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Navigating Renewable Energy Transition Challenges for a Sustainable Energy Future in Ghana

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ABSTRACT

The transition to a sustainable energy future in Ghana faces critical challenges, particularly in integrating renewable energy sources like solar and wind into the national grid. This study examined Ghana's progress in renewable energy adoption using the International Atomic Energy Agency's (IAEA) Model for Energy Supply Strategies and Their General Environmental Impacts (MESSAGE) tool. It evaluates the feasibility of achieving the 10% renewable energy target set in national energy policies by 2030 and beyond, highlighting key challenges and their impact on the country's energy transition efforts. The findings revealed a significant shortfall, with renewable energy

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penetration reaching only 4.77%, far below the targeted 10%. The actual installed capacity of renewable energy sources ranges from 150.87 MW to 377.18 MW, falling considerably short of the projected 219.75 MW to 645.71 MW from 2020 to 2050, respectively. Expanding Ghana's renewable energy sector remains challenging, with fossil-based thermal generation continuing to dominate, raising concerns about emissions and sustainability. Overcoming barriers to renewable energy penetration requires targeted policies, investment in energy storage, smart grids, and financial incentives. Additionally, integrating renewables with low-carbon baseload options like Small Modular Reactors (SMRs) could accelerate Ghana's energy transition. Achieving a sustainable energy future will depend on strong governmental commitment, private sector involvement, and technological innovation to bridge the gap between energy targets and actual capacity while significantly creating jobs.

التغلب على تحديات التحول نحو الطاقات المتجددة من اجل مستقبل طاقة مستدام في غانا

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ملخص: يواجه مستقبل الانتقال إلى الطاقة المستدامة في غانا تحديات حرجة، لا سيما في دمج مصادر الطاقة المتجددة مثل الطاقة الشمسية وطاقة الرياح في الشبكة الوطنية. تقوم هذه الدراسة بتقييم تغلغل الطاقة المتجددة باستخدام نموذج الوكالة الدولية للطاقة الذرية (IAEA's) لاستراتيجيات العرض والتأثيرات البيئية العامة، مع التركيز على تحقيق تغلغل للطاقات المتجددة في الشبكة الوطنية يصل الى 10% بحلول عام 2030. تكشف النتائج عن وجود قصور كبير في تحقيق الخطة، حيث بمكن تحقيق تغلغل للطاقات المتجددة حوالي 4.77% فقط، أي أقل بكثير من النسبة المستهدفة البالغة 10%. حيث تراوحت القدرات المركبة الفعلية للطاقات المتجددة من 150.87 ميجاوات إلى 377.18 ميجاوات، بانخفاض كبير عن القدرات المركبة المتوقعة بقيم تتراوح من 219.75 ميجاوات إلى 645.71 ميجاوات للفترة 2020–2050. ما يزال التوسع في الطاقات المتجددة في غانا يواجه تحديًا، مع استمرار هيمنة التوليد الحراري المعتمد على الوقود الأحفوري، مما يثير المخاوف بشأن الانبعاثات والاستدامة. يتطلب التغلب على العوائق أمام تغلغل الطاقات المتجددة، اصدار تشريعات وسياسات مشجعة، والاستثمار في تخزين الطاقة، والشبكات الذكية، والحوافز المالية. بالإضافة إلى ذلك، دمج مصادر الطاقات المتجددة مع خيارات التوليد الكهربائي للحمل الاساسي منخفضة الكربون، والتي تعمل على تسريع عملية تحول الطاقة في غانا. سيعتمد مستقبل الطاقة لتحقيق الاستدامة على الالتزام الحكومي القوي، ومشاركة القطاع الخاص، والابتكار التكنولوجي لسد الفجوة بين أهداف الطاقة والقدرة الفعلية مع خلق فرص عمل اضافية.

الكلمات المفتاحية – تنمية الطاقة المستدامة, تحديات الطاقة المتجددة, مزيج توليد الطاقة الكهربائية، تحول الطاقة، مستقبل الطاقة المرنة، موارد الطاقة، حلول الطاقة المستدامة.

1. INTRODUCTION

Navigating the frontier of energy transition largely relies on sustainable energy solutions (IRENA, 2023b; Phan, 2020). As a result, the globe is on the verge of an energy revolution, with demand for sustainable alternatives echoing through continents for clean energy technologies (International Energy Agency, 2024; Johansson et al., 2012). The enduring threat of greenhouse gas emissions resulting from traditional energy generation is prominent in the global environment, necessitating a paradigm change in favour of renewable alternatives (IRENA, 2019; REN21, 2019). Moreover, the alarming reality that over 700 million people globally lack access to electricity underscores the urgent need to accelerate the adoption of renewable energy sources, aligning with Sustainable Development Goal 7 (The World Bank, 2022). To help attain the 1.5°C objective by 2050, the World

Energy Transitions Outlook identified significant energy transition drivers, the most important of which was renewable energy electrification (IRENA, 2023b). Impressive advancements have been made along the sustainable energy revolutionary route, particularly with renewable energies (IRENA, 2021c; IRENA and AfDB, 2022). Thus, the debate on sustainable energy alternatives largely relies on the effectiveness of renewable energy sources (IRENA, 2022). As part of stringent efforts to achieve the needed transition stay on a 1.5°C pathway with renewable energy sources by 2050, some annual penetration of 1,000 GW is required worldwide (IRENA, 2023b). Among these sources, solar and wind energy are particularly crucial for meeting the increasing electricity demand, especially in developing countries (Ahuja et al., 2019; Asuamah et al., 2021). The study by IRENA (IRENA, 2021b) on African countries that included Côte d'Ivoire, Ghana, South Africa, Morocco and Rwanda revealed that the challenges of renewable energy penetration continue to exist. Especially for Morocco and South Africa, the study indicated that while it is difficult to achieve the objective of high renewable energy to achieve the needed energy transition, lessons are learnt (IRENA, 2021b).

Increased penetration of renewable energy sources is one of the main initiatives in Ghana's energy transition agenda with a long-term net-zero framework spanning from 2022–2070 (Ministry of Energy, 2023). The prevailing consensus is that there is a steady rise in the adoption of renewable energy sources, particularly solar and wind power, attributed to a strategic focus on diversifying the energy mix (Ministry of Energy, 2023). However, despite the country's remarkable energy journey (Energy Commission, 2023), the challenges of securing a sustainable energy transition with the determined renewable energy sources persist (Essel Ben, 2015). The challenges extend beyond technical difficulties and encompass the intricate interplay between ambition and reality (Ministry of Energy, 2023). The apparent inadequacy of current renewable energy capacity in Ghana, however, is a clear challenge that is echoed by the rising demand for electricity (Energy Commission, 2023; Ministry of Energy, 2019b). Ghana's commitment to transitioning to a sustainable energy future, particularly its renewable energy penetration, mainly solar and wind remains significantly below the projected targets (Nyasapoh, Elorm, et al., 2022). The 10% renewable energy share by 2020 has not been achieved, with actual contributions from solar, wind and mini-hydro energy remaining marginal. Several barriers, spanning from financial constraints, inadequate infrastructure, policy inconsistencies, and grid integration challenges continue to hinder large-scale deployment of these so-called other renewable energy sources (Mahama et al., 2021; Nyasapoh, Elorm, et al., 2022). While national policies such as the Renewable Energy Act (2011) (Ministry of Energy, 2011), amended in 2020 (Ministry of Energy, 2020) and feed-in tariffs aim to accelerate growth, implementation remains slow, and private-sector participation is constrained (Nyasapoh, Elorm, et al., 2022). Existing literature has primarily examined policy frameworks and renewable energy potential, but limited attention has been given to the practical deployment of renewable energy targets and benchmarking them against the barriers hindering their implementation. Specifically, previous research has focused on regulatory frameworks, potential renewable energy sources, and global best practices, yet there is a critical need for empirical data on Ghana's actual progress and the obstacles impeding large-scale adoption. The study by Mahama et al. (Mahama et al., 2021) highlights financial barriers, currency fluctuations, and grid capacity issues as significant obstacles to renewable energy deployment, yet there is little empirical data on how these barriers impact long-term sustainability.

As Ghana strive to capitalise on solar and wind power, closer examination exposes constraints that transcend national boundaries and represent the larger issues that growing African nations face (Ministry of Energy, 2021). Hybrid renewable energy systems consisting of solar, wind energy with/without biofuel electric generators integrated with energy storage and connected or isolated from the grid can represent a reliable solution to the challenges of sustainable energy supply and mitigate CO2 footprint in the local society (Ali et al., 2021; El-Khozondar et al., 2023; Nassar, El-khozondar, et al., 2024; Nassar, El-Khozondar, Khaleel, et al., 2024; Nassar, El-Khozondar, & Fakher, 2025). The grid-connected renewables in Ghana, where aspiration meets reality, presently make up only 2% (114 MW) of the total electricity generation capacity of 5,481 MW (Energy Commission, 2023). Meanwhile, a 10% penetration of these renewable energy sources is required by 2030 (Ministry of Energy, 2023).

The striking discrepancy between the desired and actual integration of the renewable energy sources, mainly solar and wind in Ghana's energy mix invites a critical examination of the future generation scenario. With such an analysis, barriers impeding the widespread integration of renewables into the generation mix can further be harnessed ahead of time.

This study, therefore, seeks to bridge this gap by analysing the feasibility of Ghana's renewable energy transition and identifying actionable solutions to address these persistent challenges for a sustainable energy future in Ghana. Thus, the study employs the International Atomic Energy Agency's (IAEA) Model for Energy Supply Strategies and Their General Environmental Impact (MESSAGE) tool to analyze Ghana's complex energy landscape focusing on the feasibility of achieving a 10% renewable energy penetration target.

This study is significant because it moves beyond policy analysis to provide quantitative insights. By identifying the renewable energy deficit and the shortfall in installed capacity, this research contributes to the ongoing discourse on Ghana's energy security and economic development. Furthermore, the study proposes practical solutions to facilitate the country's renewable energy transition, including enhanced financing mechanisms, regulatory reforms, and grid modernisation strategies. The discoveries that come to light offer a crucial understanding of the obstacles preventing renewable scalability and highlight the pressing necessity for calculated actions ahead of time. Following the introduction, the study provides a brief overview of Ghana's energy transition with renewable energy, outlines the methodology, presents the results and discussion, examines the barriers to energy transition, and explores potential solutions before concluding.

2. ENERGY TRANSITION WITH RENEWABLE ENERGY SOURCES IN GHANA

By the second half of this century, the energy transition will have led to the global energy sector switching from fossil fuels or high-emitting fuels to zero-carbon sources (IRENA, 2021c). Three distinct and recognisable energy changes have been noted on a global scale. The first change in energy sources was the gradual substitution of coal for wood. Second, oil took the lead from coal as the primary energy source. The commitment to switch from fossil fuels to renewable energy sources or clean energy technology is the last and most recent (Kabeyi & Olanrewaju, 2022). Reducing energy-related CO2 emissions is the main goal of the present global energy transition agenda to slow down climate change. A global effort is urgently needed to decarbonize the energy sector. Although a global energy transition is in progress, more must be done to lower carbon emissions and lessen the effects of climate change. Natural gas and nuclear power are now considered green energy options, which are thought to help fight climate change and hasten the global transition to a low-carbon, sustainable energy system (European Parliament, 2022). This premise suggests that long-term carbon reductions of 90% can be possibly achieved through energy efficiency measures combined with low-carbon energy sources like natural gas, nuclear, and renewable energy (IRENA, 2021c).

However, as represented in Fig. 1 Ghana's present electricity generation mix system has an average annual growth rate of 5.4%, with the total amount of electricity generated gradually increasing by more than three times, from 7,224 GWh in 2000 to 24,264 GWh in 2023. 9,187 GWh (38%) of the total electricity produced in 2023 came from hydropower, whereas 14,930 GWh (62%), came from thermal power plants.

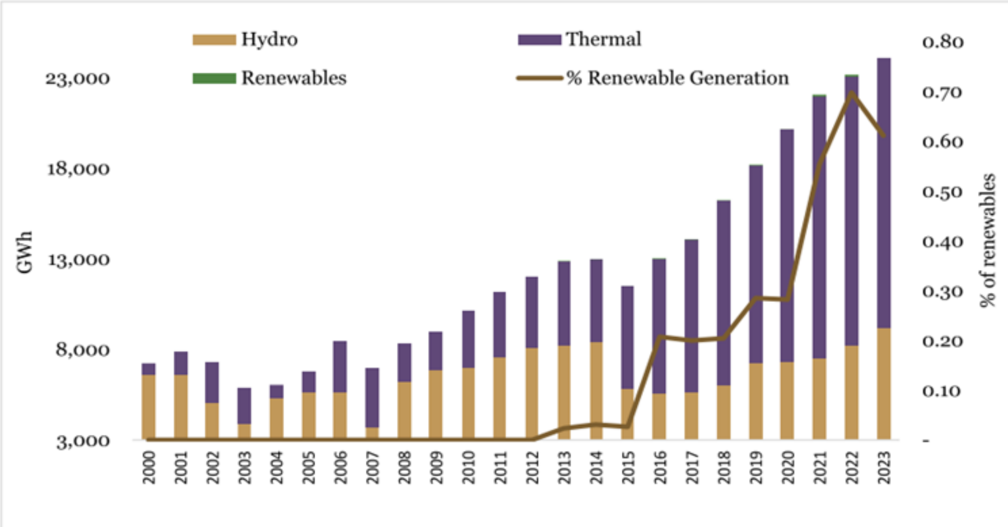

Figure 1. Ghana's electricity generation mix (Ghana Energy Commission, 2024).

Other renewable sources functioning at the sub-transmission level generated the remaining 148 GWh, or 0.61% (Ghana Energy Commission, 2024). It is concerning that renewable energy sources, including large hydropower and other renewables such as solar, wind, and mini-hydro, have been significantly overshadowed by fossil-based thermal generation since 2016 (Ghana Energy Commission, 2024). This trend highlights the continued dominance of fossil fuels in the energy mix despite the growing need for sustainably low-carbon alternatives.

As a result, the country's energy sector contributed about 45.7% (27.3MtCO2e) of the total 59.8MtCO2e greenhouse gas emissions in 2019 (Ministry of Energy, 2023). As shown in Fig. 2, Ghana's energy industry is the country's second-largest source of greenhouse gas emissions between 1960 and 2019. Primarily, the production of oil and gas for electricity generation and other purposes accounts for the second-largest portion of the energy sector emissions of 29.5% (Ministry of Energy, 2023).

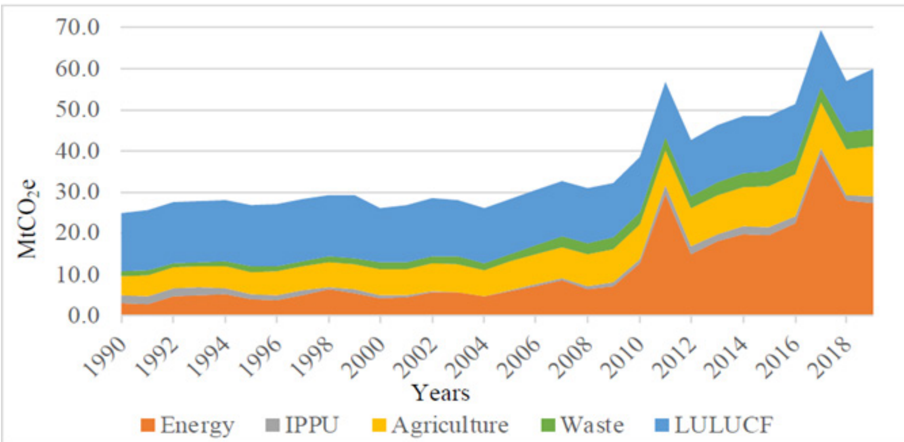

Fig. 2. Ghana's greenhouse gas emission inventory (Ministry of Energy, 2023).

The emergence of Ghana's energy transition agenda is a component of efforts to combat climate change and lower greenhouse gas emissions in response to global environmental issues (MESTI, 2021; Ministry of Energy, 2019a). The country's active participation in international agreements demonstrates the country's significant commitment as a signatory to the historic Paris Agreement

(Republic of Ghana, 2015; United Nations Climate Change, 2022). Among the essential steps to guarantee sustainable energy transitions is raising the country's renewable energy, particularly solar and wind share from the current 2% (Energy Commission, 2023) to 10% by 2030, and subsequently to 20% by 2070 (Ministry of Energy, 2023).

According to Ghana's National Energy Transition Framework, emissions will peak in 2050 and continue to drop until 2070 as a result of the penetration of renewable energy and other clean energy technologies (Ministry of Energy, 2023). Ghana's energy transition model (ETM) is shown in Fig. 3 in comparison to no policy intervention (NPI).

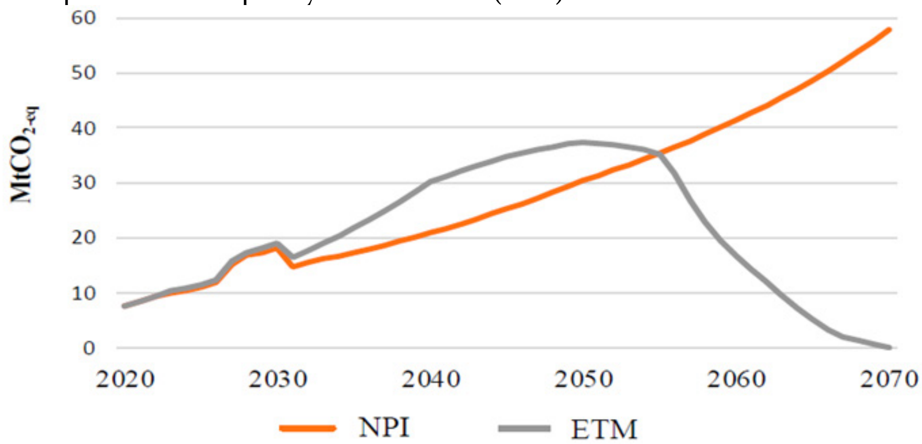

Fig. 3: No Policy Intervention (NPI) and Energy Transition Model (ETM) of Electricity Sector Emission (Ministry of Energy, 2023).

The net-zero agenda for Ghana to achieve the energy transition ambition is a long-term framework (2022–2070) with high renewable energy penetration. More significantly, 21GW of renewable energy sources are anticipated to be part of the nation's diverse energy mix, which will offer opportunities for the energy sources for commercial carbon credits (Ministry of Energy, 2023). The impetus driving Ghana's energy transition agenda hinges greatly on the potential of clean energy sources, effective policy commitment and implementation (Nyasapoh, Elorm, et al., 2022). The driving factors particularly are evident in the significant penetration of renewable energy sources, primarily solar and wind. The strategic focus of such energy sources underscores a concerted effort towards sustainability and underscores the nation's commitment to a greener future. Significantly, Ghana's shift to renewable energy, especially through the combination of solar and wind, offers significant socioeconomic advantages by lowering emissions and creating jobs (Ministry of Energy, 2023).

2.1. Potentials and readiness of solar and wind energy

Ghana uses a variety of fuels, including renewable energy sources, to produce electricity. The incorporation of renewable energy sources appears to be a fundamental component of Ghana's pathway toward a low-carbon and sustainable energy future (Ministry of Energy, 2023; Nyasapoh, Debrah, Twerefou, et al., 2022). With the technologically sophisticated and ecologically friendly solution of renewable energy sources, they are well-positioned to both meet the Ghana's growing energy needs and play a major part in lowering greenhouse gas emissions (Ministry of Energy, 2019b; Parliament of Ghana, 2020). This section delves into a thorough examination of the diverse possibilities of renewable energy, mainly solar and wind, with a particular emphasis on two fundamental components. In Ghana's continuous efforts to create a cleaner, more sustainable energy landscape, the solar and wind energy components show potential and innovation.

2.1.1. Solar Energy

Ghana's environment, with its plentiful and steady sunshine, offers a unique chance to maximise the potential of solar energy (Energy Commission Ghana, 2019a). Moreover, photovoltaic technology's ongoing development has propelled solar energy to the forefront of the renewable energy revolution (Panagoda et al., 2023; Ramachandran et al., 2022). The country is well-positioned with solar radiation, making it perfect for applications involving the combination of thermal and electrical energy (Energy Commission Ghana, 2019a). Ghana receives between 4.5 and 6.0 kWh/m2/day of solar radiation, with the northern region of the country receiving the majority of the greatest levels (Ministry of Energy, 2019b).

With a very low dispersed radiation of roughly 32%, the average daily solar radiation over the country's regions ranges from 4.4 to 5.6 kWh/m2/day. Ghana's middle belt experiences 5.3 hours of sunshine on average per day in foggy, semi-deciduous forest zones like Kumasi and 7.7 hours in arid, savannah zones like Wa in the north of the country (Energy Commission Ghana, 2019a). The PV solar energy yields can be estimated from (Amer et al., 2025; Awad et al., 2022):

$$P_{pv} = P_{STC}\left[1+\beta_{p,T}(T_{cell}-T_{STC})\right]\times\frac{H_g}{H_{STC}} \qquad (1)$$

Where P_{PV} presents the real PV power according to the operating conditions (W); P_{STC} states for the nominal PV power at the Standard Test Condition *STC*; $\beta_{p,T}$ refers to the power-temperature coefficient (%/°C); T_{STC} and H_{STC} denote the standard test conditions of temperature (°C) and solar radiation, respectively (W/m^2), in most cases equal 25°C and 1000W/m^2, respectively. The cell's temperature (T_{cell}) is expressed as (Hafez et al., 2020): $T_{cell}=T_{\infty}+0.07H_g$; T_{∞} is hourly ambient air temperature (°C). The electrical characteristics of several types of PV modules and Inverters has been documented in (Nassar et al., 2022; Nassar, El-Khozondar, Khaleel, et al., 2025).

2.1.2. Wind energy

Ghana's vast coastline, which is consistently brushed by ocean winds, offers a competitive edge for wind energy production (Ministry of Energy, 2019b). Positioned along the shore, wind turbines can harvest and transform kinetic energy into a steady stream of renewable electricity for Ghana (Energy Commission Ghana, 2019a).

Despite a non-significant wind energy installation in Ghana yet, the country is thought to have about 300 MW of recent wind farm capacity (Energy Commission Ghana, 2019a; Ministry of Energy, 2019b). The nation's wind potential is classified as marginal due to average annual wind speeds of 4 to 6 m/s at 50 m above sea level along the coast and islands. According to NREL satellite data, the country's mountainous regions, especially those near Ghana and Togo have wind speeds that are higher than eight metres per second (Energy Commission Ghana, 2019a). Wind resource studies conducted at eight locations along Ghana's coast between 2011 and 2013 determined the average monthly wind speeds at 60 metres above sea level. Furthermore, Ghana is thought to have more than 1,500 MW of wind power overall (Energy Commission Ghana, 2019a). The wind energy yields can be estimated using Equation 2, as shown by (Elnaggar et al., 2024; Salem et al., 2025):

$$P_{Wind} = \begin{cases} P_{rat}\left(\frac{V_{Z,t}-V_{cut-in}}{V_{rat}-V_{cut-in}}\right) & V_{cut-in} < V_{Z,t} < V_{cut-off} \\ 0 & V_{Z,t} \leq V_{cut-in}\, OR\, V_{Z,t} \geq V_{cut-off} \end{cases} \qquad (2)$$

3. METHODOLOGY

The study employs a quantitative research approach to evaluate the feasibility of achieving a 10% renewable energy penetration target for Ghana's energy transition. The methodology relies on accurate data, informed assumptions, and rigorous modelling techniques to ensure the reliability and validity of the analysis. This study's methodology for Ghana is similar to previous research (Kanté et al., 2023; Nyasapoh, Debrah, et al., 2023; Nyasapoh, Gyamfi, et al., 2023; Nyasapoh & Debrah, 2020), and is based on the Model for Energy Supply System Alternatives and their General Environmental Impacts (MESSAGE) analytical tool.

The primary purpose of the tool is to balance electricity demand by employing conversion technologies. Utilizing Linear Programming, the MESSAGE Model optimises objectives and addresses constraints to find optimal solutions (International Atomic Energy Agency, 2016; Messner, 1997; Schrattenholzer, 1981). The relevance of the MESSAGE model to the study is due to the tool's widespread usage in examining the effects of different courses of action and alternate sets of constraints on energy supply decisions. The model is very popular for many national energy optimisation studies (Andrianov et al., 2019; IIASA, 2020). Furthermore, IIASA (2020) disclosed that scenarios created using the MESSAGE model have been incorporated into the most current Global Energy Assessment (GEA) and assessments and special reports of the Intergovernmental Panel on Climate Change (IPCC) (Johansson et al., 2012). More significantly, using the IAEA's MESSAGE model, the International Atomic Energy Agency (IAEA) and the International Renewable Energy Agency (IRENA) are presently working together as model partners to build the African Continental Power Systems Master Plan (CMP) (IRENA, 2021a).

3.1. Adoption of MESSAGE Mathematical Model

Utilizing dynamic linear programming, the MESSAGE model reduces both the total power system's net present value and the objective function (Messner, 1997). Equation 3 presents the objective function used in the minimizeaition process to optimize costs and other factors related to electricity production.

$$min\sum_{j}\sum_{t=1}^{T}\left[d_t^0\Delta_t X_{jt}\cdot i_{jt}+d_t^c\Delta_t Y_{jt}\cdot O_{jt}\right] \quad (3)$$

Where;

T : the number of periods in the model.

j and t : technology and period, respectively.

d_t^0 and d_t^0 : discount factors applied for operating and capital costs, respectively.

Δ_t : Length of period t in years.

X_{jt} : fuel consumption of technology j in period t.

Y_{jt} : capacity variables for annual new installation of technologies

i_{jt} : Specific investment of technology j at period t

O_{jt} : operating cost of technology j in period t.

The key equations used in electricity system modeling, including environmental modeling, are the electricity demand equation, electricity balance equation, technology capacity equation, and environmental impact accounting, following Nyasapoh et al. (2023). The electricity demand equation is specified as Equation 4. This depicts the power demand-supply balance at the ideal level, when the supply must at least match the demand.

$$\sum sup\,ply \geq Demand$$

$$\sum_{j=1}^{J}\sum_{i=1}^{I}\eta_{i,j,t}\times x_{i,j,t}\geq D_{i,t} \quad (4)$$

Where;

t :period of study.
η :efficiency of plant.
x :installed capacity.
i :modelling years.
j :conversion technology.
D :electricity demand.

3.2. Electricity Demand and Reference Systems

Matching electricity demand is needed by the MESSAGE model as an exogenous variable to enable the estimation of the supply of electricity (Rao et al., 2008; Scire et al., 2000). The analysis used Ghana's Energy Commission's forecasts of electricity demand. The Long-range Energy Alternatives Planning (LEAP) model was employed by the Ghanaian Energy Commission to project the country's energy needs. Therefore, it is anticipated that the power consumption will rise from 18,542 GWh (1,594 ktoe) in 2020 to 32,460 GWh (2,629 ktoe) in 2050 (Energy Commission Ghana, 2019b).

Resources, primary and secondary fuel types taken into account for modelling, and electricity generation comprise the study's electrical supply system (Nyasapoh, 2018). Based on Ghana's electrical infrastructure, the reference electrical system (RES) was created. Starting from the energy resource and ending with the consumer's ultimate electricity supply, the RES is a framework of energy carriers. Therefore, the RES framework is a procedure that enables the representation of the existing energy chain or network, including potential avenues for Ghana's infrastructure growth related to the development of electricity (Rečka, 2011; Selvakkumaran & Limmeechokchai, 2011).

3.3. General Assumptions

- The years 2020–2050 are included in the modelling period.
- The maximum capabilities for Ghana are determined by taking into account the possible solar irradiation capacity of 6.0 kWh/m2/day and the wind speed of 6 m/s at 50 m above sea level.
- Based on Ghana's goals for a sustainable energy supply, consideration of current, projected, and future power plants was simulated. (Ministry of Energy, 2021, 2023).
- 10% renewable energy target was calculated on the renewable energy generation sources.

4. RESULTS AND DISCUSSIONS

The study's results and discussion section focus on the electricity generation analysis in Ghana from 2020 to 2050. With the energy transition policy agenda, the study further discusses the 10% renewable energy penetration target by 2030 compared to the current situation of renewable energy penetration. It is important to note that the study's results, as discussed in the electricity generation section, represent a combination of existing, planned, and committed power plants, reflecting an optimal outcome. In this context, each fuel source or technology, such as gas, is considered as a single entity rather than as separate power plants over the study period. Renewable energy technologies mainly comprised of hydro, solar and wind. This study primarily discusses solar, wind, and mini-hydro generation options, collectively classified as renewable energy (RE), and 'other renewables' by the Energy Commission of Ghana (Energy Commission, 2023).

4.1. Electricity generation by fuel source

The electricity generation analysis for the period 2020 to 2050 satisfies the demand of 2116.7 MW in 2020 to 6213.0 MW in 2050. Fig. 6 illustrates the generation mix for Ghana for the study period 2020 to 2050. The total electricity generation span from 2,197.46 MW in 2020 to 6457.10 MW in 2050. The electricity generation components are made of renewable energy sources and non-renewable energy sources.

The non-renewable energy technologies captured in the generation analysis include gas, light cycle oil (LCO), coal, and diesel fuel oil (DFO). As shown in Figure 4, fossil fuels dominate the electricity generation mix, a trend that has persisted throughout the study period. This aligns with the historical pattern of Ghana's electricity generation, as depicted in Figure 1 (Ghana Energy Commission, 2024). The non-renewable energy comprised of fossil fuel dominance is largely attributed to gas and coal technologies in Ghana. Gas began with 1442.89 MW in 2020 to 1749.036 MW in 2050. Coal also started generation in 2025 with 391.11 MW to 3684.10 MW in 2050. The behaviour of the fossil fuel generation option in the study's assessment is also confirmed in similar studies for Ghana by (Awopone et al., 2017), (Abban & Awopone, 2021), (Nyasapoh, Debrah, et al., 2023) and (Nyasapoh, Debrah, Anku, et al., 2022).

The study by Awopone et al. (Awopone et al., 2017), employed the Long-range Energy Alternatives Planning system (LEAP) tool to investigate the techno-economic and environmental impacts of clean energy sources like solar in Ghana's energy mix. The findings suggest that without investment in clean energy, the penetration of fossil fuels is expected to persist, hindering energy transition and the realisation of environmental sustainability and reduced carbon emissions by 2030 (Awopone et al., 2017). In the study by Nyasapoh et al. (Nyasapoh, Debrah, et al., 2023), it was demonstrated that to meet the needed energy transition ambition for Ghana a technological trade-off involving clean baseload options like nuclear power can effectively mitigate the dominance of fossil fuels in the energy sector. Although Ghana has announced the inclusion of nuclear energy in its energy mix, the exact date for the commissioning of the country's first nuclear power plant remains uncertain (Ghana News Agency, 2024; Nuclear Engineering International, 2023; World Nuclear News, 2024). The study further concluded that national energy policies should prioritise sustainable energy solutions to ensure effectiveness in addressing energy challenges to achieve the needed transition targets (Nyasapoh, Debrah, et al., 2023).

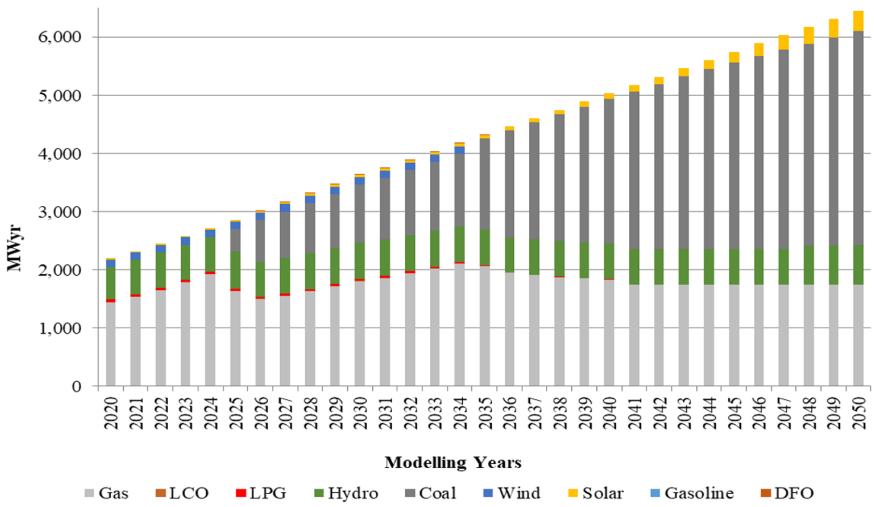

Fig. 4. Electricity generation by fuel source.

4.2. Total electricity generation of renewable and no-renewables

Given the composition of the generation mix in Figure 4, the entire system has been categorized into renewable energy (RE) and non-renewable energy (non-RE) sources to facilitate a more structured analysis and discussion. Fig. 5 presents the generation mix of REs and non-REs. The actual generation of RE otherwise termed "other renewables" by the Energy Commission of Ghana is expected to start at 150.87 MW in 2020 and expand to 377.18 MW by 2050, while the non-RE is forecast to generate electricity from 2,046.59 MW in 2020 to 6,079.92 MW in 2050. The difference in the generation system stands at 1895.72 MW in 2020 to 5702.74 MW in 2050.

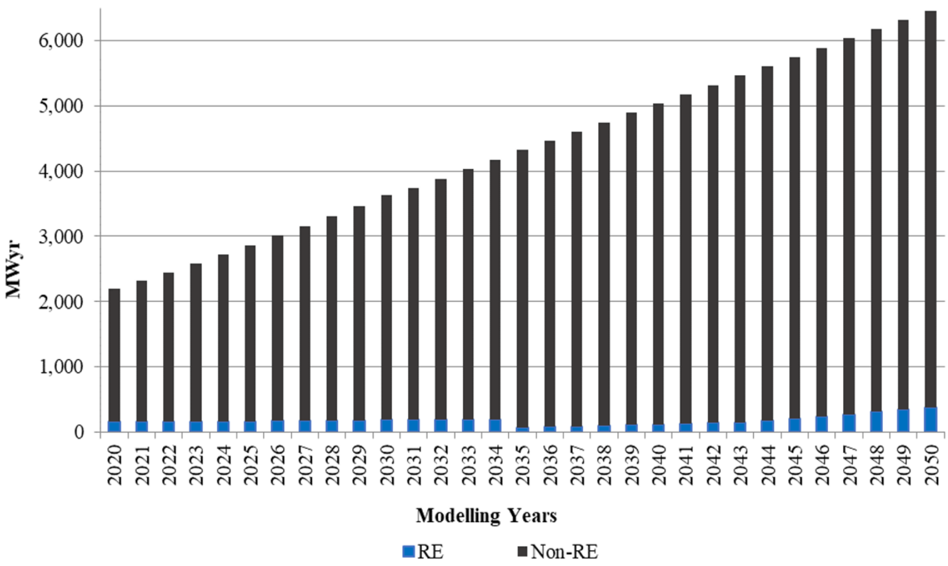

Fig. 5. Renewable and non-renewable electricity generation.

The significant disparity between renewable (RE) and non-renewable (non-RE) energy sources remains a major concern for Ghana's sustainable energy future, particularly in terms of emissions (Nyasapoh, Debrah, Anku, et al., 2022). Similar circumstances exist in Morocco, which has achieved universal access to electricity but still has low rates of renewable energy penetration, and Rwanda, which is recognised for having difficult energy transition issues. Consequently, social, economic, and environmental issues are given priority in energy policy ambitions (IRENA, 2021b). Therefore, the discrepancy between the targeted and actual renewable energy penetration in the energy mix must be examined to support effective policy recommendations.

4.3. Renewable Energy target vs the actual Renewable Energy generation

Ghana aims to achieve a renewable energy penetration target of 10% by 2030 as part of its energy transition agenda with various strategies (Ministry of Energy, 2023). To support this goal, various policies (Ministry of Energy, 2019b, 2020, 2021, 2023) have been implemented to promote RE adoption, particularly in solar and wind sectors, termed other renewable (Energy Commission, 2023). In assessing the country's ambition to achieve a 10% renewable energy (RE) penetration against the business as usual (BaU) penetration level, Fig. 6 illustrates the disparity between the 10% renewable energy (RE) target/expected and normal electricity generation circumstances. The projected 10% RE-Target for Ghana ranges from 219.75 MW in 2020 to 645.71 MW in 2050, while actual renewable energy penetration starts at 150.87 MW in 2020 and increases to 377.18 MW by 2050. Thus, the RE penetration in the electricity generation mix falls short of the targeted 10%, reaching only 4.77% instead of the expected 9.52% equivalent to the 10% RE target. This shortfall highlights the challenges in achieving the country's RE goals. These disparities highlight the challenges in meeting Ghana's 10% RE-targets at various stages, with deficits ranging from 31.34% (68.88 MW) in 2020 to 41.59% (268.53 MW) in 2050. The discrepancy has widened from 105.234 MWyr in 2023 to 268.5282 MWyr in 2050. It was argued that the nationally determined contributions (NDCs') targets for renewable energy are not only unmet but also insufficient, which is at odds with policy aspirations (IRENA, 2023a). Particularly, for this study, between 2035 and 2047, the deficits to meet the RE-targets range from 83.12% (359.44 MW) to 56.08% (338.24 MW), respectively. This aspect of the investigation is substantiated by IRENA in the World Energy Transition Outlook of 2023 (IRENA, 2023b).

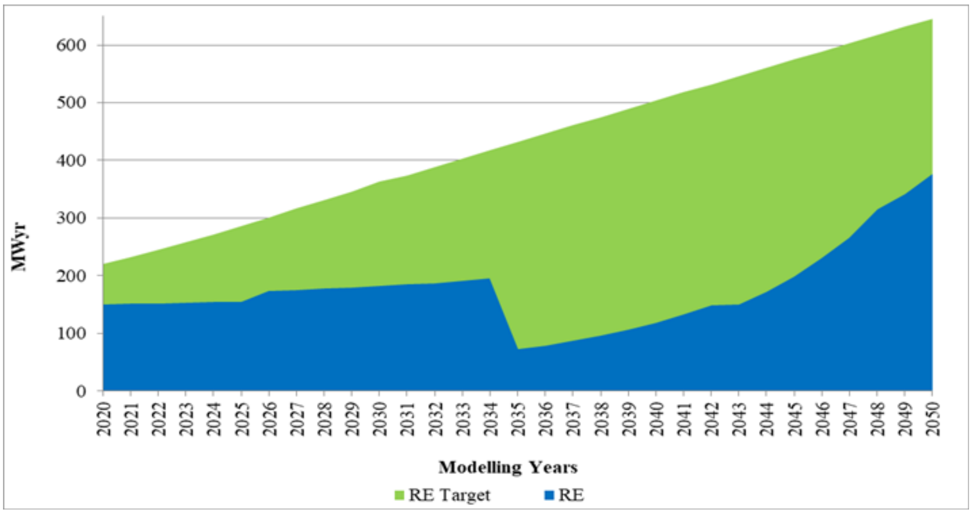

Fig. 6. Renewable energy target and actual renewable energy generation.

In general, the findings of this study corroborate and reinforce the analyses conducted in previous research regarding the varying degrees of renewable energy source penetration at specific targets. Notably, the disparity largely persists between the renewable energy target of 10% and the actual/conventional, or "business as usual," approach in Ghana's energy landscape until 2050. To address this disparity, it is imperative to tackle the numerous challenges impeding the adoption and integration of renewable energy sources to ensure the social and economic benefits of the RE integration are met.

More importantly, Ghana's transition to renewable energy, particularly through solar and wind integration, presents substantial socio-economic benefits for Ghana (Ministry of Energy, 2023). Economically, it reduces dependence on fossil fuel imports, lowers energy costs, and fosters job creation in the manufacturing, installation, and maintenance sectors (Mohammadi et al., 2023). Socially, it enhances energy accessibility, promotes environmental sustainability by reducing carbon emissions, and improves public health by minimizing air pollution, ultimately contributing to a more resilient and inclusive economy (Odunayo Adewunmi Adelekan et al., 2024).

Thus, imperative to identify the key barriers to renewable energy penetration and have actionable solutions to address these persistent challenges for a sustainable energy future in Ghana.

5. BARRIERS TO ENERGY TRANSITION

An important turning point in the continuing energy transition has been reached with the worldwide quest of sustainable development driving a considerable shift towards renewable energy sources (IRENA, 2023b). When successful, the energy transition trajectory in Ghana as seen in Figure 3 above will help to achieve the desired sustainable energy (Ministry of Energy, 2023). Although switching to greener energy sources has many advantages, there are drawbacks to this paradigm change as well. This section examines some of the major obstacles that must be overcome in order to move towards a future with more renewable and sustainable energy sources.

i. Intermittency and Reliability: The intrinsic intermittency of renewable energy sources, like solar and wind, is one of the main problems with their successful integration (Debrah et al., 2020; Esteves & Gabbar, 2023). In contrast to conventional fossil fuels, which offer a consistent and reliable energy source, renewable energy sources are contingent upon meteorological factors (Nyasapoh, Elorm, et al., 2022). The existence of the intermittency of renewable energy sources such as solar and wind leading to unreliable electricity supply sets back the transition agenda and sustainable energy future.

ii. Energy Storage Technologies: One of the most important ways to mitigate intermittent problems is to store energy produced by renewable sources (Almihat et al., 2022). Even though battery technologies have come a long way, more innovation is still required to improve storage capacity, price, and efficiency (Huang et al., 2023; Tan et al., 2021). Hence, a robust energy infrastructure with advanced storage technologies, and improved batteries is needed to over the bottlenecks of energy storage.

iii. Infrastructure Upgrades: There exist obstacles that need to be overcome when incorporating renewable energy into the current energy infrastructure (International Energy Agency, 2024). The decentralised nature of renewable energy sources such as solar and wind can necessitate significant improvements to outdated energy distribution networks and ageing grids (Kabeyi & Olanrewaju, 2022). Therefore, the shift to a more sustainable energy landscape requires investments in updating the grid infrastructure for the smooth integration of renewable energy facilities (Kabeyi & Olanrewaju, 2022).

iv. Economic Viability: Despite the long-term significant environmental benefits of renewable energy sources, the capital investment of such technologies might be a hurdle (Chien et al., 2023). More significantly, foreign assistance in the form of money, technical assistance, technology transfer, and capacity building applies to about half of the established targets for the adoption of renewable energy (IRENA, 2023a). Managing the economic factors of renewable energy sources such as solar and wind is imperative to guarantee affordability and accessibility (Chien et al., 2023). The economic viability and appeal of renewable energy for mass adoption are largely dependent on incentive programmes, subsidies, and supportive legislative frameworks (Enerdatics, 2022).

v. Technological Innovation and Research: Enhancing the effectiveness, longevity, and affordability of renewable technologies such as solar and wind requires developments in materials science, engineering, and data analytics (International Energy Agency, 2024). For this reason, the absence of constant innovative research is key to fully realise the promise of renewable energy sources and overcoming the many bottlenecks (IRENA, 2021b). Hence, spurring innovation and quickening energy transition requires the teamwork of governments, businesses, academia and international support (Quitzow et al., 2019).

6. OVERCOMING THE CHALLENGES IN RENEWABLE ENERGY DEPLOYMENT TO AID THE NEEDED ENERGY TRANSITION

National energy policies around the world have set some goals for the penetration of renewable energy for a smooth energy transition (IRENA, 2021c, 2023b). Nevertheless, several obstacles have prevented the targets from being met, and they still are. The obstacles presented by RE sources such as wind and solar need formidable solutions (Kabeyi & Olanrewaju, 2022). Therefore, overcoming and staying current with the challenges that stalled the targeted RE penetration is imperative (Cosgrove et al., 2023; Pérez-Arriaga, 2012). Thus, important elements for reorienting the global energy transition toward climate goals include constructing the required infrastructure and making large-scale investments to support new production locations (IRENA, 2023b).

A thorough understanding of the supportive measures in place and areas that require further development is provided by Ghana's evolving policy and regulatory frameworks, particularly the Renewable Energy Amended Act (Ministry of Energy, 2020), the Renewable Energy Master Plan (Ministry of Energy, 2019b), and the 2021 National Energy Policy (Ministry of Energy, 2021). However, the pursuit of a sustainable energy future amid the country's transition agenda necessitates strong governmental commitment and effective implementation of supportive measures. Long-term energy planning in Ghana, a developing nation, must prioritize balanced electricity generation policies that address economic, environmental, and social considerations to advance the green energy transition agenda (Nyasapoh, 2018; Nyasapoh, Debrah, et al., 2023). Besides that, Ghana's energy mix must closely monitor the intermittent nature of renewable energy sources like wind and solar power to guarantee supply sustainability. Addressing the intermittency of renewable energy sources like solar and wind requires the development of advanced energy storage technologies, smart grid technologies, and improved forecasting methodologies. This adoption is expected to ensure a continuous and dependable power supply for a sustainable energy future (Kabeyi & Olanrewaju, 2022). Furthermore, policies, strategies, models, and enabling technologies for the energy transition powered by renewable energy must incorporate an appropriate mix of clean energy sources (Kabeyi & Olanrewaju, 2022).

It is imperative to ensure key mechanisms comprising thermal storage, integrated energy systems and core ramping allow nuclear energy systems to be adaptable with RE sources (Bragg-Sitton et al., 2020). That is, intermittent RE sources can be tied with a baseload such as small modular reactors (SMRs) (Nyasapoh, Gyamfi, Debrah, Gabber, & Derkyi, 2024) which is environmentally friendly (Nyasapoh, Gyamfi, et al., 2023) . Nuclear energy is known to produce electricity that can enhance several advantages of the RE sources (Jenkins et al., 2018; Nyasapoh, Gyamfi, Debrah, Gabber, & Agyemang-Derkyi, 2024). In addition to improving energy security, the combination of nuclear power and intermittent renewable energy sources will guarantee that energy transition goals are met with cost-effectiveness (IAEA, 2023; Nyasapoh, Gyamfi, et al., 2022). Hybrid renewable energy systems integrated with a baseload power option like nuclear provide numerous benefits to provide the grid with consistent, long-term, and carbon-free electricity generation (IAEA, 2023). According to a recent report by the International Energy Agency (IEA), the energy transition ambition targets include the utilisation of clean energy technologies like nuclear and renewable (International Energy Agency, 2024). More importantly, it is essential to further investigate the energy system's complementary benefits of intermittent renewable energy sources, like solar, wind power, and nuclear.

6.1. Addressing Financial and Political Obstacles

It is imperative to recognise and tackle the barriers to energy transition discussed an attempt to ensure a successful energy transition implementation. More importantly, financial and political obstacles to renewable energy in Ghana require urgent attention to ensure a smooth energy transition. To address the financial challenges, the government should establish dedicated renewable energy funds, green bonds, and public-private partnerships to lower capital barriers. Additionally, introducing tax waivers and subsidies will incentivise investment. Attracting foreign direct investment through policy guarantees, risk mitigation strategies, and currency stabilisation measures is also crucial. Strengthening feed-in tariffs and ensuring stable pricing mechanisms will further encourage private sector participation.

To overcome political obstacles, it is essential to strengthen the Renewable Energy Amended Act for Ghana (Ministry of Energy, 2020) and maintain long-term policy commitment regardless of political transitions. Streamlining bureaucratic processes through digitised licensing and approval systems will enhance efficiency. Promoting competition and reducing the monopoly of state-owned utilities can further stimulate renewable energy growth. Lastly, establishing a transparent and accountable governance system will ensure consistent energy policy implementation across different administrations. With the effective implementation of the renewable energy integration challenges on the backdrop of the suggested solutions society can recognise the needed energy transition and create a more resilient, sustainable, and environmentally friendly energy landscape.

7. CONCLUSION

This study employed the IAEA MESSAGE model to assess Ghana's progress in integrating renewable energy into the country's electricity generation mix, to achieve a 10% renewable energy (RE) target by 2030. The results reveal a persistent shortfall between projected and actual RE penetration from 2023 to 2050, falling more than halfway short of the RE target. To close this gap, policymakers must prioritize targeted interventions, including:

• Invest in modernized smart grid infrastructure systems and robust transmission infrastructure to accommodate variable renewable energy sources efficiently.

• Promote research and incentives for large-scale battery storage and hybrid storage systems to mitigate intermittency issues that usually come with renewable energy sources such as solar and wind.

• Strengthening policy and regulatory frameworks to implement clear, long-term RE policies with attractive feed-in tariffs, risk guarantees, and streamlined licensing to boost private sector investments.

• Expanding Financial Support Mechanisms by establishing green energy funds, tax incentives, and public-private partnerships to lower investment risks and enhance RE adoption.

• Commitment to integrate low-carbon baseload solutions through the facilitation and the adoption of nuclear energy, particularly Small Modular Reactors (SMRs), as a complementary power source to stabilise the grid.

• Develope local technical expertise to increase funding for technical training programs and partnerships with academic institutions to build a skilled workforce for RE deployment and maintenance.

By implementing these measures, Ghana can accelerate its energy transition, reduce reliance on fossil fuels, and foster a resilient, sustainable, and economically viable RE energy future. Future research should further explore the socio-economic and environmental implications of RE expansion to optimise policy effectiveness.

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