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THE IMPLEMENTATION OF ENERGY TRILEMMA CONCEPT IN ACTIVE DISTRIBUTION HYBRID MICROGRID: A REVIEW

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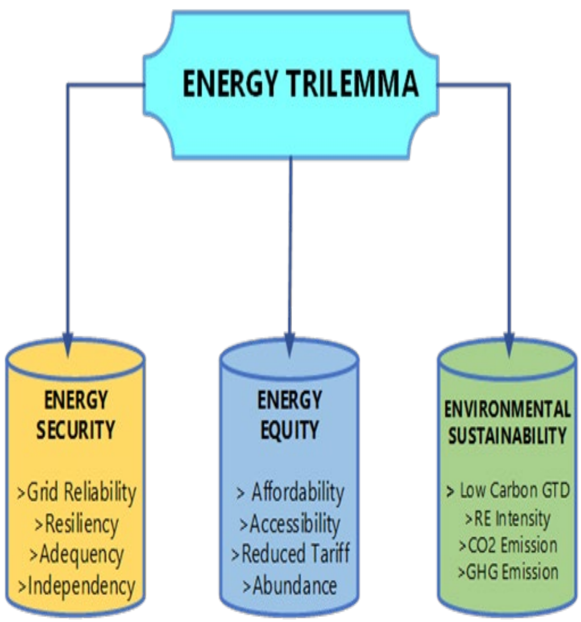
Graphical abstract



Abstract

The search for sustainable energy systems has been a multidimensional focus area comprising the United Nation (UN), Governments and corporate organizations over last three decades. The UN sustainable development goal (SDG) goals 7 and 13 encourages the generation, transmission and utilization of clean, affordable and eco-friendly energy systems. On the other hand, researchers are more engaged in trying to balance the trade-offs emerging in balancing energy security, energy access and environmental sustainability. The World Energy Council (WEC) is the organ responsible for developing standards into which each country is assessed based on the sixteen indicators and five sub indicators of the electricity utility sector. This paper seeks to review the various works on the application of a long existing concept of energy trilemma (ET) to the energy management strategy (EMS) in power system. The concept envisages flexibility in generation, reliability in transmission and affordability in active distribution hybrid microgrid (AD-HMG) in addition to mitigating environmental emissions. In achieving the sustainable energy management system, several literatures have attempted to proper different alternative pathways with a view at arriving in the same destination. The ET concept ensures harmony in balancing conflicted trade-offs within a universally acceptable framework with each country redefining its effective EMS policies and laws. Inconclusion, this study attempts to uncover the various efforts in the research spectrum of the ET and its implication on microgrid EMS. Based on the various salient technical, economic and environmental breakthroughs, the study recommends future direction to achieve universally sustainable energy system.

Keywords: Energy trilemma concept; active distribution hybrid microgrids; energy management system; sustainability energy system, GHG emission

Abstrak

Pencarian sistem tenaga lestari telah menjadi bidang tumpuan pelbagai dimensi yang terdiri daripada Pertubuhan Bangsa-Bangsa Bersatu (PBB), Kerajaan dan organisasi korporat sejak tiga dekad yang lalu. Matlamat pembangunan mampan PBB (SDG) matlamat 7 dan 13 menggalakkan penjanaan, penghantaran dan penggunaan sistem tenaga yang bersih, berpatutan dan mesra alam. Sebaliknya, penyelidik lebih terlibat dalam cuba mengimbangi pertukaran yang muncul dalam mengimbangi keselamatan tenaga, akses tenaga dan kelestarian alam sekitar. Majlis Tenaga Dunia (WEC) ialah organ yang bertanggungjawab untuk membangunkan piawaian di mana setiap negara dinilai berdasarkan enam belas penunjuk dan lima sub penunjuk sektor utiliti elektrik. Kertas kerja ini bertujuan untuk mengkaji pelbagai kerja mengenai aplikasi konsep trilemma tenaga (ET) yang sedia ada kepada strategi pengurusan tenaga (EMS) dalam sistem kuasa. Konsep ini membayangkan fleksibiliti dalam penjanaan, kebolehpercayaan dalam penghantaran dan kemampuan dalam mikrogrid hibrid pengedaran aktif (AD-HMG) selain mengurangkan pelepasan alam sekitar. . Dalam mencapai sistem pengurusan tenaga mampan, beberapa literatur telah mencuba untuk memperbetulkan laluan alternatif yang berbeza dengan tujuan untuk tiba di destinasi yang sama. Konsep ET memastikan keharmonian dalam mengimbangi pertukaran yang bercanggah dalam rangka kerja yang boleh diterima secara universal dengan setiap negara mentakrifkan semula dasar dan undang-undang EMS yang berkesan. Kesimpulannya, kajian ini cuba untuk mendedahkan pelbagai usaha dalam spektrum penyelidikan ET dan implikasinya terhadap microgrid EMS. Berdasarkan pelbagai penemuan teknikal, ekonomi dan alam sekitar yang menonjol, kajian ini mencadangkan hala tuju masa depan untuk mencapai sistem tenaga lestari secara universal.

Kata kunci: konsep trilema tenaga, mikrogrid hibrid pengagihan aktif, sistem pengurusan tenaga, sistem tenaga lestari, pelepasan gas rumah hijau (GHG)

1.0 INTRODUCTION

Trilemma in philosophy is a choice between three unfavourable options [1]. When referred to energy security, equity and environmental sustainability, trilemma entails achieving all the three goals simultaneously, within the parameters representing the requirements in question [2, 3]. Energy trilemma describes how the three requirements that should be achieved and cannot be independently considered [4, 5] as shown in Figure 1. The concept was first reported by Brundtland in 1987 on achieving sustainable development. He outlined three dimensions of energy sustainability – environmental protection, economic development and social equity and the immediate need to include these components into political decision in global energy management [6]. The reported concluded on sound environmentally safe, and energy management is economically viable, that will inevitable improve human advancement in the distant future [3]. This was what later would become energy trilemma concept.

The energy security component of the trilemma concept is often subject of several definitions. Sovaccol 2011 discovered 45 definitions of 'energy security' from different researchers. The term is context subjective to discipline, individuals and nations depending on the perspective of the writer. However, reliability, adequacy, quality and resiliency of energy generation, transmission and distribution stands out more acceptable in most literatures [7]. The elements of energy dependency is also included in some literatures to portray the import of energy as insecurity [8]. The resilience component of energy security defines the ability of the energy network to regain normalcy when subjected to disruptions as a result of natural disasters.

The concept of energy access, energy poverty and energy equity are continuously argued with different scholars trying to proper comprehensive definitions. For instance, the authors in [9] reported 'energy access' as affordable price and connection to the grid. Where [10] added adequacy, affordability, and quality in addition to achieving basic energy needs. This comprehensively captured the whole meaning of energy access. However, [11] emphasizes more on the dynamic nature of access which includes connection, minimum consumption level and increasing electricity tariffs over time as a result of consumer preferences [12]. In the opinion of this authors, the terms affordability, adequacy and basic needs are subjective to the consumption characteristics and income level of the target groups. Therefore, it is ideal to include the dynamic nature of the definition of energy access to capture the target group preferences and economic status [13, 14].

The third component of the trilemma triangle provides for deliberate environmental protection measures to ensure sustainability. This rather complicated dimension entangles both the energy security and access as well as their political dimensions which includes energy law [15]. Principally, human economic advancement is interwoven with quality energy management system [16]. Cumulatively, the ultimate consequences of such uncontrolled efforts may cause global climate change in the form of flooding, water receding, global warming and several human survival threatening disasters [17]. That is why the authors in [9] called for global concerted efforts to streamline energy laws as championed by UN SDG goal 7. The comparative improvement in trilemma index over the last two decades shows significant breakthrough in over 90% of the 119 countries surveyed. The top three countries in the overall trilemma index as at 2019 were Switzerland, Sweden and Denmark [18]. Figure 1 shows the three components of energy trilemma and how its relates to sustainable future energy perspectives. The world energy council (WEC) 2019 formally defines the three dimensions of the energy trilemma as energy security which reflects a nation's capacity to meet current and future energy demand realistically [14], withstand and bounce back swiftly from system shocks with the utmost minimal disruption to energy supplies [19-21].

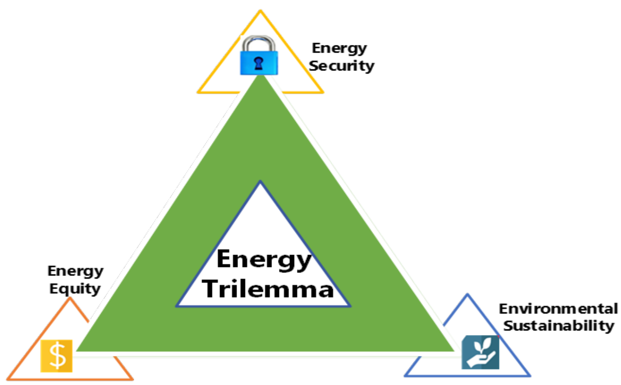


Figure 1 Components of Energy Trilemma

The second part of energy equity assesses a country's ability to provide both domestic and commercial residents with affordable and abundant energy; and the third part relates to environmental sustainability [22], which refers to the transition of a country's energy system towards reducing and avoiding potential environmental and climate change harms [23, 24]. In many countries, energy policies are aimed at supporting a cleaner environment, strengthening supply security, and providing consumers with energy [25].

However, since each of these objectives involves trade-offs with the other, the existing power sector epitome does not allow meeting them simultaneously, leading to an energy trilemma [26-28]. The 16 indicators proposed by the WEC, and 5 indicators of electrical utility assessment are the voltage violations, loading affordable LCOE, low losses and CO2 intensity violations. In addition, it's also entails the evaluation of the distance of energy sources, mode of transportation to the demand side and safeguarding the transmission and distribution networks [10]. Figure 2 also indicates the sustainable energy system as a result of achieving ET objectives by debliberate adoption of the ET concept.

In achieving the needed level of transition from the hitherto fossil based economy to a more environmentally friendly energy consumption and generation, several technological and socio-economic consideration has to be made [10, 27-28]. The technicalities of co-generation of energy sources to relate to the transmission and distribution networks effectively while adequately considering the intermittency of renewable energy sources need to be addressed as outlined by authors in [20, 30, 31].

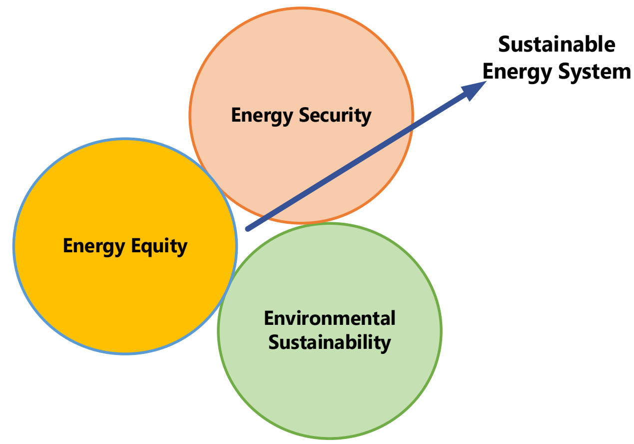


Figure 2 Energy Trilemma Concept

2.0 METHODOLOGY

A proposal for an architecture for choosing the possible literature to be thoroughly examined has been made after browsing the accessible databases. Additionally, the backward and forward search process was implored to find even more relevant papers at stage one. All the manuscripts reviewed both English and non-English language were examined for linguistic compatibility, year of publication limitations and keywords were done at stage two. The title of the research papers is screened as the next step of elimination.

Filtering the papers' titles and content relevancy is done at the third level. To achieve this, a sizable number of studies that have addressed the issue are recognized, and optimisation techniques for the MG system is introduced. The current dynamic energy system environment calls for an increasing trend of autonomous search, hence this paper's attention is limited to energy trilemma and its relationship with microgrid system. In google scholars and Scopus over 1,000 literatures reported the keyword 'trilemma' while web of science reported over a 200. However, over 16,000 literatures reported on 'Microgrid' either as relates to radial distribution or smart grids, economic dispatch [32], optimal power flow [33]. The criterions were used to sort only relevant to search keywords only.

2.1 An overview of Energy Trilemma Concept

The authors in [34] reported a survey of over 104 literatures to justify the non-uniformity of terms used in the trilemma concept especially as its regards applicability in global perspective. A country wide study of over 125 countries was also surveyed in [35] with individual indicators and sub indicator scores [36].

The security dimension comprises of sub indicators which addresses the efficacy of internal and external energy sources as well as reliability and resiliency of energy infrastructure in other to establish the score card[37]. The third dimension in the trilemma is relatively the most difficult to realise without compromise on production and industrialization[38, 39]. The carbon emission from power generation can be mitigated by penetration in renewables[40, 41], however, production of the renewable equipment requires heavy industrial waste management to conserve the environment[8, 42-43]. Figure 3 shows the various subcomponents of the ET concept.

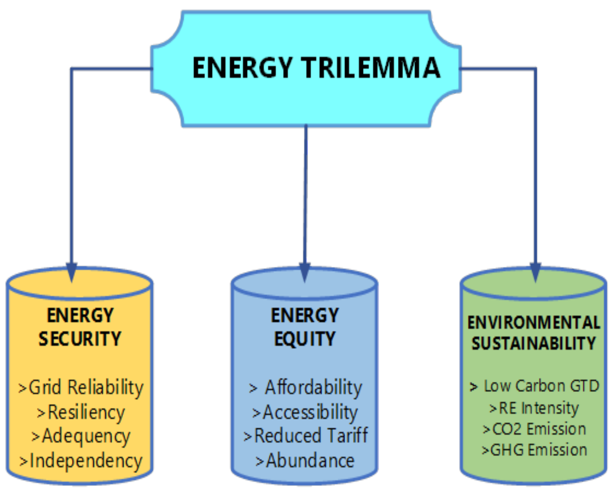


Figure 3 Subcomponents of Energy Trilemma

Therefore, the term sustainability was deliberately adopted to indicate the growth of economic and transformation of societies. Consequently, the global renewable energy penetration of solar and wind was only 33% (600 and 597 GW) in 2019 and is projected to reach up to 40% of the world power generation by 2025 [46]. Additional generation from onshore wind turbines is also expected to further complement the existing renewable targets. Furthermore, the need to include the smart transportation network system to cushion the cost of energy utilization in addition to reliability improvement was discussed in [45-48]. Smart grids are classification of microgrids complemented by renewable energy sources. Whereas [49] defined energy management system as the information interchange between the various functionalities on the network and the generation, transmission and distribution terminals through a platform [50-52].

2.2 Transition to Sustainable Energy System

The transition to sustainable energy with minimum environmental pollution vis-a-vis the economic growth of top 10 large emission countries was reviewed by [8] and there has been greater research attention to ensure reliability in power distribution network [53], social equity and nature sustainability [54-56]. The objective of the energy transition scenario is to build a low-carbon economy on a stable, long-term basis [57-59]. Moving to sustainable energy would generate more employment, improve living conditions, and ensure long-term economic prosperity [60-62].

This includes micro/macroeconomic situations, energy management systems and investment stability and energy innovations [4, 44, 63-65]. To examine the interrelationship between the three dimensions of the energy trilemma triangle it is important to analyze their interconnections [80], but the existing reviewed literatures mostly often consider the conflicts between the trilemma's components [81-85]. Figure 4 indicates the implementation of ET concept to enhance hybrid microgrid reliability and sustainability.

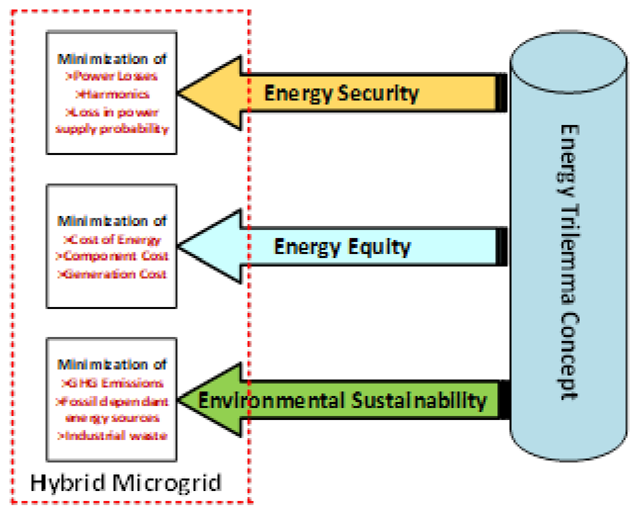


Figure 4 Implementation of ET Concept in Hybrid Microgrid

2.3 Application of Energy Trilemma in Power System

The ET exemplifies the basic problem of the global transition of energy [69]. The security component encompasses the capacity to satisfy present and future demands of energy, as well as the capacity to curtail and recover from system disruptions, which includes dependability and reliability. Hybrid microgrids provide a strategic resolution to the energy trilemma by bolstering energy security, advancing energy justice, and fostering environmental sustainability. Their capacity to combine various energy sources and function autonomously renders them optimal for distant, disaster-prone, and off-grid situations [70]. The equity components assess the system's ability to supply affordable, dependable, and adequate energy. In addition, the environment conservation component should provide the capacity to minimize and prevent the effects of GHG emission and environmental deterioration [71]. However, additional five electrical utility indicators are included by the authors in to further assist in informed and quantifiable decision making [72], [73], affordable levelized cost of energy (LCOE) [74, 75], decrease losses and reduce carbon emissions [76-78]. Table 1 shows the summary of implementation of ET concept in power system configurations.

Table 1 Application of Energy Trilemma Concept in Power System

Component of Trilemma	Implementation in power system Main Focus	G	T	D	Application
Energy Security	Stable GTD Diversification Resiliency	√	√	√	Smart Grid Microgrid Grid retrofitting
Energy Equity	Access Affordability Reduce tariff	√	x	√	Solar Mini grid Wind Turbine Hydro Pump
Sustainability	GHG reduction RE Transition Consumption	√	x	x	CO2 capture DERs with RE Decarbonization

*G=Generation T=Transmission D=Distribution

In the same vein, energy equity has also been considered as a separate field of research again, often with little consideration to its relation to energy security or climate change mitigation, or even the possible conflicts between them. The decarbonization and digitalization in electricity distribution networks has resulted in increased penetration of DER and migration from passive to active distribution networks [86, 87]. However, the cost of some renewables such as photovoltaic panels is decreasing while the wide integration of variable renewables without destabilizing the electricity grid remains the major challenge [88-90].

3.0 MICRORID AND ENERGY MANAGEMENT

The power system set up is a multi-constraint as well as flexible network. The flexibility aspect is more prone to several optimization techniques and energy management strategies. Mainly MG studies are classified into energy management which considers optimal distribution, economic dispatch and load flow analysis and control system that deals with the frequency, voltage, active and reactive power controls [93, 94] The energy consumption attitude of individuals differs and also the nonlinearity of renewable energy sources integrated into the MG further confirms the utmost relevance of effective energy management system [95]. In the overall analysis, an effective EMG in MG system must be able address energy demand increase, nonlinearity of renewable sources, stability and security of transmission and distribution facilities, high cost of energy and environmental sustainability concerns among others [96]. The generation component of electrical power systems requires several sub systems to deliver the required energy to the demand side. Therefore, it requires an efficient control mechanism to coordinate and manage the operation of the whole network [97].

An efficient EMS should have the capability to deliver power with minimum losses, economical generation, enhance performance and minimize carbon emission [98, 99]. The authors in [100] introduced three constraints to minimize cost of generation and at the same time reducing environmental emissions. The energy balance, feasible energy dispatch and feasible builds are the constraints to optimize the objective functions [101, 102]. In the same regards, the decarbonization, decentralization and digitalization must be given a global outlook in terms of general overview of energy policies [103].

The concept MG of microgrid was adopted to include more penetration of renewable energy sources to the main grid. Efficient and effective deployment of more energy sources will certainly improve the grid reliability in terms of lower loss power supply probability (LPSP) and reduce the cost of energy at the demand side [104]. The analysis of diversity factors and country's energy production and consumption ratios indicates that achieving the energy trilemma framework concurrently is feasible considering Indian's breakthrough in renewable energy penetration between 1990 to 2020 as well as Pakistan's waste incineration drive to convert human waste to energy [105-106]. To further buttress the implementation of ET concept to optimize microgrid and energy management system, the following points enunciate the significance of adoption. Table 2 depicts the summary of literature reviewed while applying components of ET and the methods used in achieving the optimized microgrid.

Table 2 Summary of relevant Literature Reviews

Ref. No.	Trilemma Component	Methods Adopted	Optimization Objective Functions	Advantages	Disadvantages
[1]	Security Equity Sustainability	DigSILENT Energy Plan Simulation	Minimization of >CO_2 Emission >Voltage Violations >Line Losses > LCOE	Wider Application Risk Management Cost Optimization Flexibility application	High license cost Limited GUI Prone to black swan Single Optimization
[2]	Sustainability	Markowitz MCDM SMAA	Minimization of >Risk of returns >CO_2 Emission	Flexibility application Interdisciplinary Realtime optimization	Complex data required Over sensitivity Correlation mismatch
[3]	Security Equity Sustainability	Overview	Maximization of >Smart Grid Integration	General solution Simple in approach Easy referencing	User bias data Limited input data Simplicity

Ref. No.	Trilemma Component	Methods Adopted	Optimization Objective Functions	Advantages	Disadvantages
[4]	Security Equity Sustainability	Principal Component Analysis (PCA) Simulation	Maximization of >Eigenvalues (λ) >Variability (%) >Cumulative (%)	Dimension reduction Improved data view Noise reduction Easy computation	Interpretation loss Assumes linearity Risk of overfitting Scaling sensitivity
[5]	Security Sustainability	Dynamic Estimation Model (DEM)	Maximization of >Smart Transportation Penetration	Realtime estimation Predictive capability RE integration Threat resiliency	Sensitivity to error High Cost Limited performance Complexity
[6]	Security Equity Sustainability	Epsilon-Const. Mixed Integer linear Program (EMILP)	Minimization of >Cost of Energy >Realibility >GHG Emission	Multi-objective Accuracy Robust application Supports Sensitivity	High complexity Selection challenges Limited performance Limited real-time
[7]	Security Equity Sustainability	HOMER Pro	Maximization of >RE Penetration Minimization of >GHG Emission	Easy hybrid design Economic analysis Flexible versatility Cloud-based features	High license cost Limited real-time High computational Intensity to large data
[8]	Security Equity Sustainability	Reviews	Maximization of >Integrated Renewables	Simple application Quick referencing Generic solution	Simplicity in approach Limited input data User defined data
[9]	Security Equity Sustainability	Country-Based Review	Recommend >Policy Transition to Energy ET Concept	Local planning Originality Input data accuracy	Idea localization Limited application Prone to user biasing
[10]	Security Equity	Nodal Pricing Zonal Pricing Uniform Pricing	Recommend Minimization of >Cost of Energy using single pricing	Good price signal Congestion reduction Price transparency Economic dispatch	Higher Complexity Prone to volatility Data intensity High investment risk
[11]	Security Equity Sustainability	PVSyst HOMER Pro	Minimization of >LCOE >CO_2 Emission Maximization of Annual (Generation)	Optimal hybrid design Effective economic analysis Cloud-based features Flexibility application	Higher cost of license Limited real-time Higher computational Insensitivity to large data

a. Security in EMS: This area addresses numerous types of MG properties that have reliability considerations, such as how they collaborate and execute without causing system failure [107]. Alternating between on-grid and off-grid modes of operations [108].
b. Equity in EMS: The cost-effective and efficient operation of all MG components was addressed by EMS as social affordability. Economic considerations is the main goal in this category. Cost minimization and the system benefits maximization were also considered [109, 110].
c. Adaptability in EMS: To consider the flexibility in operation, the MG must meet the demand using available energy resources with the goal of emissions reduction and increase RE penetration targets [31]. The environmental conservation considerations are the major concern in this component [111].

Figure 5 shows the various interrelationship between configurations of MG and EMS.

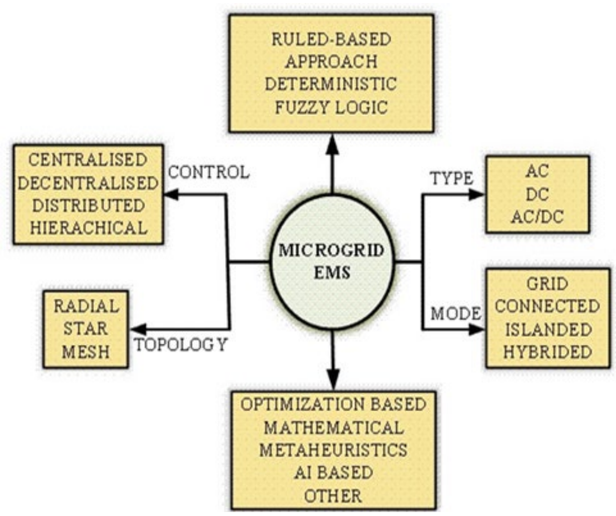


Figure 5 Microgrid Energy Management System

In the same vein, the authors in [49] opined that, microgrid reliability is as reliable as the various generational sources' storages output while isolated or Hybrided [112]. To complement the intermittency of renewable sources such wind and PV, deliberate technical feasibility and compatibility of the distribution network could be plausible [113]. The authors in [3] also assert that, the trilemma concept is multidimensional, with each component adjustment ordinarily requires the realignment of the remaining pillars. For instance, in certain countries, energy policies on diversification of sources using renewable energy could improve energy security and environmental sustainability [114, 115].

On the other hand, to promote grid intensity and efficiency can also enhance energy security by reducing grid dependency [116]. Therefore, in the energy trilemma angle, it will be extremely difficult to define a single component or dimension without also consequently affecting the other pillar of the triangle [117]. Meanwhile, due to the intermittency of renewable energy sources, the dependability and reliability issues caused in the power network have resulted in a disadvantage status of integration. To overcome this problem, several optimization techniques have been offered to successfully schedule energy supplies or storage facilities to maximize network efficiency [118]. On the other hand, the resiliency of microgrid is enhanced by energy storage system. The case of Hurricane Maria in 2017, California wildfire and Australia bush fire compelled the utilities in the prone regions to opt for battery-backed hybrid microgrid to mitigate sudden grid outages as a result of disasters.

The MG-EMS goals are divided into three categories according to the energy trilemma concept. Thus, secure system operation, cost-effective (affordable), and environmentally sustainable system. Affordability aims to include minimizing operational and general energy expenses, minimizing economic load dispatch problems (ELDP) at the same time maximizing individual and collective benefits [119, 120]. The MG system may be made more adaptable and sustainable by using distributed energy resources, reduction in peak load, day-ahead appliance scheduling, and internal energy trading, maximizing renewable energy penetration, energy availability, and minimizing the cost of emission [121, 122]. The MG system is made secure by supply and demand balance, reducing load shedding, mitigating load curtailment due to unexpected attacks or sudden failures [123, 124]. The EMS's objective classification of MG as either flexible,

This paper analysis MG EMS from a variety of perspectives, including the use of contemporary equipment, methods of control, problem solving approaches, ultimate goal functions, various limitations and its application to energy trilemma [125]. Basically, the two major components of MG networks are energy management and control. The cost of energy and demand trade-offs were also discussed in [126, 127]. Therefore, a critical examination of MG and control optimization methods that account for energy trilemma components is imperative [128].

As depicted in figure 6 the interconnection of ET concept and Active Distribution Hybrid Microgrid (AD-HMG) is embedded in the energy management strategy adopted to optimize the MG. Energy storage technologies, especially batteries, are essential for bolstering the resiliency of microgrids against disturbances, natural disasters, sudden grid failures, and unforeseen demand surges. The literatures indicates feasible implementation of ET principles in MG optimization considering reliability, access and address environmental concerns in both generation and transmission [61, 68].

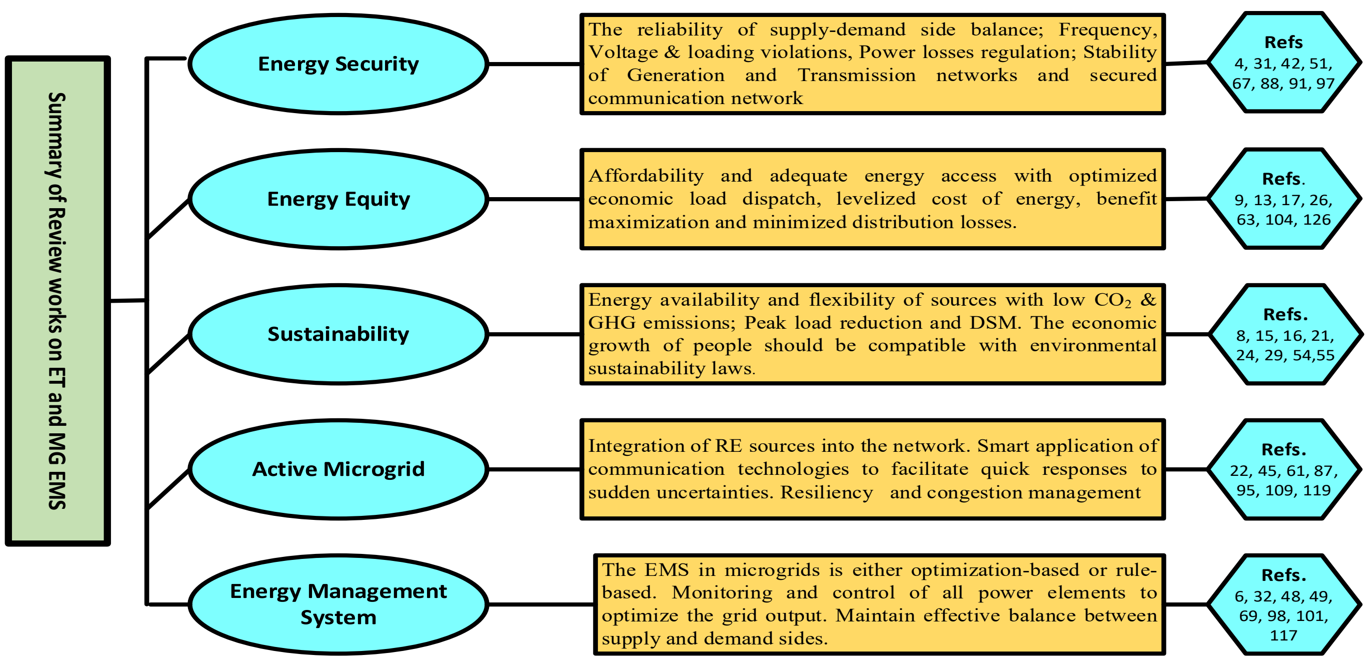


Figure 6 Review works on Energy Trilemma and Microgrid Energy Management System

3.1 General Discussion

The Paris agreement commits the industrialized countries to reduce emission by domestication of energy efficiency policies while ensuring sustainable energy system. Energy reliability enhancement strategies should be incorporated to existing legal framework to achieve resiliency, adequacy and sustainable energy management system. Therefore, optimization of all the energy trilemma components simultaneously can provide an efficient breakthrough in arriving at a secure energy strategy. Some researchers opined the emission reduction of 46%, reliability improvement of 43% and affordability rise of 19% with the implementation of energy trilemma concept. However, reconfiguration of existing networks to be compatible with high renewable penetration requires detailed feasibility studies and technical optimization analysis. Although the major challenge in the trilemma concept adoption of energy is the trade-offs that are achievable with distributed energy resources, the heavy capital investment calls for stronger commitment.

Meanwhile, some researchers are of the opinion of more islanded microgrids to diversify the energy sources to achieve greater access penetration to local communities. This could only seem feasible when the people involved have being integrated into the social aspect of the design for ownership and protection. At the same time, advocacy and sensitization on the use of renewable sources as against the consequences and implications of the use of fossil fuels should be favored. In order to achieve compromise solution within the objective function of the energy trilemma (cost, reliability and emission reduction), proper analysis of the performance indicators is inevitable. Furthermore, most of reviewed literatures that adopted energy trilemma concepts to optimize the microgrids distribution system emphasized more on integration of renewable sources, smart application of communication technologies, emergency control mechanism and complex power sharing with voltage and frequency capabilities while using different topologies. However, some reviews have incorporated mitigation GHG emission to satisfy the environmental sustainability criteria. The five sub indicators developed by the WEC to effectively satisfy the trilemma dimensions with specific applicability to electricity utility sector were only implemented by some studies.

4.0 CONCLUSION AND FUTURE PERSPECTIVES

The adoption and implementation of energy trilemma concept by several developing economies have yielded significant reduction in GHG emission, greater access to affordable energy and improved reliability in both generation and transmission sources. However, the microgrid energy management strategies have so far not fully incorporated the optimization of loading violations, voltage violations, and technical power losses in the distribution network as well as levelized cost of energy consumption to achieve a harmonized sustainable energy system. The efficient and effective utilization of flexibility components of energy sources requires deliberate investment in high precision technology to raise the energy security dimension of the trilemma concept. The aggressive competitions by the Paris Agreement signatories to achieve zero carbon emission by 2030 have significantly reduced the global threat to climate change mitigation as highly industrialized countries are working towards the conditional targets of emission free pathways.

The implementation of the Energy Trilemma Concept in electrical power systems requires new solutions that concurrently satisfies the need for secure, accessible, and environmentally sustainable energy management system. Balancing these three aspects is intricate yet vital for establishing a robust and future-proof electricity grid. The deliberate optimization of each parameter within the trilemma triangle will certainly enhance the threshold and boost the sustainability of future energy management plans. Therefore, it is recommended that future research directions on the application of energy trilemma to active distribution hybrid microgrid networks should include but not limited to:

- Optimization and integration of emission free renewable energy sources such as solar photovoltaic, wind, geothermal, hydro power and nuclear power generation capabilities.
- Implementation of hybrid energy sources microgrids models based on distributed renewable sources penetration to include various social inclusion dimensions.
- Deliberate policy shift to incorporate energy trilemma components in National Energy Policy frameworks by incentivizing renewable energy generation and discouraging fossil fuel consumption.
- Review various feasible energy generation, transmission, and distribution strategies with a view to adopt and adapt an optimized solution for sustainable energy system realization.
- Advance the course of collaboration with various multinational energy stakeholders to meet universal clean energy access.
- The investment in the above should be channeled to the acquisition of new technologies under a strong policy and legal regulatory frameworks.
- Optimization of Energy Trilemma should include developing algorithms or frameworks that optimize the balance between energy security, affordability, and environmental sustainability in power system.

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Conflicts of Interest

The author(s) declare(s) that there is no conflict of interest regarding the publication of this paper.

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