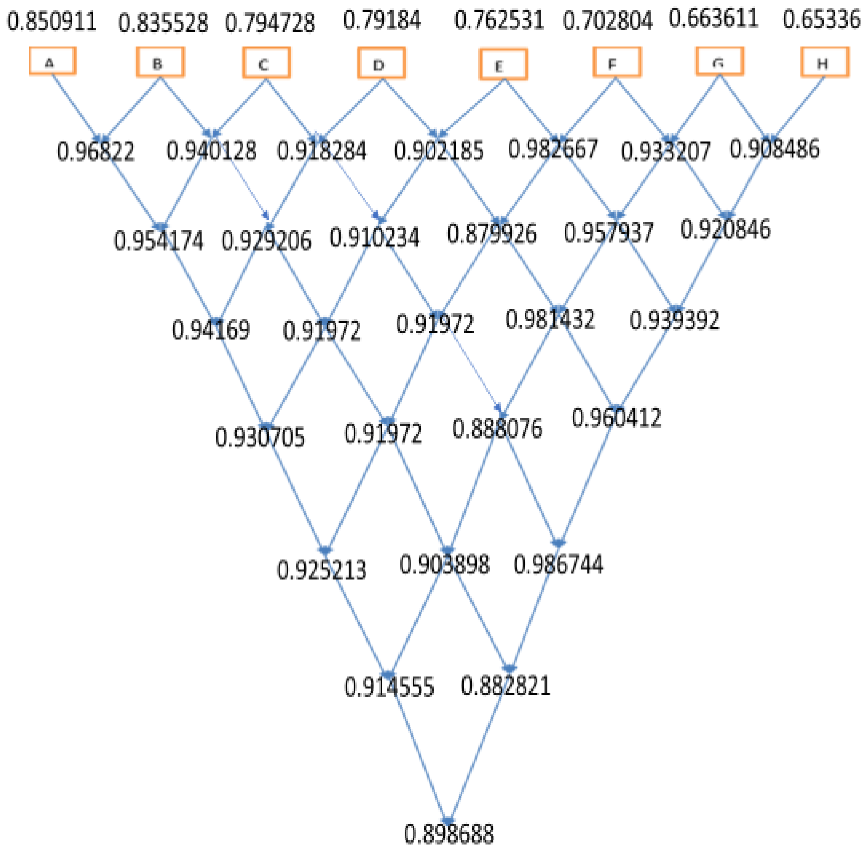


Figure 4.1. The 2R renewable energy MGA scheme

S/N	Configuration	TEREVI	H1	H2
1	A – Solar Photovoltaic Power (SPV)	0.850911		
2	B – Solar Thermal Power (STE)	0.835528		
3	C – Hydro Electric Power (HDE)	0.794728		
4	D – Biomass Power (BIO)	0.79184		
5	E – Offshore Wind Power (WDO)	0.762531		
6	F – Onshore Wind Power (WDL)	0.702804		
7	G – Wave Power (WVE)	0.663611		
8	H – Tidal Power (TDE)	0.65336		

9	AB	0.84322	**0.96822**	1.09322
10	BC	0.815128	**0.940128**	1.065128
11	CD	0.793284	**0.918284**	1.043284
12	DE	0.777185	**0.902185**	1.027185
13	EF	0.732667	0.857667	**0.982667**
14	FG	0.683207	0.808207	**0.933207**
15	GH	0.658486	0.783486	**0.908486**
16	ABBC	0.829174	**0.954174**	1.079174
17	BCCD	0.804206	**0.929206**	1.054206
18	CDDE	0.785234	**0.910234**	1.035234
19	DEEF	0.754926	**0.879926**	1.004926
20	EFFG	0.707937	0.832937	**0.957937**
21	FGGH	0.670846	0.795846	**0.920846**
22	ABBCBCCB	0.81669	**0.94169**	1.06669
23	BCCBCDDE	0.79472	**0.91972**	1.04472
24	CDDEDEEF	0.79472	**0.91972**	1.04472
25	DEEFEFFG	0.731432	0.856432	**0.981432**
26	EFFGFGGH	0.689392	0.814392	**0.939392**
27	ABBCBCCB BCCBCDDE	0.805705	**0.930705**	1.055705
28	BCCBCDDE CDDEDEEF	0.79472	**0.91972**	1.04472
29	CDDEDEEF DEEFEFFG	0.763076	**0.888076**	1.013076
30	DEEFEFFG EFFGFGGH	0.710412	0.835412	**0.960412**
31	ABBCBCCB BCCBCDDE BCCBCDDE CDDEDEEF	0.800213	**0.925213**	1.050213
32	BCCBCDDE CDDEDEEF CDDEDEEF DEEFEFFG	0.778898	**0.903898**	1.028898
33	CDDEDEEF DEEFEFFG DEEFEFFG EFFGFGGH	0.736744	0.861744	**0.986744**
34	ABBCBCCB BCCBCDDE BCCBCDDE CDDEDEEF BCCBCDDE CDDEDEEF CDDEDEEF DEEFEFFG	0.789555	**0.914555**	1.039555
35	BCCBCDDE CDDEDEEF CDDEDEEF DEEFEFFG CDDEDEEF DEEFEFFG DEEFEFFG EFFGFGGH	0.757821	**0.882821**	1.007821
36	ABBCBCCB BCCBCDDE BCCBCDDE CDDEDEEF BCCBCDDE CDDEDEEF CDDEDEEF DEEFEFFG BCCBCDDE CDDEDEEF CDDEDEEF DEEFEFFG CDDEDEEF DEEFEFFG DEEFEFFG EFFGFGGH	0.773688	**0.898688**	1.023688

Table 4.9: Hybridized optimization of probable renewable energy resources in Southwest Nigeria

4.0. Discussion of Results

As shown on Figure 5.1, 5.3, and 5.4, the results show a mean TEREVI value of 0.756914 and a standard deviation of 0.07564 highlighting good convergence such that almost all sources are within 1 standard deviation for probable energy resources and higher for proven ones with a positive mean deviation of 11.05%, 9.41%, 4.76%, 4.41%, and 0.74% for Solar Photovoltaic, Solar Thermal, Small Hydro Power, Bioenergy, and Offshore Wind Power respectively.

The negative mean deviations were -7.70%, - 14.06%, and – 15.85% representing Onshore, Wind, Wave, and Tidal Power systems, respectively. In effect, the TEREVI result ranks the renewable energy sources in Southwest

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Nigeria in descending order of Solar Photovoltaic, Solar Thermal, Small Hydro, Bioenergy, Offshore Wind, Onshore Wind, Wave, and Tidal power.

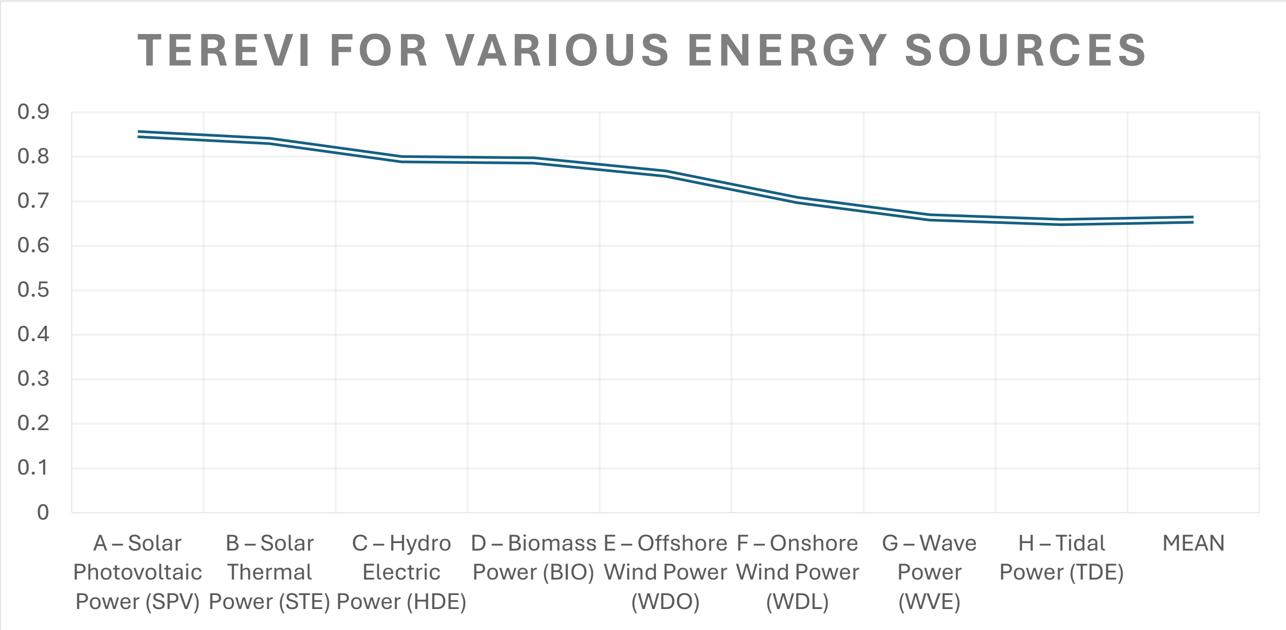

Figure 5.1: TEREVI variation for 2R energies

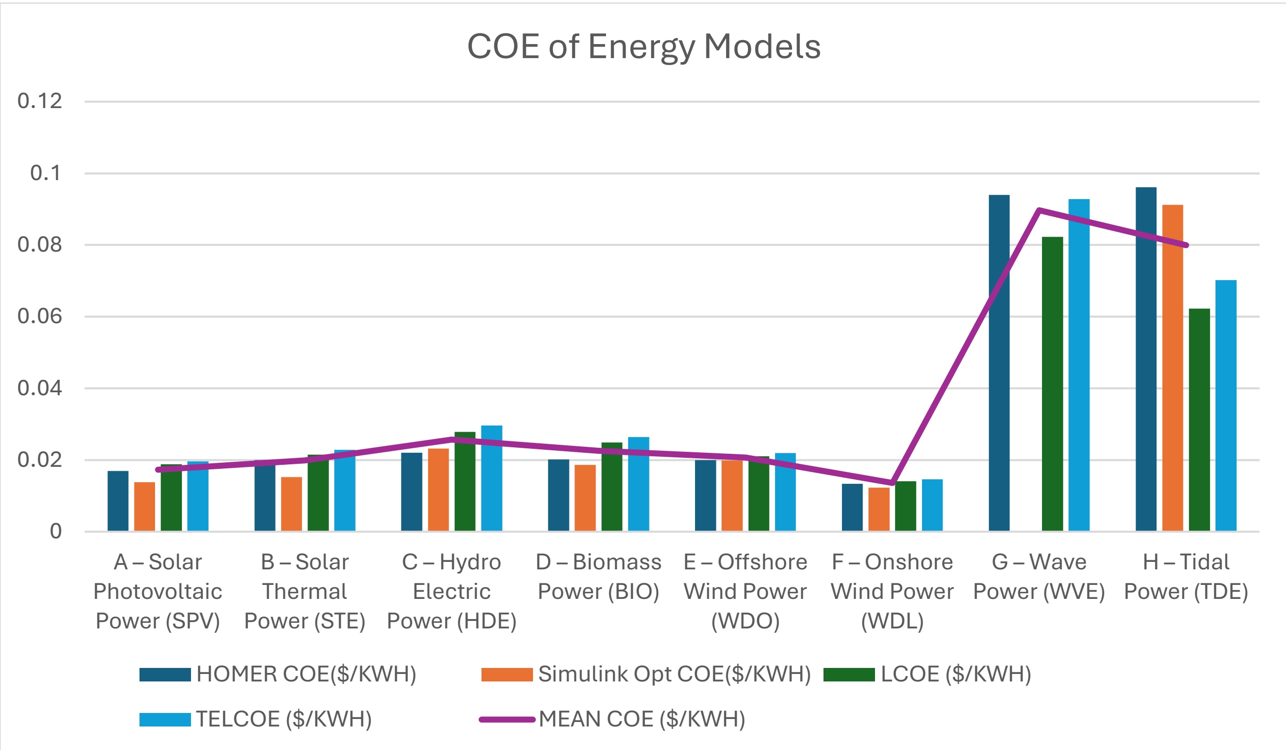

Table 5.2: Cost of Energy evaluations

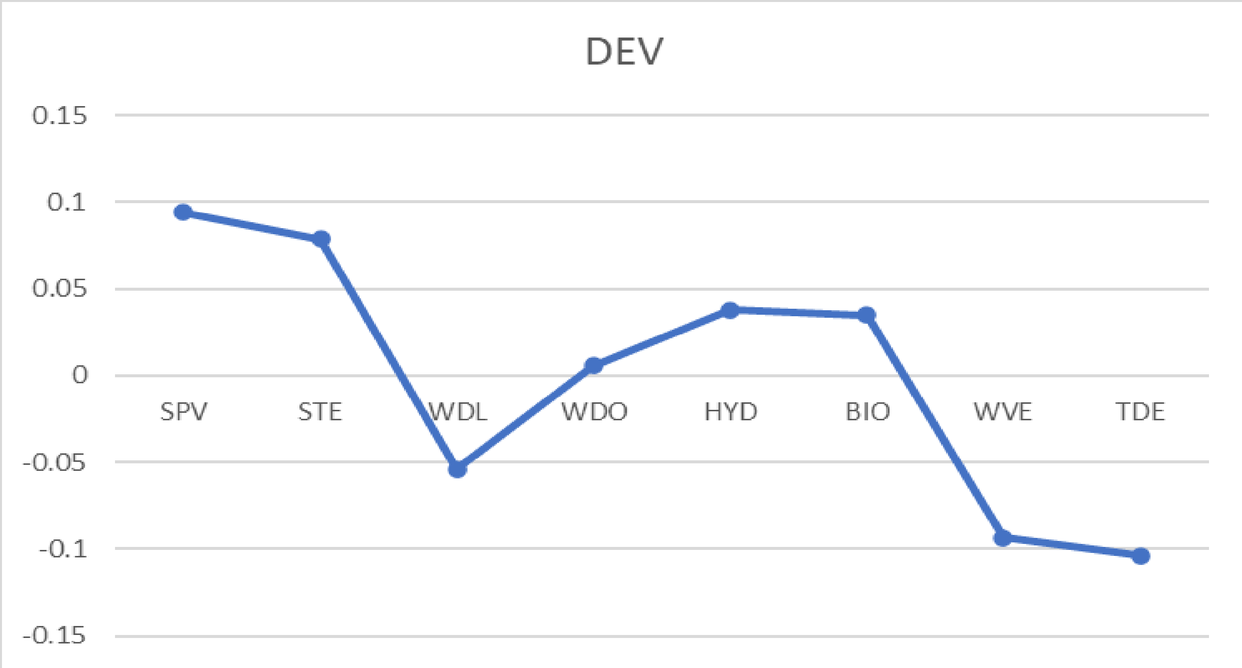

Figure 5.3: TEREVI mean deviation for 2Renergoes

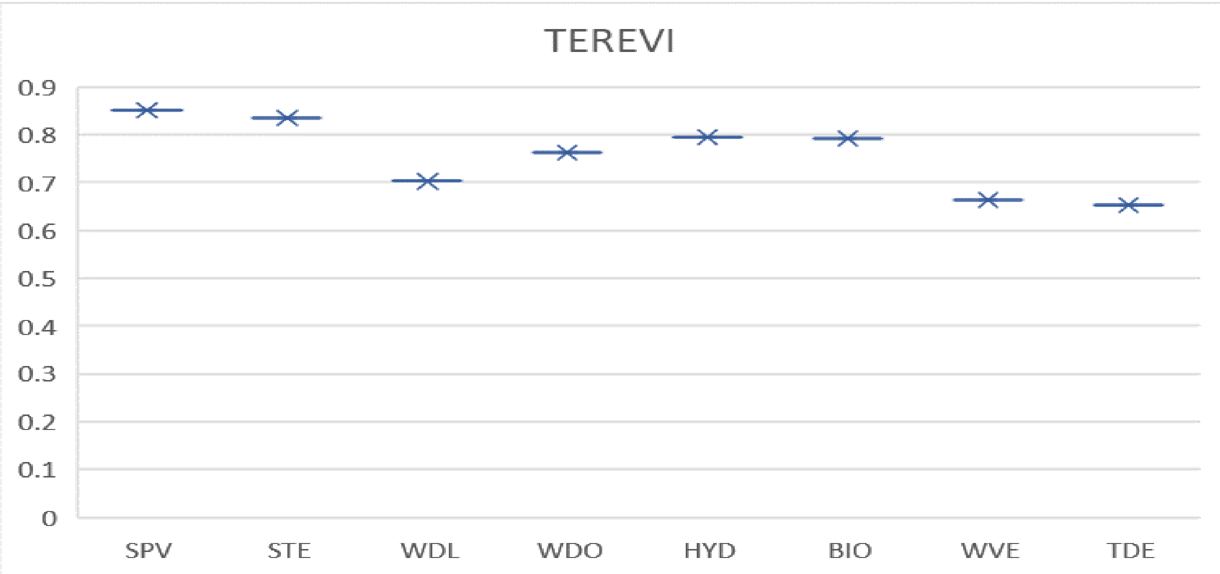

Figure 5.4: TEREVI results

On a granular level, Onshore Wind Energy resources show strong values in specific geolocations at various heights. For example, Obafemi Owode recording a mean windspeed of 6.29m/s is the only Southwest town that meets the commercial threshold of 3.5m/s at 10m ASL. However, at a height of 50m ASL, 18 of the 26 locations representing 69.23% of the towns in South–West Nigeria under study qualify for commercial-scale wind farms by virtue of meeting or exceeding the 3.5m/s wind power generation threshold. As much as the minimum resource thresholds are critical, it is noteworthy that the relative stability of energy resource variation within the power conversion range is key in order to ensure a higher capacity factor. Similarly, wave and tidal energy resources show strong variations on the South–West Nigerian Bight of Benin coastline or littoral zones along and across from the western boundary at Cotonou to the eastern edge of Akassa, bounding the Bight of Bonny in all the Gulf of Guinea sector of the Atlantic Ocean.

Thus, a key insight and observation of this study's dataset is the strong localization of results owing to the high modularization of locations leading to the discovery of several viable sites, unlike virtually all other researches in the region that blanketly categorized it between only 1 (as a single area) to 6 (based on individual states) wide dataset or study points which resulted in the gross misleading of the zone's true renewable energy vegetation and energy mapping that makes many energy planners, investors, researchers, policy managers, and decision makers to wrongly cancel out the region as not being viable for certain renewable energy power generation.

Figure 5.2 shows the results of energy cost from the hypothetical 100KW hybrid mini-grid system computation as well as results of HOMER and MATLAB Simulink simulation as a proportionality insight to TEREVI variation across the respective energy sources. The COE results help to systematically compare and analyse as well as granulate the TEREVI assessment process being a component index. Hence, further researches diving deeper into each location by breaking up to as much nodes or stations as possible will increase the accuracy and convergence of results and analysis and better guide energy system designers, regulators, organizations, and researchers on the leeway to cost effective and efficient off-grid electrification or islanding for sustainable solutions and ancillary benefits.

Figure 4.1 shows the Mutative Genetic Algorithm (MGA) result for the technoeconomic model output based on the TEREVI chromosome defining each respective energy source as optimized generational progeny across the various options, tipping out at best crossing convergence. The convergence peak represents the optimal hybrid energy configuration for each given mini-grid, whose granularity is the composition of renewable energy sources driving it. This makes TEREVI both a qualitative and quantitative assessment technique for designing, planning, and deciding the configuration and sizing of mini-grids, especially based on renewable energy sources, as shown. As a result, high up TEREVI values are first to reach optimal iterations in performance and compared to lower TEREVI sources for a given geographical location.

Conclusion

The TEREVI is a very potent tool and all – encompassing index as a one – stop – shop for compressively judging the commercial viability of renewable energy technologies and sources based on technical, economic, enabling environmental, and sustainability indicators as well as their sub-criterion as has been revealed by the successes recorded and confirmed by both conservative and HOMER software-based analysis.

The most techno-economically viable renewable energy resources/technologies across South–West Nigeria are solar photovoltaic and solar thermal power systems with close TEREVI values of 0.850911132 and 0.835528397, respectively. Solar photovoltaic power and solar–thermal power systems are also readily integrable with other viable sources like small hydro power and biomass, having TEREVI scores of 0.794727616 and 0.791839506, respectively.

Offshore Wind Power system with a score of 0.762531038 is readily hybridizable with marginal marine-based renewable energy resources like wave and tidal power, having South–West Nigeria scores of 0.663611024 and 0.653360129 respectively.

With a score of 0.70280359 on the TEREVI scale, onshore wind energy resource at 10m altitude is only technically feasible in Obafemi – Owode area, while at 50m altitude is technically feasible in 18 out of the 26 stations observed in this study making it very commercially alluring with Beaufort Scale of 3 – 8 wherein the 75th percentile locations may be creamed off for immediate pilot project planning and development.

Therefore, the energy sources with TEREVI above a mean of 0.756914 in addition to onshore wind energy for some selected locations with minimum mean windspeed from 3.5m are proven veritable renewable energy resources for hybrid off-grid power generation while sources below the mean are marginal renewable energy resources with strong medium and long term promises of technological advancement in South – West Nigeria.

The TEREVI is also applicable for non–renewable and hybrid energy design and configurations in any geographical location and thus recommended for more informed research by financial, public, academic, and research institutions as a standard yardstick for accurately judging locally available energy resources

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