IJEES

International Journal of Electrical Engineering and Sustainability (IJEES)

ISSN (online): 2959-9229

https://ijees.org/index.php/ijees/index

ISI 2023-2024: (0.557) Arab Impact Factor: 1.51 SJIF 2024 = 5.274

Volume 3 | Number 1 | January-March 2025 | Pages 143-156

Article

Toward Achieving Net-Zero in the Evolution of the Global Energy Sector

Oum Saad Abualoyoun[1], Ahmed A Amar[2*]

[1]Department of Mechanical Engineering, Higher Institute of Science and Technology, Al-jufrah, Sokna, Libya

[2]Department of Human Resources Management, Educational Facilities Security Agency, Al-jufrah, Libya

[*]Corresponding author: **ahmadalruhe@gmail.com**

Received: January 11, 2025 Accepted: March 12, 2025 Published: March 25, 2025

Abstract: The transition to a net-zero emissions future represents one of the most significant challenges and imperatives facing the global energy sector. This article critically examines long-term trends and projections in total energy supply, final energy consumption, and electricity generation, while analyzing the associated implications for carbon dioxide (CO_2) emissions under the Stated Policies Scenario (STEPS) and the Announced Pledges Scenario (APS). It explores the structural transformations occurring across regions and sectors, highlighting the divergence between advanced and developing economies in their decarbonization trajectories. The study emphasizes the accelerating electrification of end-use sectors, the evolving global fuel mix, and the role of renewables, bioenergy, nuclear, and fossil fuels in shaping energy futures. Significant disparities in energy access and technology readiness remain, particularly in emerging economies, posing challenges to equitable decarbonization. The article addresses Attaining net-zero emissions in the global energy sector requires a cohesive policy strategy that expedites clean energy implementation, improves overall efficiency, and guarantees fair involvement in the energy transition. The findings underscore that while the APS offers a more favorable outlook in emissions reduction and renewable energy penetration, substantial policy and technological efforts are still required to close the gap toward achieving the Paris Agreement goals.

Keywords: Net-Zero Emissions, Global Energy Transition, Decarbonization Pathways, Renewable Energy, Climate Policy Scenarios.

1. Introduction

Under the Stated Policies Scenario (STEPS), global CO_2 emissions exhibit only marginal improvements relative to recent historical trends. Although the transition to renewable energy sources prompts an early peak in emissions from the electricity sector, emission reductions across all sectors remain significantly inadequate to achieve the trajectory necessary for net-zero emissions by 2050 [1-3]. Following the temporary decline induced by the Covid-19 pandemic in 2020, annual CO_2 emissions rapidly rebound, rising from 34 gigatonnes (Gt) in 2020 to approximately 36 Gt by 2030, and thereafter stabilizing at this level through 2050, as illustrated in Figure 1. Should this emissions trajectory persist beyond 2050, and assuming analogous developments across other greenhouse gas (GHG) sources, the global mean surface temperature is projected to increase by approximately 2.7 °C by the year 2100, with a probability of 50% [3-6]. A marked divergence characterizes the projected emissions trajectories of advanced economies and those of emerging market and developing economies (EMDEs).

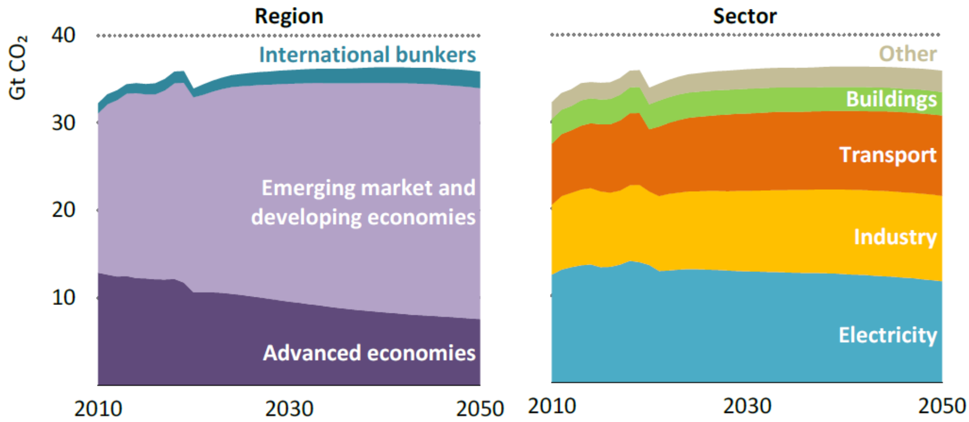

Figure 1. CO2 emissions from energy-related activities and industrial processes by area and sector in the STEPS [7].

In advanced economies, notwithstanding a modest resurgence in CO_2 emissions in the early 2020s, a sustained downward trend is anticipated, culminating in an approximate 33% reduction by 2050 relative to 2020 levels [8-11]. This decline is principally driven by the implementation of stringent climate policies, advancements in energy efficiency, and a systemic transition toward low-carbon and renewable energy sources [12-15].

In contrast, EMDEs are expected to witness a continued escalation in energy demand, fueled by rapid population growth, robust economic development, accelerated urbanization, and extensive infrastructure expansion [16-19]. These structural drivers effectively outweigh gains achieved through efficiency improvements and the adoption of clean energy technologies. Consequently, CO_2 emissions in these regions are projected to increase by nearly 20% by the mid-2040s, followed by only a marginal decline approaching 2050 [20-24]. This divergence underscores the complex interplay between development imperatives and climate goals, highlighting the critical need for enhanced international collaboration, equitable resource distribution, and targeted support to enable sustainable transitions in developing regions.

Several studies have explored the pathways and strategies associated with achieving net-zero emissions in the evolving global energy sector. A recent study conducted by Khaleel [25] analyzed the annual variations in energy-related CO_2 emissions over the period 2015–2023. The findings reveal notable fluctuations, particularly in response to global economic and structural shifts. In 2023, emissions from energy combustion and industrial processes totaled approximately 0.41 gigatonnes (Gt), reflecting a decline from 0.49 Gt in 2022. In contrast, the year 2021 recorded a substantial increase, with emissions reaching 1.92 Gt. The most pronounced reduction occurred in 2020, coinciding with the global economic slowdown induced by the COVID-19 pandemic, during which emissions fell sharply by -1.92 Gt. These trends underscore the sensitivity of energy-related emissions to macroeconomic conditions and highlight the importance of sustained structural policy measures to achieve long-term decarbonization.

Obobisa [26] underscores the critical importance of achieving net-zero carbon emissions, particularly in the context of global commitments under the Paris Climate Agreement. In pursuit of this objective, the study employs Augmented Mean Group (AMG) and Common Correlated Effects Mean Group (CCEMG) estimators to empirically examine the roles of renewable energy deployment and financial development in reducing CO_2 emissions. The analysis is based on annual data spanning the period from 1990 to 2018, encompassing 73 countries, which are categorized into four major global regions: Africa, Asia-Pacific, the Americas, and Europe. The study offers region-specific insights into how financial and energy-sector dynamics contribute to progress toward the 1.5 °C climate target and the broader net-zero emissions goal.

The analysis presented in [27] underscores that, although renewable energy sources offer a promising pathway to strengthening energy security, the ongoing global energy crisis has exposed the insufficiency of current investment levels in renewables to meet rising energy demands. This shortfall has compelled several countries to revisit and expand the use of hydrocarbon-based energy sources, including coal, thereby stalling progress in the global energy transition. The study concludes by offering targeted policy recommendations aimed at catalyzing clean energy investments, even within the constraints of a volatile and geopolitically strained environment.

This article makes a significant contribution to the literature on global energy transition by providing a comprehensive assessment of the pathways toward achieving net-zero emissions within the framework of the Stated Policies Scenario (STEPS) and the Announced Pledges Scenario (APS). The article offers a critical evaluation of long-term trends in total energy supply, final energy consumption, and electricity generation, while drawing attention to the sectoral and regional disparities that shape decarbonization trajectories. By investigating the evolving global fuel mix and the increasing role of renewables, bioenergy, nuclear, and fossil fuels, the study advances understanding of the structural shifts required for a low-carbon future. Importantly, the article highlights the persistent challenges in energy access and technological readiness in emerging economies, underscoring the need for equitable solutions. The article also delivers actionable insights into the policy and technological frameworks necessary to bridge the gap between current national pledges and the ambitious targets of the Paris Agreement. Through its analytical depth and policy relevance, the study provides a valuable foundation for guiding future research and informing international energy and climate policy dialogues.

2.Total Energy Supply, Final Consumption, and Electricity Generation

The trajectory of global CO_2 emissions under the Stated Policies Scenario (STEPS) is intrinsically linked to evolving patterns in energy demand and the composition of the energy mix [28-30]. Between 2020 and 2050, total energy supply (TES) is projected to increase by just over 30%, as presented in Figure 2. This moderate growth is contingent upon an anticipated average annual decline of 2.2% in energy intensity, defined as energy consumption per unit of gross domestic product (GDP). In the absence of such efficiency gains, TES in 2050 would be approximately 85% higher than in 2020 [31-33].

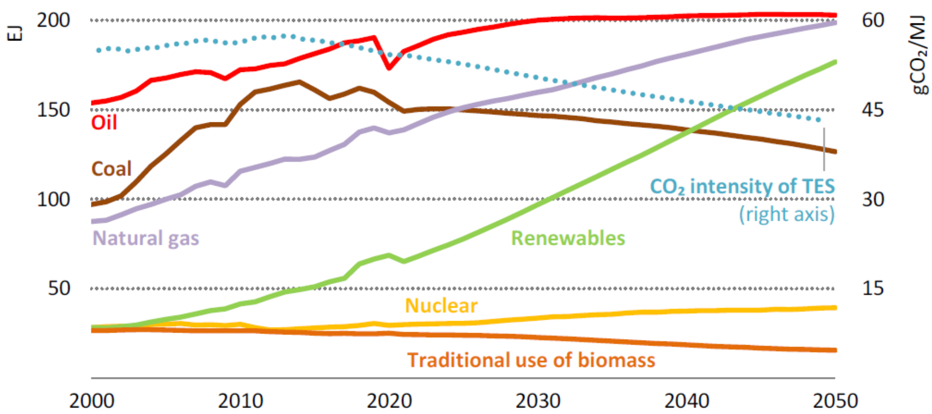

Figure 2. Overall energy supply and emissions of carbon dioxide intensity in the STEPS scenario [7].

In advanced economies, overall energy consumption is expected to decrease by approximately 5% by 2050, despite a projected 75% expansion in economic output, reflecting substantial decoupling of economic growth from energy use through technological advancement and policy interventions [34-36]. In contrast, energy demand in emerging market and developing economies (EMDEs) is projected to rise by 50% over the same period, consistent with a tripling of economic activity. Despite these economic and energy-use gains, profound disparities in energy access persist: by 2050, an estimated 750 million people, predominantly in sub-Saharan Africa, will remain without access to electricity, while 1.5 billion individuals are projected to continue relying on traditional biomass for cooking [37-39].

Significant structural shifts in the global fuel mix are anticipated over the projection horizon. Coal consumption, having peaked in 2014, is expected to decline by approximately 15% by 2050 [40-46]. Oil demand, which contracted sharply during the Covid-19 pandemic, is projected to rebound to pre-pandemic levels of 98 million barrels per day (mb/d) by 2023 and stabilize at approximately 104 mb/d shortly after 2030 [46-50]. In parallel, natural gas consumption is forecast to rise from 3,900 billion cubic metres (bcm) in 2020 to 4,600 bcm by 2030, and further to 5,700 bcm by 2050, driven by its role as a transition fuel in many regions [51-56]. Nuclear energy is also poised for moderate expansion, with a 15% increase projected between 2020 and 2030, largely reflecting capacity additions in China [57-63]. These developments underscore the complex interplay between energy security, economic development, and climate objectives that will shape the global energy system over the coming decades.

Total final energy consumption is projected to rise across all sectors under the Stated Policies Scenario (STEPS), with the most significant increases attributed to electricity and natural gas as demonstrated in Figure 3. This growth is entirely concentrated in emerging market and developing economies (EMDEs), reflecting their ongoing industrialization, urbanization, and rising living standards.

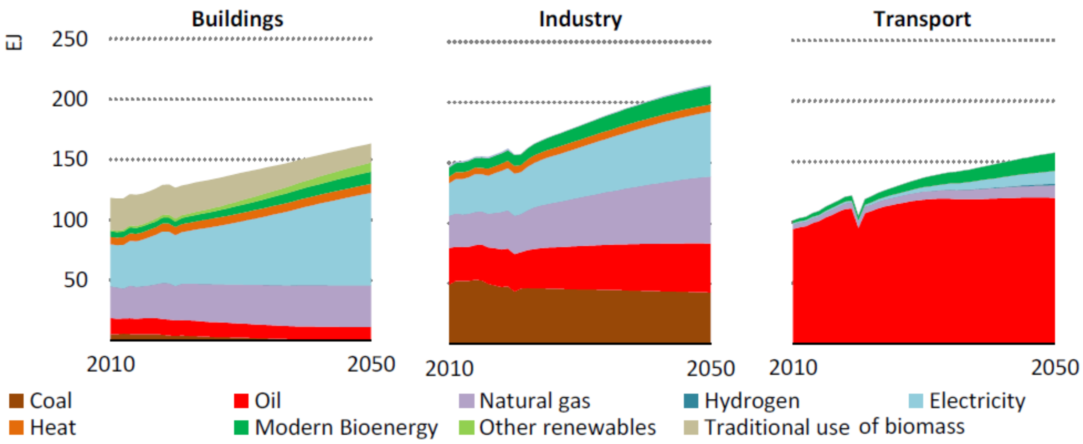

Figure 3. Aggregate final consumption categorized by sector and fuel in the STEPS.

The electricity sector experiences the most profound transformation in energy use as shown Figure 4. Globally, electricity demand is anticipated to surge by approximately 80% between 2020 and 2050, nearly twice the growth rate of total final energy consumption. This pronounced expansion is overwhelmingly driven by EMDEs, which account for over 85% of the projected increase in global electricity demand [64-69].

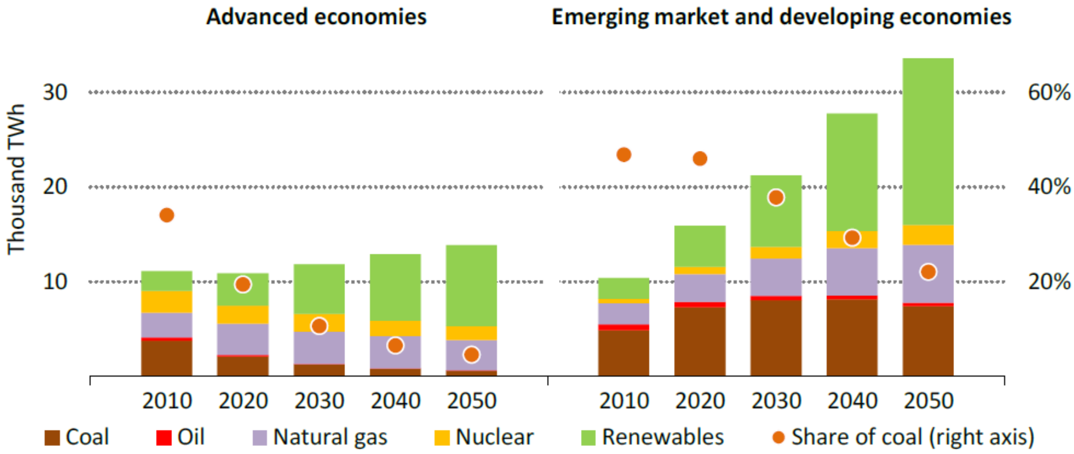

Figure 3. Electricity generation by fuel type and the proportion of coal in the STEPS.

Despite the rapid deployment of renewable energy technologies, coal is expected to retain a significant share in electricity generation within these economies through 2050, reflecting both structural energy dependencies and economic considerations. In contrast, advanced economies are projected to undergo a substantial decline in coal-based electricity generation, facilitated by stringent environmental regulations, market reforms, and a strong policy push towards decarbonization and the integration of low-carbon technologies. This divergence further underscores the heterogeneous nature of the global energy transition and the differentiated pathways required to achieve sustainable electrification.

3.CO_2 Emissions

Under the Announced Pledges Scenario (APS), global CO_2 emissions experience a modest rebound through 2023; however, this increase is significantly less pronounced than the post-recession surge observed following the 2008–2009 global financial crisis. Notably, emissions never return to their previous peak of 36 gigatonnes (Gt). Instead, they follow a declining trajectory, falling by approximately 10% to reach 30 Gt by 2030, and further decreasing to 22 Gt by 2050 [70-73]. This latter figure represents a 35% reduction relative to 2020 levels and is 14 Gt lower than the projected emissions under the Stated Policies Scenario (STEPS), as illustrated in Figure 5.

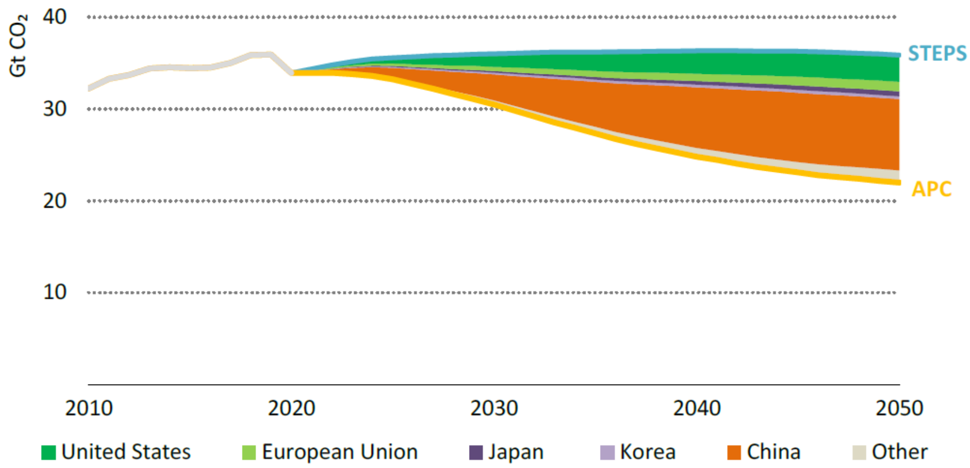

Figure 5. The global CO2 emissions from energy-related and industrial processes by scenario and regional reductions, 2010-2050.

If this downward trend were to persist beyond 2050, and if analogous reductions were achieved in non-energy-related greenhouse gas (GHG) emissions, the rise in global average surface temperature by 2100 would be limited to approximately 2.1 °C, with a 50% likelihood. This outcome underscores the potential climate benefits of full implementation of announced policy pledges, though it also highlights the continued shortfall relative to the Paris Agreement target of limiting warming to well below 2 °C, and ideally to 1.5 °C [73-76].

The most substantial reduction in CO_2 emissions under the Announced Pledges Scenario (APS) occurs within the electricity sector, where global emissions are projected to decline by nearly 60% between 2020 and 2050. This pronounced decarbonization is achieved despite an almost twofold increase in electricity demand over the same period, driven by the accelerating electrification of end-use sectors, most notably transport and buildings. The scale of this reduction reflects the rapid deployment of low-carbon generation technologies, coupled with structural shifts in energy consumption patterns. By contrast, under the Stated Policies Scenario (STEPS), emissions from the electricity sector are projected to decline by less than 15% over the same timeframe, underscoring the critical importance of ambitious policy commitments and their implementation in achieving deep emissions reductions.

In the Announced Pledges Scenario (APS), the transport and industrial sectors exhibit more modest reductions in CO_2 emissions by 2050, relative to the electricity and buildings sectors. While significant mitigation efforts are undertaken in regions that have committed to net-zero targets, these gains are partially offset by rising energy demand in regions lacking comparable pledges. This geographic asymmetry in policy ambition tempers the overall decarbonization trajectory for these sectors.

The buildings sector, by contrast, achieves a more substantial reduction in emissions, with a projected decline of approximately 40% between 2020 and 2050. This compares to a mere 5% reduction under the Stated Policies Scenario (STEPS). The decline is primarily attributed to the phase-out of fossil fuels, particularly those used for space and water heating, in countries with ambitious climate commitments, which collectively account for a disproportionately large share of global heating demand.

Despite progress in pledged regions, residual emissions persist in 2050, particularly within the transport and industrial sectors. These residuals largely stem from the limited commercial availability of zero-emission technologies for hard-to-abate applications, including heavy-duty road freight, aviation, maritime shipping, and energy-intensive industrial processes. This highlights the ongoing technological and infrastructural challenges associated with achieving full decarbonization across all sectors of the economy.

4.Evolution of the Global Energy

Under the Announced Pledges Scenario (APS), global total energy supply (TES) is projected to increase by just over 15% between 2020 and 2050, a significantly more restrained growth compared to the approximately 33% increase anticipated under the Stated Policies Scenario (STEPS), as illustrated in Figure 6. This moderated expansion in TES under the APS is largely attributable to accelerated improvements in energy efficiency, with global energy intensity, defined as energy use per unit of GDP, declining at an average annual rate of approximately 2.6%, in contrast to 2.2% in the STEPS [77-78].

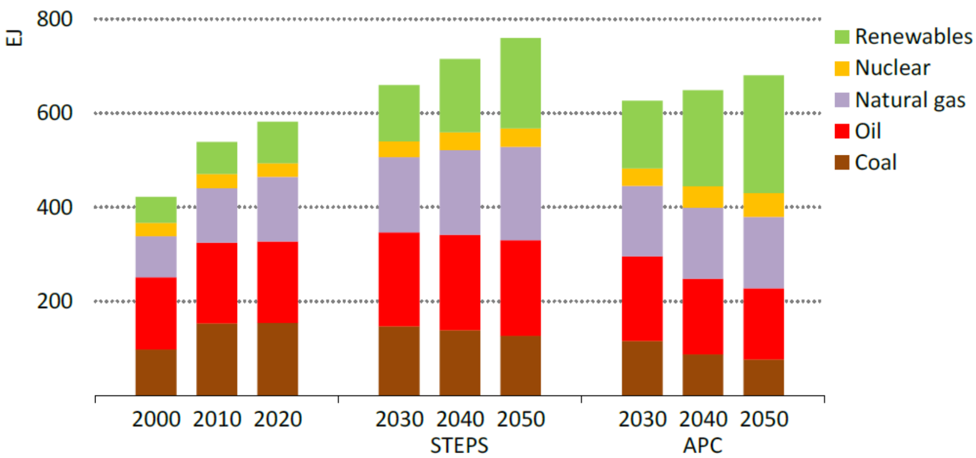

Figure 6. Comprehensive energy supply categorized by source in STEPS and APC.

Despite these efficiency gains, a substantial rise in energy demand is observed in emerging market and developing economies (EMDEs), where economic and demographic growth is most pronounced. These regions, which tend to lack comprehensive net-zero commitments, exhibit robust energy consumption trends that outweigh reductions achieved in countries with formalized net-zero pledges. These dynamic underscores the critical role of equitable global engagement and capacity-building in ensuring that the pursuit of economic development in EMDEs is aligned with global climate objectives [78-80].

In the Announced Pledges Scenario (APS), the global increase in total energy supply is predominantly driven by the expansion of renewable energy sources, whose share in the primary energy mix rises substantially, from 12% in 2020 to 35% by 2050. This is markedly higher than the 25% share projected under the Stated Policies Scenario (STEPS) [79-82]. The electricity sector, in particular, is the principal arena for renewable growth, with solar photovoltaics (PV) and wind energy jointly accounting for approximately 50% of the total increase in renewable energy supply. Bioenergy also emerges as a major contributor, responsible for around 30% of the growth [83-88].

The role of bioenergy expands significantly across sectors: its consumption in industry doubles, it triples in electricity generation, and increases fourfold in the transport sector. Notably, when integrated with carbon capture, utilization, and storage (CCUS) technologies, bioenergy contributes not only to emissions reductions in heat supply but also to negative emissions by actively removing CO_2 from the atmosphere. In this direction, nuclear energy maintains a stable share in the global energy mix, with its output projected to increase by 25% by 2030, compared to a 15% rise under the STEPS. This growth is supported by the extension of operational lifetimes of existing nuclear facilities and the commissioning of new reactors, particularly in countries with long-term decarbonization commitments.

Coal consumption, by contrast, experiences a far more pronounced decline in the APS compared to the STEPS. Global coal use decreases from 5,250 million tonnes of coal equivalent (Mtce) in 2020 to 4,000 Mtce in 2030 and 2,600 Mtce by 2050. This is substantially lower than the 4,300 Mtce projected under the STEPS for the same year. The decline is largely driven by the phase-down of coal-fired power generation in countries with net-zero pledges, where plants are either repurposed, retrofitted with carbon abatement technologies, or retired altogether. In advanced economies, the complete phase-out of unabated coal-fired power is expected within the next 10 to 15 years. China, in particular, is projected to reduce coal use for power generation by 85% between 2020 and 2050 as part of its trajectory toward carbon neutrality by 2060. These reductions more than compensate for ongoing coal demand growth in countries without net-zero targets. Additionally, global industrial coal use declines by 25% over the same period, significantly outperforming the modest 5% reduction anticipated in the STEPS [89-91].

Oil demand, after a brief post-pandemic recovery in the early 2020s, is not expected to return to its historical peak of 2019. It declines steadily, reaching 90 million barrels per day (mb/d) in the early 2030s and 80 mb/d by 2050, approximately 25 mb/d lower than the level projected in the STEPS. This trend is driven by aggressive electrification of the transport sector and increased adoption of alternative fuels such as biofuels and hydrogen, particularly in economies with strong climate pledges [92-94].

Natural gas consumption rises modestly from approximately 3,900 billion cubic metres (bcm) in 2020 to around 4,350 bcm by 2025. However, demand then plateaus and remains broadly stable through 2050. This contrasts sharply with the STEPS, in which natural gas use continues to grow, reaching approximately 5,700 bcm by mid-century [95-98]. The levelling of gas demand in the APS reflects a more aggressive transition toward low-carbon alternatives, especially in power generation and heating applications, and the implementation of net-zero-aligned policy frameworks.

5.Policy Recommendations

Achieving net-zero emissions in the global energy sector necessitates an integrated policy approach that accelerates clean energy deployment, enhances system-wide efficiency, and ensures equitable participation in the energy transition. A central priority is the rapid scaling of renewable energy technologies, especially solar photovoltaics, wind power, and sustainable bioenergy. Governments must provide stable investment environments through mechanisms such as feed-in tariffs, tax credits, and public-private partnerships. At the same time, increased support for research, development, and deployment (RD&D) of emerging solutions, including green hydrogen, advanced nuclear technologies, and long-duration energy storage, is essential to diversify the low-carbon technology portfolio and support deep decarbonization.

Electrification of end-use sectors must be expedited, particularly in transport, buildings, and industry, where fossil fuel dependency remains high. Policy measures should facilitate the adoption of electric vehicles, heat pumps, and electric industrial processes, supported by coordinated investments in charging infrastructure, smart grids, and demand-side flexibility. These efforts must be integrated with broader energy system planning to ensure grid reliability and resilience as electricity demand grows.

Fossil fuel phase-down is a critical component of the net-zero agenda. Policymakers should establish clear phase-out timelines for unabated coal-fired power plants, particularly in advanced economies, while supporting just transition programs that protect workers and communities affected by plant closures. Oil and gas consumption must also be reduced through a combination of fuel switching, efficiency standards, and regulatory measures, with careful consideration of energy security and affordability.

Global cooperation is vital to address disparities in decarbonization capabilities. International financial institutions and donor governments should substantially increase climate finance to emerging market and developing economies (EMDEs), enabling them to invest in low-carbon infrastructure and build institutional capacity. In parallel, the transfer of clean technologies should be facilitated through cooperative agreements, knowledge-sharing platforms, and mechanisms that lower intellectual property barriers.

Carbon management technologies will also play an indispensable role in mitigating residual emissions from hard-to-abate sectors. Governments should prioritize the deployment of carbon capture, utilization, and storage (CCUS) in industrial hubs and promote the development of carbon dioxide removal (CDR) options such as bioenergy with carbon capture and storage (BECCS) and direct air capture. These solutions require dedicated funding, regulatory frameworks, and long-term infrastructure planning.

To ensure long-term progress, national energy and climate policies must be embedded within legally binding net-zero frameworks. This includes enhancing governance structures, integrating climate objectives into national development strategies, and strengthening emissions monitoring, reporting, and verification (MRV) systems to promote transparency and accountability.

Finally, equity and access must remain core principles of the energy transition. Universal access to modern, reliable, and affordable energy services, particularly in sub-Saharan Africa and other underserved regions, must be prioritized through targeted electrification initiatives and distributed energy systems. At the same time, transition policies should be designed to ensure that vulnerable populations do not bear a disproportionate share of the costs, thereby safeguarding social inclusion and economic justice throughout the global shift toward a net-zero energy future.

6.Conclusion

This analysis demonstrates that the pathway toward a net-zero global energy system is both achievable and increasingly urgent. Under the APS, meaningful progress is observed in reducing CO_2 emissions, particularly within the electricity sector, through enhanced energy efficiency, accelerated deployment of renewables, and the gradual phasing out of coal in countries with net-zero pledges. However, significant disparities persist between advanced and emerging economies in terms of energy demand growth, access to clean technologies, and policy implementation. Although the APS scenario delivers a more optimistic trajectory than the STEPS, it still falls short of limiting global warming to 1.5°C. Achieving net-zero will require deeper integration of clean energy technologies, expanded electrification of transport and industry, and widespread adoption of carbon capture and removal strategies. Furthermore, robust international cooperation, climate finance mechanisms, and capacity-building initiatives are essential to ensure an inclusive, secure, and equitable energy transition for all regions. The article emphasizes that achieving net-zero emissions in the global energy sector necessitates an integrated policy framework that accelerates the deployment of clean energy technologies, enhances systemic energy efficiency, and ensures inclusive participation in the energy transition.

Author Contributions: Authors have contributed significantly to the development and completion of this article.

Funding: This article received no external funding.

Data Availability Statement: Not applicable.

Acknowledgments: The authors would likes to express their sincere gratitude to Higher Institute of Science and Technology, Al-jufrah, Sokna, Libya for their invaluable support and resources throughout the course of this research.

Conflicts of Interest: The author(s) declare no conflict of interest.

ORCID
Oum Saad Abualoyoun https://orcid.org/0009-0004-4353-5555
Ahmed A Amar https://orcid.org/0009-0004-0716-3547

References

[1] A. Das, V. Saini, K. Parikh, J. Parikh, P. Ghosh, and M. Tot, "Pathways to net zero emissions for the Indian power sector," *Energy Strat. Rev.*, vol. 45, no. 101042, p. 101042, 2023.

[2] J. Markard and D. Rosenbloom, "Phases of the net-zero energy transition and stategies to achieve it," in *Routledge Handbook of Energy Transitions*, London: Routledge, 2022, pp. 102–123.

[3] R. Quitzow and Y. Zabanova, "Geoeconomics of the transition to net-zero energy and industrial systems: A framework for analysis," *Renew. Sustain. Energy Rev.*, vol. 214, no. 115492, p. 115492, 2025.

[4] M. Ma, N. Zhou, W. Feng, and J. Yan, "Challenges and opportunities in the global net-zero building sector," *Cell Reports Sustainability*, vol. 1, no. 8, p. 100154, 2024.

[5] J. E. T. Bistline and G. J. Blanford, "The role of the power sector in net-zero energy systems," *Energy Clim. Chang.*, vol. 2, no. 100045, p. 100045, 2021.

[6] Y. F. Nassar *et al.*, "Design of reliable standalone utility-scale pumped hydroelectric storage powered by PV/Wind hybrid renewable system," *Energy Convers. Manag.*, vol. 322, no. 119173, p. 119173, 2024.

[7] IEA (2024), *Global Energy and Climate Model*, IEA, Paris https://www.iea.org/reports/global-energy-and-climate-model.

[8] H. Omrany, R. Chang, V. Soebarto, Y. Zhang, A. Ghaffarianhoseini, and J. Zuo, "A bibliometric review of net zero energy building research 1995–2022," *Energy Build.*, vol. 262, no. 111996, p. 111996, 2022.

[9] O. S. M. Jomah, N. Mohamed, A. A. Ahmed, A. Alsharif, M. M. Khaleel, and Y. F. Nassar, "Simulating photovoltaic emulator systems for renewable energy analysis," in *2024 IEEE 4th International Maghreb Meeting of the Conference on Sciences and Techniques of Automatic Control and Computer Engineering (MI-STA)*, 2024.

[10] S. A. Apostu, M. Panait, and V. Vasile, "The energy transition in Europe-a solution for net zero carbon?," *Environ. Sci. Pollut. Res. Int.*, vol. 29, no. 47, pp. 71358–71379, 2022.

[11] Y. Nassar *et al.*, "Solar and wind atlas for Libya," *Int. J. Electr. Eng. and Sustain.*, pp. 27–43, 2023.

[12] N. Stern and A. Valero, "Innovation, growth and the transition to net-zero emissions," *Res. Policy*, vol. 50, no. 9, p. 104293, 2021.

[13] M. M. Khaleel, A. Alsharif, and I. I. K. Imbayah, "Renewable energy technologies: Recent advances and future predictions," *AJAPAS*, pp. 58–64, 2022.

[14] A. Alsharif *et al.*, "Applications of solar energy technologies in north Africa: Current practices and future prospects," *Int. J. Electr. Eng. and Sustain.*, pp. 164–173, 2023.

[15] M. M. Khaleel, T. Mohamed Ghandoori, A. Ali Ahmed, A. Alsharif, A. J. Ahmed Alnagrat, and A. Ali Abulifa, "Impact of mechanical storage system technologies: A powerful combination to empowered the electrical grids application," in *2022 IEEE 2nd International Maghreb Meeting of the Conference on Sciences and Techniques of Automatic Control and Computer Engineering (MI-STA)*, 2022.

[16] S. Abdulwahab, Y. F. Nassar, H. J. El-Khozondar, M. Khaleel, A. A. Ahmed, and A. Alsharif, "Meeting solar energy demands: Significance of transposition models for solar irradiance," *Int. J. Electr. Eng. and Sustain.*, pp. 90–105, 2023.

[17] E. Ohene, A. P. C. Chan, and A. Darko, "Review of global research advances towards net-zero emissions buildings," *Energy Build.*, vol. 266, no. 112142, p. 112142, 2022.

[18] A. O. M. Maka, T. Ghalut, and E. Elsaye, “The pathway towards decarbonisation and net-zero emissions by 2050: The role of solar energy technology,” *Green Technologies and Sustainability*, vol. 2, no. 3, p. 100107, 2024.
[19] Y. F. Nassar *et al.*, “Thermoelectrical analysis of a new hybrid PV-thermal flat plate solar collector,” in *2023 8th International Engineering Conference on Renewable Energy & Sustainability (ieCRES)*, 2023.
[20] J. DeAngelo *et al.*, “Energy systems in scenarios at net-zero CO2 emissions,” *Nat. Commun.*, vol. 12, no. 1, p. 6096, 2021.
[21] K. R. Ullah, V. Prodanovic, G. Pignatta, A. Deletic, and M. Santamouris, “Technological advancements towards the net-zero energy communities: A review on 23 case studies around the globe,” *Sol. Energy*, vol. 224, pp. 1107–1126, 2021.
[22] M. M. Khaleel, A. A. Ahmed, and A. Alsharif, “Energy Management System Strategies in Microgrids: A Review,” *NAJSP*, pp. 1–8, 2023.
[23] S. Pye *et al.*, “Modelling net-zero emissions energy systems requires a change in approach,” *Clim. Policy*, vol. 21, no. 2, pp. 222–231, 2021.
[24] S. Aziz, I. Ahmed, K. Khan, and M. Khalid, “Emerging trends and approaches for designing net-zero low-carbon integrated energy networks: A review of current practices,” *Arab. J. Sci. Eng.*, vol. 49, no. 5, pp. 6163–6185, 2024.
[25] M. Khaleel *et al.*, “Evolution of emissions: The role of clean energy in sustainable development,” *Chall. Sustain.*, vol. 12, no. 2, pp. 122–135, 2024.
[26] E. S. Obobisa, “Achieving 1.5 °C and net-zero emissions target: The role of renewable energy and financial development,” *Renew. Energy*, vol. 188, pp. 967–985, 2022.
[27] F. Belaïd, A. Al-Sarihi, and R. Al-Mestneer, “Balancing climate mitigation and energy security goals amid converging global energy crises: The role of green investments,” *Renew. Energy*, vol. 205, pp. 534–542, 2023.
[28] A. Ahmed, T. Ge, J. Peng, W.-C. Yan, B. T. Tee, and S. You, “Assessment of the renewable energy generation towards net-zero energy buildings: A review,” *Energy Build.*, vol. 256, no. 111755, p. 111755, 2022.
[29] S. Qiu, T. Lei, J. Wu, and S. Bi, “Energy demand and supply planning of China through 2060,” *Energy (Oxf.)*, vol. 234, no. 121193, p. 121193, 2021.
[30] K. R. Abbasi, J. Abbas, and M. Tufail, “Revisiting electricity consumption, price, and real GDP: A modified sectoral level analysis from Pakistan,” *Energy Policy*, vol. 149, no. 112087, p. 112087, 2021.
[31] S. Algarni, V. Tirth, T. Alqahtani, S. Alshehery, and P. Kshirsagar, “Contribution of renewable energy sources to the environmental impacts and economic benefits for sustainable development,” *Sustain. Energy Technol. Assessments*, vol. 56, no. 103098, p. 103098, 2023.
[32] M. Tutak and J. Brodny, “Renewable energy consumption in economic sectors in the EU-27. The impact on economics, environment and conventional energy sources. A 20-year perspective,” *J. Clean. Prod.*, vol. 345, no. 131076, p. 131076, 2022.
[33] Y. F. Nassar *et al.*, “Regression model for optimum solar collectors’ tilt angles in Libya,” in *2023 8th International Engineering Conference on Renewable Energy & Sustainability (ieCRES)*, 2023.
[34] T.-Z. Ang, M. Salem, M. Kamarol, H. S. Das, M. A. Nazari, and N. Prabaharan, “A comprehensive study of renewable energy sources: Classifications, challenges and suggestions,” *Energy Strat. Rev.*, vol. 43, no. 100939, p. 100939, 2022.
[35] A. M. Makhzom *et al.*, “Carbon dioxide Life Cycle Assessment of the energy industry sector in Libya: A case study,” *Int. J. Electr. Eng. and Sustain.*, pp. 145–163, 2023.
[36] S. Potrč, L. Čuček, M. Martin, and Z. Kravanja, “Sustainable renewable energy supply networks optimization – The gradual transition to a renewable energy system within the European Union by 2050,” *Renew. Sustain. Energy Rev.*, vol. 146, no. 111186, p. 111186, 2021.

[37] M. De Rosa, K. Gainsford, F. Pallonetto, and D. P. Finn, “Diversification, concentration and renewability of the energy supply in the European Union,” *Energy (Oxf.)*, vol. 253, no. 124097, p. 124097, 2022.

[38] Q. Li *et al.*, “Exploring the relationship between renewable energy sources and economic growth. The case of SAARC countries,” *Energies*, vol. 14, no. 3, p. 520, 2021.

[39] S. Solaymani, “A review on energy and renewable energy policies in Iran,” *Sustainability*, vol. 13, no. 13, p. 7328, 2021.

[40] Y. F. Nassar *et al.*, “Assessing the viability of solar and wind energy technologies in semi-arid and arid regions: A case study of Libya’s climatic conditions,” *Appl. Sol. Energy*, vol. 60, no. 1, pp. 149–170, 2024.

[41] R. B. Finkelman, A. Wolfe, and M. S. Hendryx, “The future environmental and health impacts of coal,” *Energy Geoscience*, vol. 2, no. 2, pp. 99–112, 2021.

[42] V. Vinichenko, A. Cherp, and J. Jewell, “Historical precedents and feasibility of rapid coal and gas decline required for the 1.5°C target,” *One Earth*, vol. 4, no. 10, pp. 1477–1490, 2021.

[43] H. A. Aguirre-Villegas and C. H. Benson, “Expectations for coal demand in response to evolving carbon policy and climate change awareness,” *Energies*, vol. 15, no. 10, p. 3739, 2022.

[44] J. L. Holechek, H. M. E. Geli, M. N. Sawalhah, and R. Valdez, “A global assessment: Can renewable energy replace fossil fuels by 2050?,” *Sustainability*, vol. 14, no. 8, p. 4792, 2022.

[45] A. Husika, N. Zecevic, I. Numic, and E. Dzaferovic, “Scenario analysis of a Coal reduction share in the power generation in Bosnia and Herzegovina until 2050,” *Sustainability*, vol. 14, no. 21, p. 13751, 2022.

[46] A. Razmjoo, L. Gakenia Kaigutha, M. A. Vaziri Rad, M. Marzband, A. Davarpanah, and M. Denai, “A Technical analysis investigating energy sustainability utilizing reliable renewable energy sources to reduce CO2 emissions in a high potential area,” *Renew. Energy*, vol. 164, pp. 46–57, 2021.

[47] A. N. Adedeji, F. F. Ahmed, and S. U. Adam, “Examining the dynamic effect of COVID-19 pandemic on dwindling oil prices using structural vector autoregressive model,” *Energy (Oxf.)*, vol. 230, no. 120813, p. 120813, 2021.

[48] H. C. Ezeaku, S. A. Asongu, and J. Nnanna, “Volatility of international commodity prices in times of COVID-19: Effects of oil supply and global demand shocks,” *Extr. Ind. Soc.*, vol. 8, no. 1, pp. 257–270, 2021.

[49] D. Bourghelle, F. Jawadi, and P. Rozin, “Oil price volatility in the context of Covid-19,” *Int. Econ.*, vol. 167, pp. 39–49, 2021.

[50] A. K. Patidar, P. Jain, P. Dhasmana, and T. Choudhury, “Impact of global events on crude oil economy: a comprehensive review of the geopolitics of energy and economic polarization,” *GeoJournal*, vol. 89, no. 2, 2024.

[51] J. Liu, S. Wang, N. Wei, X. Chen, H. Xie, and J. Wang, “Natural gas consumption forecasting: A discussion on forecasting history and future challenges,” *J. Nat. Gas Sci. Eng.*, vol. 90, no. 103930, p. 103930, 2021.

[52] J. Ding, Y. Zhao, and J. Jin, “Forecasting natural gas consumption with multiple seasonal patterns,” *Appl. Energy*, vol. 337, no. 120911, p. 120911, 2023.

[53] N. Tian, B. Shao, G. Bian, H. Zeng, X. Li, and W. Zhao, “Application of forecasting strategies and techniques to natural gas consumption: A comprehensive review and comparative study,” *Eng. Appl. Artif. Intell.*, vol. 129, no. 107644, p. 107644, 2024.

[54] N. Wei, L. Yin, C. Li, C. Li, C. Chan, and F. Zeng, “Forecasting the daily natural gas consumption with an accurate white-box model,” *Energy (Oxf.)*, vol. 232, no. 121036, p. 121036, 2021.

[55] Q. Wang, R. Suo, and Q. Han, “A study on natural gas consumption forecasting in China using the LMDI-PSO-LSTM model: Factor decomposition and scenario analysis,” *Energy (Oxf.)*, vol. 292, no. 130435, p. 130435, 2024.

[56] M. Yucesan, E. Pekel, E. Celik, M. Gul, and F. Serin, “Forecasting daily natural gas consumption with regression, time series and machine learning based methods,” *Energy Sources Recovery Util. Environ. Eff.*, vol. 47, no. 1, pp. 4605–4620, 2025.

[57] M. Khaleel *et al.*, “Harnessing nuclear power for sustainable electricity generation and achieving zero emissions,” *Energy Explor. Exploit.*, 2025.

[58] A. A. Abulifa, F. A. Enbais, and D. M. Shwehdy, “Artificial intelligence for nuclear waste management: Opportunities, challenges, and future prospects,” *Int. J. Electr. Eng. and Sustain.*, pp. 19–30, 2025.

[59] N. D. Bokde, J. Lazić, and C. Fanara, “Carbon reduction and cost analysis in solar-biomass synergy for UAE’s 2030 energy transition,” *Renew. Energy Focus*, vol. 53, no. 100691, p. 100691, 2025.

[60] M. R. Islam, S. D. Turja, D. Van Nguyen, D. Forcellini, and D. Kim, “Seismic soil-structure interaction in nuclear power plants: An extensive review,” *Results Eng.*, vol. 23, no. 102694, p. 102694, 2024.

[61] S. Shannak, L. Cochrane, and D. Bobarykina, “Global uranium market dynamics: analysis and future implications,” *Int. J. Sustain. Energy*, vol. 44, no. 1, 2025.

[62] B. Li, L. Wang, L. Zhang, H. Wu, and Z. Yuan, “Navigating copper demand-supply dynamics for China’s energy transition: Pathways to sustainable supply,” *Energy (Oxf.)*, vol. 330, no. 136913, p. 136913, 2025.

[63] M. Kordrostami and A. A. Ghasemi-Soloklui, “Innovative applications of biochar in nuclear remediation and catalysis,” *Biochar*, vol. 7, no. 1, 2025.

[64] R. van Heerden *et al.*, “Demand-side strategies enable rapid and deep cuts in buildings and transport emissions to 2050,” *Nat. Energy*, vol. 10, no. 3, pp. 380–394, 2025.

[65] C. D. Burleyson, Z. Khan, M. Kulshresta, N. Voisin, M. Zhao, and J. S. Rice, “When do different scenarios of projected electricity demand start to meaningfully diverge?,” *Appl. Energy*, vol. 380, no. 124948, p. 124948, 2025.

[66] J. Siddiki and P. Singh, “The cost of uncertainty: Analysing the influence of coal price changes, the Russia-Ukraine war and geopolitical risk on risk premiums in the Indian electricity spot market,” *Energy Econ.*, vol. 141, no. 108129, p. 108129, 2025.

[67] D. A. Canul-Reyes, O. Rodríguez-Hernández, M. E. Barragán-Peña, and J. A. del Rio, “Analysis of offshore wind energy and solar photovoltaic production and its relationship with regional electricity demand in the Yucatan peninsula,” *Energy (Oxf.)*, no. 134060, p. 134060, 2024.

[68] A. A. Mir, M. Alghassab, K. Ullah, Z. A. Khan, Y. Lu, and M. Imran, “A review of electricity demand forecasting in low and middle income countries: The demand determinants and horizons,” *Sustainability*, vol. 12, no. 15, p. 5931, 2020.

[69] V. Z. Castillo, H.-S. de Boer, R. M. Muñoz, D. E. H. J. Gernaat, R. Benders, and D. van Vuuren, “Future global electricity demand load curves,” *Energy (Oxf.)*, vol. 258, no. 124741, p. 124741, 2022.

[70] L. Zhao, K. Wang, H. Yi, Y. Cheng, J. Zhen, and H. Hu, “Carbon emission drivers of China’s power sector and its transformation for global decarbonization contribution,” *Appl. Energy*, vol. 376, no. 124258, p. 124258, 2024.

[71] I. Madi, L. Morales, B. Andreosso-O’Callaghan, and S. Sarwar, “China’s ambition for energy sustainability,” in *Geoeconomics of the Sustainable Development Goals*, London: Routledge, 2025, pp. 85–103.

[72] O. Ostapenko, "Assessment of solar-driven green generation potential in renewable energy development: Global forecasts and opportunities for Ukraine," *Renewable Energies*, vol. 2, no. 1, 2024.

[73] R. Matsuyama, Y. Sugimura, R. Shibasaki, and T. T. T. Tran, "Scenario analysis on CO2 emission reductions in hinterland transport of Japan through intermodal logistics network simulation," *J. Clean. Prod.*, vol. 458, no. 142503, p. 142503, 2024.

[74] B. Miao *et al.*, "Carbon footprint analysis of Chinese household smart electricity meters based on life cycle assessment," in *2024 4th International Conference on Intelligent Power and Systems (ICIPS)*, 2024, pp. 1141–1151.

[75] S. Abulifa, M. Elbar, M. Mohamed, A. Khoudiri, and S. Khoudiri, "Performance evaluation of MG systems interfaced with wind turbines employing DFIG technology," *Int. J. Electr. Eng. and Sustain.*, pp. 22–35, 2024.

[76] M. Khaleel, Z. Yusupov, A. Ahmed, A. Alsharif, Y. Nassar, and H. El-Khozondar, "Towards sustainable renewable energy," *Appl. Sol. Energy*, vol. 59, no. 4, pp. 557–567, 2023.

[77] M. Swadi, D. Jasim Kadhim, M. Salem, F. Mohammed Tuaimah, A. S. Majeed, and A. Jawad Alrubaie, "Investigating and predicting the role of photovoltaic, wind, and hydrogen energies in sustainable global energy evolution," *Global Energy Interconnection*, vol. 7, no. 4, pp. 429–445, 2024.

[78] R. Vakulchuk and I. Overland, "The failure to decarbonize the global energy education system: Carbon lock-in and stranded skill sets," *Energy Res. Soc. Sci.*, vol. 110, no. 103446, p. 103446, 2024.

[79] J. Einolander, A. Kiviaho, and R. Lahdelma, "Detecting changes in price-sensitivity of household electricity consumption: The impact of the global energy crisis on implicit demand response behavior of Finnish detached households," *Energy Build.*, vol. 306, no. 113941, p. 113941, 2024.

[80] C. Carà, P. Marocco, R. Novo, M. Koivisto, M. Santarelli, and G. Mattiazzo, "Modeling the long-term evolution of the Italian power sector: The role of renewable resources and energy storage facilities," *Int. J. Hydrogen Energy*, vol. 59, pp. 1183–1195, 2024.

[81] Y.-Q. Liu *et al.*, "Revealing the evolution of global energy trade patterns amidst the COVID-19 epicenter storm," *Energy Strat. Rev.*, vol. 53, no. 101367, p. 101367, 2024.

[82] Y. Bahini, R. Mushtaq, and S. Bahoo, "Global energy transition: The vital role of cobalt in renewable energy," *J. Clean. Prod.*, vol. 470, no. 143306, p. 143306, 2024.

[83] Y. F. Nassar *et al.*, "Carbon footprint and energy life cycle assessment of wind energy industry in Libya," *Energy Convers. Manag.*, vol. 300, no. 117846, p. 117846, 2024.

[84] A. Alsharif, A. A. Ahmed, M. M. Khaleel, Y. Nassar, M. A. Sharif, and H. J. El-Khozondar, "Whale optimization algorithm for renewable energy sources integration considering solar-to-vehicle technology," in *2023 IEEE 9th International Women in Engineering (WIE) Conference on Electrical and Computer Engineering (WIECON-ECE)*, 2023, pp. 397–401.

[85] A. Alsharif, E. Almabsout, A. A. Ahmed, M. Khaleel, Y. F. Nassar, and H. J. El-Khozoadar, "Optimal sizing of hybrid renewable system for residential appliances," in *2024 IEEE 4th International Maghreb Meeting of the Conference on Sciences and Techniques of Automatic Control and Computer Engineering (MI-STA)*, 2024.

[86] M. Khaleel *et al.*, "Emerging issues and challenges in integrating of solar and wind," *Int. J. Electr. Eng. and Sustain.*, pp. 1–11, 2024.

[87] F. Alasali, A. S. Saidi, N. El-Naily, O. Alsmadi, M. Khaleel, and I. Ghirani, "Assessment of the impact of a 10-MW grid-tied solar system on the Libyan grid in terms of the power-protection system stability," *Clean Energy*, vol. 7, no. 2, pp. 389–407, 2023.

[88] G. Katoch *et al.*, "Fusion energy: a sustainable pathway to meeting future global energy demands," *Discov. Sustain.*, vol. 6, no. 1, 2025.

[89] Y. Liu, Y. Li, and Y. Pu, "Exploring the endogenous structure and evolutionary mechanism of the global coal trade network," *Energy Econ.*, vol. 136, no. 107710, p. 107710, 2024.

[90] A. Lai and Q. Wang, "How coal de-capacity policy affects renewable energy development efficiency? Evidence from China," *Energy (Oxf.)*, vol. 286, no. 129515, p. 129515, 2024.

[91] S. O. Mamman, J. Iliyasu, U. A. Ahmed, and F. Salami, "Global uncertainties, geopolitical risks and price exuberance: Evidence from international energy market," *OPEC Energy Rev.*, vol. 48, no. 2, pp. 96–107, 2024.

[92] D. Hu and Y. Zhao, "Outlook for global oil demand in the post-COVID-19 era," in *Current Chinese Economic Report Series*, Singapore: Springer Nature Singapore, 2024, pp. 93–105.

[93] A. Kumar and S. Mallick, "Oil price dynamics in times of uncertainty: Revisiting the role of demand and supply shocks," *Energy Econ.*, no. 107152, p. 107152, 2023.

[94] S. Degiannakis, G. Filis, and S. Panagiotakopoulou, "Oil price shocks and uncertainty: How stable is their relationship over time?," *Econ. Model.*, vol. 72, pp. 42–53, 2018.

[95] W. Qiao *et al.*, "Natural gas consumption forecasting using a novel two-stage model based on improved sparrow search algorithm," *Journal of Pipeline Science and Engineering*, vol. 5, no. 1, p. 100220, 2025.

[96] R. T. Mittakola, P. Ciais, and C. Zhou, "Short-to-medium range forecast of natural gas use in the United States residential buildings," *J. Clean. Prod.*, vol. 437, no. 140687, p. 140687, 2024.

[97] B. Gaweł and A. Paliński, "Global and local approaches for forecasting of long-term natural gas consumption in Poland based on hierarchical short time series," *Energies*, vol. 17, no. 2, p. 347, 2024.

[98] X. Xu *et al.*, "Integrating multi-modal data into transformer model for short-term gas consumption forecasting," *Alex. Eng. J.*, vol. 122, pp. 655–664, 2025.