AI-Driven Smart Grid Solutions for Energy Justice: Integrating Technical Efficiency with Inclusive Social Welfare Policy Design

Hafize Nurgul Durmus Senyapar*, Ramazan Bayindir**‡

* Faculty of Health Sciences, Gazi University, Ankara 06490, Türkiye

** Faculty of Technology, Gazi University, Ankara 06560, Türkiye

(nurguld@gazi.edu.tr, bayindir@gazi.edu.tr)

‡ Corresponding Author; Ramazan Bayindir, Gazi University, Ankara, 06560, Turkey, Tel: +90 312 2028540
bayindir@gazi.edu.tr

Received: 04.04.2025 Accepted:09.06.2025

Abstract- This study examines the evolving role of Artificial Intelligence (AI) and Smart Grid systems in shaping policy frameworks that promote energy justice and inclusive social welfare. As Smart Grids enable real-time data exchange, decentralized energy management, and two-way communication between utilities and consumers, they provide a dynamic infrastructure for deploying AI-driven solutions. AI technologies—ranging from demand forecasting and anomaly detection to predictive maintenance—offer powerful tools for optimizing energy distribution and aligning technical efficiency with social equity goals. When integrated with Smart Grid platforms, these tools can enhance energy governance by identifying underserved regions, supporting dynamic pricing strategies, and enabling context-sensitive subsidy programs. Moreover, by incorporating data on social vulnerability and systemic inequities, AI can inform cross-sectoral policies that enhance housing conditions, improve health outcomes, and promote income security. However, the adoption of AI and Smart Grid technologies in policymaking raises critical concerns about algorithmic bias, data opacity, and the exclusion of marginalized voices. This paper explores the dual role of AI-enabled Smart Grids as both enablers of equitable policies and potential sources of new barriers. Using a qualitative, exploratory approach, the study investigates how these technologies can be implemented ethically, transparently, and inclusively to support both equitable energy transitions and resilient social welfare systems.

Keywords Smart Grid, energy justice, social welfare policy, inclusive policymaking, ethical AI, equity in energy policy

1. Introduction

The global energy justice movement has emerged as a critical response to the inequities and challenges in energy access, distribution, and sustainability. Rooted in principles of fairness, equity, and inclusivity, energy justice seeks to ensure that all individuals, regardless of socioeconomic status, geographic location, or demographic background, have access to affordable, reliable, and sustainable energy [1]. It emphasizes addressing systemic disparities, such as energy poverty in marginalized communities and the disproportionate environmental burdens borne by vulnerable populations. Recent years have seen a growing recognition of the interconnectedness between energy justice and other global goals, including climate action, human rights, and sustainable development [2].

Artificial intelligence (AI) has become a crucial tool in shaping energy policies, providing innovative solutions to complex challenges in the energy sector. By enabling the collection and analysis of vast amounts of data, AI facilitates informed decision-making, predictive modelling, and optimization of energy networks [3]. It also supports the development of more inclusive energy policies by identifying patterns of inequity and proposing targeted interventions.

AI-driven policy tools hold significant promise for addressing inequities in energy systems, particularly in the fields of distribution, resource allocation, and governance [4], 5]. In energy distribution, AI algorithms can identify underserved regions, optimize grid infrastructure, and predict energy demand patterns to ensure equitable access to energy. For instance, machine learning models can map energy deserts and areas with limited access to modern energy services and recommend strategies for infrastructure development tailored to local needs. These tools also enhance the efficiency and sustainability of energy delivery by minimizing waste and reducing costs, making energy systems more accessible to disadvantaged communities [6]. In resource allocation, AI can prioritize investments and interventions that maximize social and environmental benefits. Tools utilizing AI can analyze diverse datasets, including socioeconomic indicators, geographic constraints, and environmental risks, to allocate resources in a manner that promotes equity [7]. AI can help policymakers design subsidy schemes that target low-income households or identify renewable energy projects with the highest potential to benefit marginalized populations. Such targeted approaches reduce the risk of reinforcing existing disparities and contribute to more inclusive energy transitions. By enabling real-time monitoring and evaluation of energy systems, AI enhances transparency and accountability in decision-making processes and supports participatory governance by integrating stakeholder feedback into policy models [7]. This study focuses on the critical intersection of AI technologies and energy justice, specifically examining how AI can support the development and implementation of policies that promote equitable access to and governance of energy. With the global push toward sustainable energy transitions, there is a growing need for innovative tools to address disparities in energy systems. This study addresses a critical gap in the existing literature: while numerous works explore either AI applications or energy justice frameworks separately, few studies integrate both from a policy design perspective, especially considering inclusive welfare mechanisms in low- and middle-income contexts. AI offers significant potential in this context, providing data-driven insights, predictive modelling, and optimization capabilities that can enhance policy design and execution. However, the dual nature of AI, as both a transformative enabler and a potential barrier, necessitates a nuanced exploration of its role in equitable policymaking. While AI can uncover and address systemic inequities, it also carries risks of perpetuating existing biases and excluding marginalized voices if not implemented responsibly.

The primary aim of this study is to explore the role of AI in supporting policy frameworks that advance energy justice. By examining AI's applications and limitations, the research seeks to contribute to the growing discourse on integrating technological innovation with social equity principles. The study acknowledges the pressing need for comprehensive strategies to utilize AI in ways that foster fairness, inclusivity, and sustainability in energy systems. To achieve this aim, the study is guided by three specific objectives. First, it examines AI applications in the development and implementation of energy policies, with a focus on their capacity to address inequities in energy access, resource allocation, and governance. This includes exploring case studies and current practices where AI has been successfully integrated into energy policy frameworks. Second, the study identifies challenges and risks associated with AI-driven policymaking, such as the potential for algorithmic bias, data privacy concerns, and the digital divide. Understanding these challenges is crucial for mitigating unintended consequences and ensuring that AI tools do not reinforce existing disparities. Third, the research proposes strategies for using AI in a manner that ensures energy justice. These strategies emphasize the importance of inclusive design, transparent governance, and accountability mechanisms to align AI applications with the principles of energy justice.

While AI holds immense promise as an innovative tool for policy development, its uncritical adoption in energy systems poses significant risks. If not designed and implemented with equity in mind, AI algorithms can unintentionally perpetuate existing inequities and biases. Biased data inputs or exclusionary modeling approaches may perpetuate systemic disparities in energy access, resource allocation, and governance. These challenges highlight the need to critically examine how AI technologies are integrated into energy policy frameworks, ensuring that their transformative potential is harnessed to advance energy justice rather than exacerbate social and economic divides. Smart Grids, characterized by two-way communication, real-time monitoring, and decentralized energy exchange, provide the necessary infrastructure for deploying AI tools that promote energy justice. By utilizing high-resolution data from smart meters, distributed energy resources, and IoT-enabled devices, AI can support demand-side management, optimize load balancing, and predict equipment failures more accurately. These capabilities enable more equitable distribution of energy resources, allowing utilities and policymakers to target underserved communities, reduce energy costs, and improve reliability for vulnerable populations [8], [9].

This study is guided by three key research questions to explore the intersection of artificial intelligence (AI), energy justice, and inclusive social welfare policymaking.

First, it aims to understand the current applications of AI in energy policy development and implementation, with a particular focus on how these applications contribute to promoting equity in energy access, resource allocation, and governance. This includes examining existing tools and practices where AI has been employed to optimize energy distribution, forecast consumption patterns, inform regulatory decisions, and support socially targeted energy interventions. The research examines the extent to which AI contributes to equitable energy transitions and its potential to enhance the effectiveness of social support mechanisms, including targeted subsidies and affordable access programs.

Second, the study examines the challenges and risks associated with AI-driven policymaking in the context of energy justice, as well as its broader implications for social welfare systems. This entails analysing issues such as algorithmic bias, data representativeness, lack of transparency in decision-making (the “black box” problem), and the exclusion of marginalized populations from policy design. These challenges are assessed not only in terms of energy distribution outcomes but also in terms of their potential to exacerbate structural inequalities in housing, health, and income security if left unaddressed.

Third, the research examines strategies for effectively leveraging AI to advance both energy justice and inclusive social welfare outcomes. This involves identifying best practices for inclusive data governance, explainable and ethical AI design, and participatory policymaking frameworks that incorporate the voices of disadvantaged communities. The study considers how these strategies can be embedded into cross-sectoral policy models that align AI innovations with the goals of fairness, sustainability, and resilience in both energy and welfare systems.

This study examines how artificial intelligence (AI) can promote energy justice and support inclusive social welfare policies. Recognizing energy access as a key social determinant, it examines how AI-driven tools—such as targeted subsidies, dynamic pricing, and infrastructure planning—can help reduce structural inequalities. By integrating social vulnerability data into energy policy models, AI can inform cross-sectoral strategies that strengthen welfare systems and community resilience.

The significance of this study lies in its interdisciplinary contribution to integrating AI into energy and welfare governance through a lens of equity and sustainability. It offers actionable insights for designing AI systems that are not only technically efficient but also ethically grounded and socially responsive. Ultimately, the research positions AI as a policy instrument capable of advancing justice, transparency, and inclusive development.

2. Methodology

This study adopts a qualitative exploratory research approach to examine the policy implications of artificial intelligence (AI) in promoting energy justice and inclusive social welfare systems. Qualitative methods are particularly appropriate for investigating interdisciplinary and evolving topics, especially at the intersection of technology, equity, and governance [10]. By focusing on policy design and implementation, this approach enables a deeper understanding of how AI can be leveraged to address structural inequalities in energy access, distribution, and social protection mechanisms.

The analysis is based on a systematic review of academic literature covering AI in energy governance, social welfare policy, and technology ethics, supplemented by policy reports from international organizations that reflect global priorities and practical challenges. To interpret these materials, the study applies a thematic analysis framework designed to identify recurring trends, policy gaps, and design opportunities in AI-supported governance. The process involved (1) initial coding of literature and reports, (2) clustering of data into overarching themes—such as transparency, bias mitigation, and participatory design—and (3) synthesis and refinement of these themes in relation to international best practices and conceptual frameworks [11]. Several qualitative indicators—such as targeting accuracy, inclusion rates, and bias mitigation—were used to assess the social policy relevance of AI applications. By systematically categorizing themes such as accessibility, governance adaptability, and fairness, the analysis highlights both the transformative potential and the practical limitations of AI in achieving equitable energy and welfare outcomes.

3. Findings

3.1. AI Applications in Energy Policy Development and Implementation (Answering RQ1)

AI has emerged as a transformative tool in policy modelling and simulation, enabling policymakers to assess the potential impacts of energy policies across diverse socio-economic and environmental scenarios [12]. By utilizing machine learning algorithms and advanced simulation techniques, AI can model complex interactions within energy systems, considering variables such as population growth, economic fluctuations, and climate change. These simulations offer valuable insights into the long-term consequences of policy decisions, enabling governments and organizations to assess trade-offs and optimize outcomes [13]. For instance, AI-driven models can simulate the effects of transitioning to renewable energy sources on employment, energy prices, and emissions. This capability enables decision-makers to develop policies that strike a balance between sustainability goals and economic and social considerations. Efficient allocation of renewable energy resources is a critical challenge in achieving energy justice, and AI-driven tools offer innovative solutions to address this issue. By analyzing large datasets on energy production, consumption patterns, and geographical constraints, AI systems can optimize resource distribution to ensure maximum efficiency and equity [14]. For example, AI can identify ideal locations for solar and wind energy installations based on weather patterns and energy demand, minimizing waste and maximizing impact. Additionally, these tools can prioritize resource allocation to underserved or energy-poor regions, addressing disparities in access to clean and affordable energy. This application enhances operational efficiency and supports the broader objective of equitable energy transitions. See Table 1 for a comparative overview of AI techniques and their policy applications.

Digital technologies, such as AI, might contribute up to 20% of the 2050 reduction, shown in Fig. 1, required to meet the International Energy Agency’s net-zero trajectories in the energy, materials, and mobility sectors, according to an analysis conducted by Accenture in partnership with the World Economic Forum. The rapid adoption of digital technologies can already reduce emissions by 4–10% in certain industries [15], [16].

Table 1. Comparative overview of AI techniques and their policy applications

AI Technique	Policy Application	Example Use Case	Equity Contribution
Machine Learning	Demand forecasting	Predicting peak demand in urban slums	Ensures grid stability in underserved areas
NLP (Natural Language Processing)	Public sentiment analysis	Analyzing feedback from marginalized communities	Informs inclusive policy adjustments
Predictive Analytics	Subsidy targeting	Identifying low-income households for dynamic pricing	Increases financial protection for vulnerable users
Reinforcement Learning	Grid optimization	Adaptive energy distribution based on real-time load	Enhances access reliability in resource-poor regions
Classification Algorithms	Social risk identification	Mapping energy poverty indicators	Supports integrated social-energy interventions

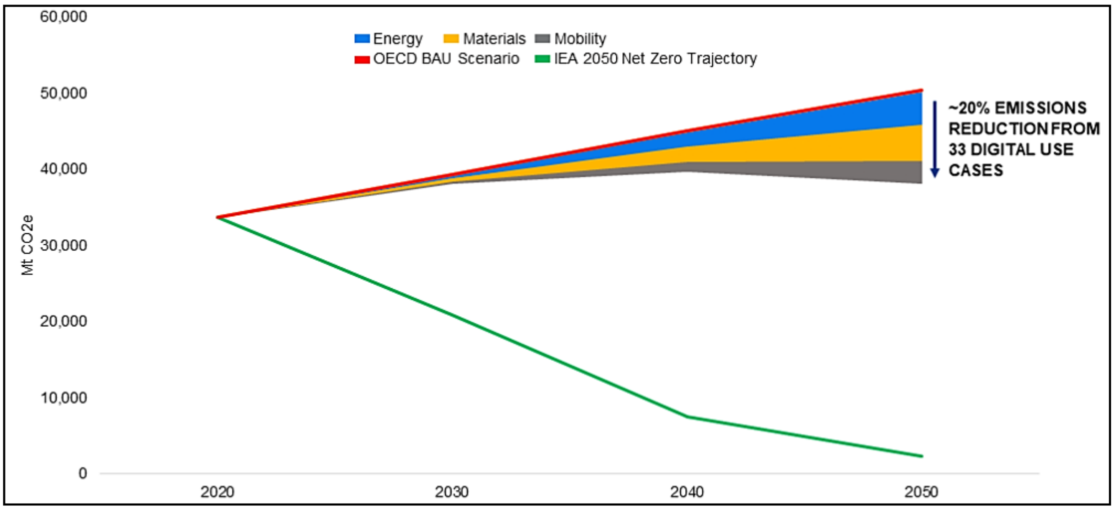

Fig. 1. Digital technology's significant contribution to achieving net zero [17].

AI's ability to process and analyse vast amounts of data makes it an invaluable tool for energy demand forecasting, a critical component of informed policy decisions. By integrating data from Smart Grids, weather reports, and historical consumption trends, AI systems can accurately predict future energy demand. This foresight enables policymakers to design proactive measures to address anticipated demand surges or shortages, ensuring a reliable energy supply. For example, AI-powered forecasting tools can inform investment decisions in energy infrastructure or guide the timing and scale of renewable energy deployment [18]. Furthermore, demand forecasting facilitates the creation of dynamic pricing models that promote energy conservation and support grid stability. The development of robust regulatory frameworks is essential for governing the rapidly evolving energy sector, and AI plays a vital role in this process. By analysing large-scale datasets from diverse sources, such as market trends, compliance records, and environmental metrics, AI can provide evidence-based insights to craft effective regulations. For instance, AI systems can identify patterns of non-compliance, assess the impact of existing regulations, and recommend adjustments to enhance the effectiveness of these regulations. Additionally, AI can support the creation of adaptive regulatory mechanisms that evolve in response to technological advancements and changing market conditions. This capability ensures that regulations remain relevant, fair, and aligned with the principles of energy justice.

Artificial intelligence can play a pivotal role in aligning energy justice with broader social welfare policy goals by informing the design and delivery of targeted social assistance mechanisms. AI-driven tools can optimize energy subsidy schemes by accurately identifying low-income households most in need, thereby enhancing the efficiency and equity of public spending [19]. Predictive analytics can also support dynamic pricing systems that protect vulnerable populations from energy price volatility, contributing to more stable household economics [20]. Within the context of Smart Grids, these AI applications gain further operational depth. Smart Grids serve as digital backbones, transmitting real-time data from consumers and infrastructure nodes. Machine learning algorithms trained on smart meter data can anticipate localized consumption trends, detect anomalies in energy flows, and enable predictive maintenance of critical infrastructure. For instance, when paired with weather data and real-time load signals, AI can help modulate decentralized energy dispatch to avoid blackouts, particularly in energy-poor neighbourhoods. This deepens the role of AI not just as a modelling tool, but as a real-time decision-making engine embedded in the technical fabric of energy systems. Beyond the energy domain, inclusive and equitable [21], [22], [23]. AI applications can indirectly advance welfare objectives in housing, health, and education—areas closely tied to energy security [24], [25]. By mapping patterns of energy poverty, AI can guide investments in energy-efficient housing or prioritize renewable energy deployment in regions with poor health outcomes linked to inadequate heating or cooling [26]. As such, AI-enabled energy governance holds the potential not only to address structural inequalities in access to energy but also to reinforce the multidimensional goals of social welfare policy [27]. AI's multifaceted applications in energy policy extend beyond technical efficiency to encompass broader social objectives [28]. Figure 2 provides a visual summary of how AI intersects with major policy domains such as modelling, resource allocation, regulation, and social alignment. Each arrow represents a functional link, highlighting the flow from technical processes to social outcomes. This structure reinforces the study's argument that AI serves both governance and welfare objectives simultaneously. As illustrated in Fig. 2, AI supports not only policy modelling, resource allocation, and demand forecasting but also contributes to social welfare alignment through targeted subsidies, dynamic pricing mechanisms, and investment guidance in areas such as housing, health, and education.

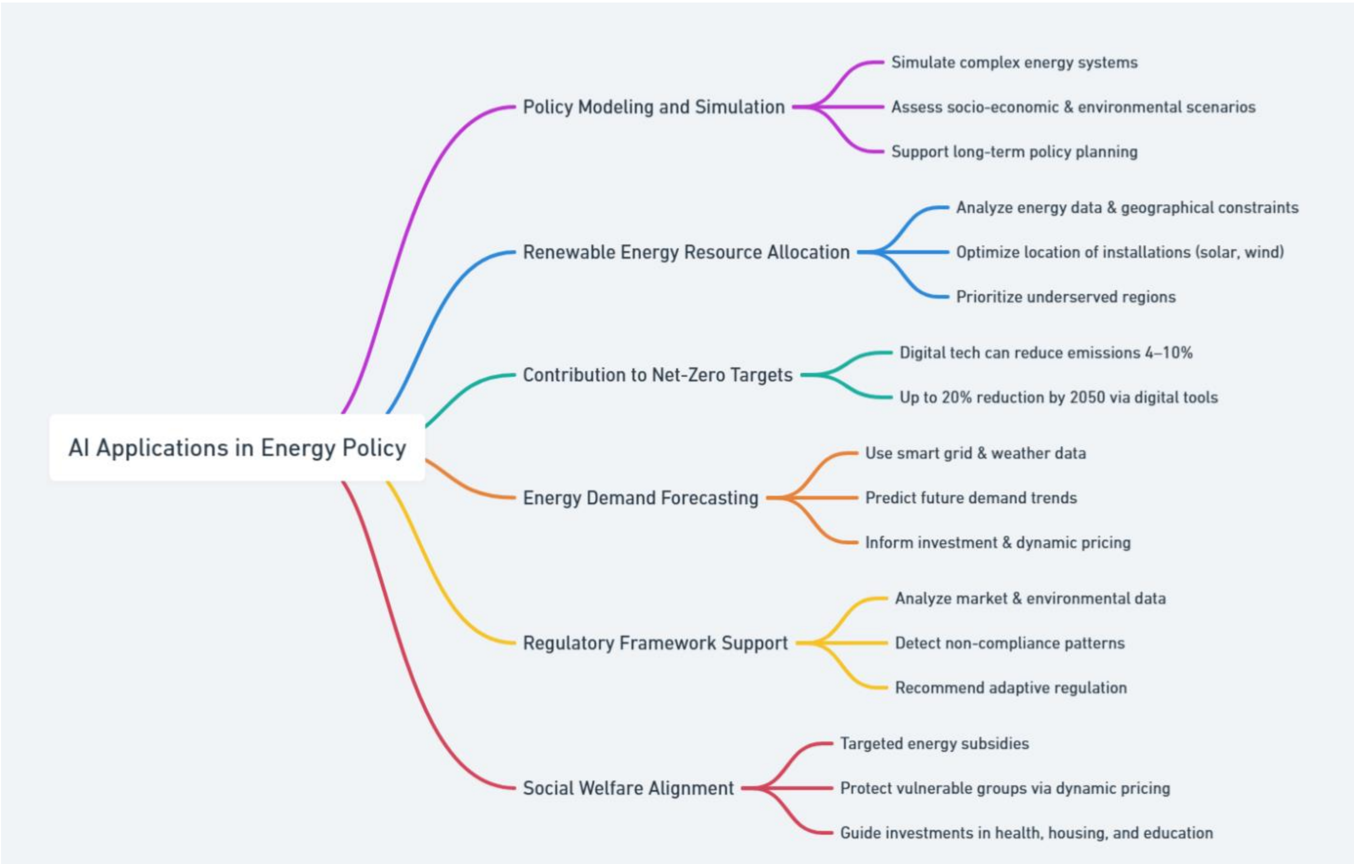

Fig. 2. AI in energy policy. Source: Author's visualization based on the study's conceptual framework (2025).

3.2. Challenges and Risks in AI-Driven Policymaking (Answering RQ2)

One of the most significant challenges in using AI for energy policy is the risk of algorithmic bias, which can lead to unfair or inequitable policy decisions. Bias in AI models often arises from the data used for training, which may reflect existing societal inequalities or systemic disparities [29]. For instance, datasets that underrepresent marginalized communities may result in AI models that overlook these groups when designing energy allocation strategies. Additionally, biases embedded in the algorithms themselves, whether intentional or unintentional, can skew policy outcomes in favour of already privileged populations. Such risks underscore the importance of rigorous data auditing, bias detection, and inclusive model design to ensure that AI-driven policies uphold the principles of energy justice.

The opacity of AI decision-making processes poses another critical challenge to its integration into energy policy. Beyond technical risks, contextual limitations also shape the effectiveness of AI in achieving energy justice—especially in low- and middle-income countries (LMICs). In low- and middle-income countries (LMICs), the implementation of AI-driven energy solutions faces additional structural constraints. These include limited digital infrastructure, low levels of data availability, inadequate regulatory capacity, and gaps in digital literacy among both citizens and policymakers.

Without targeted support mechanisms, AI adoption in such contexts risks reinforcing existing inequalities or failing to reach vulnerable populations altogether. Therefore, policy strategies must account for contextual barriers and emphasize capacity-building, infrastructure investment, and inclusive digital governance. Often referred to as the "black box" problem, this lack of transparency can erode trust among stakeholders, including policymakers, industry professionals, and the public. If stakeholders cannot understand or verify the reasoning behind AI-generated recommendations, it becomes challenging to ensure accountability and address concerns about fairness and equity [20]. This issue is particularly problematic in energy policy, where decisions can have widespread social and economic implications. To address this challenge, the development of explainable AI (XAI) systems, which makes the decision-making process more transparent and interpretable to stakeholders, is essential. These systems should provide clear, interpretable insights into how decisions are made, enabling stakeholders to evaluate and trust the outcomes.

Adoption and trust in AI systems vary significantly across different regions, as shown in Fig. 3, particularly between Western nations and emerging economies. Generally, Western countries have been more hesitant to adopt AI-driven systems, particularly in private and personal contexts. This reluctance is often attributed to a deep-seated concern regarding privacy, with individuals in these regions reluctant to share personal data or entrust decisions to AI algorithms. Additionally, there is resistance to the idea of replacing human workers with machine-driven processes, particularly in areas that traditionally relied on human oversight and decision-making. In contrast, emerging economies, particularly the BRICS countries (Brazil, Russia, India, China, and South Africa), have shown a greater willingness to trust and adopt AI systems. Among these nations, AI-driven policies and technologies have been met with more openness, as these countries often perceive AI as a means to leapfrog technological gaps and accelerate development. These differences in AI acceptance have significant implications for global energy policy, as nations with differing attitudes toward AI may prioritize or adopt AI technologies at varying rates, influencing the implementation of AI-driven solutions in energy policy frameworks.

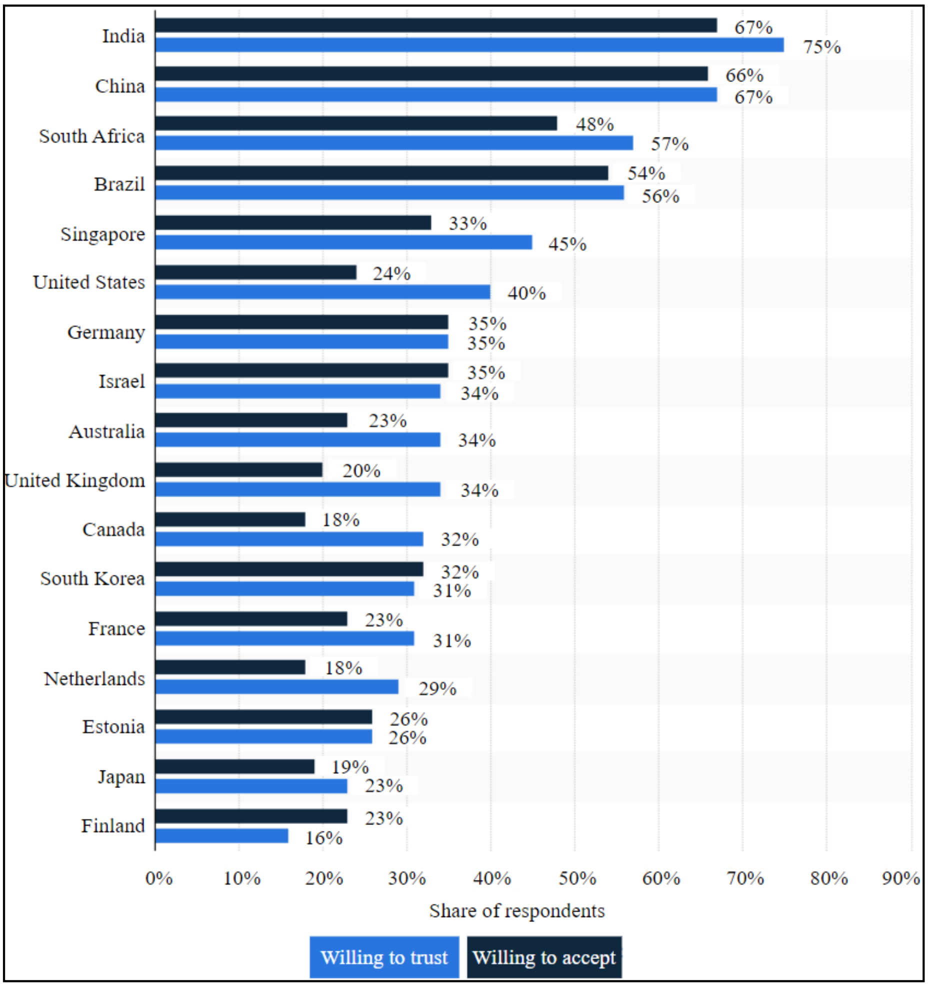

Fig. 3. Willingness to trust and accept AI systems [30].

While AI offers powerful tools for policy development, an overreliance on these technologies without critical human oversight can lead to suboptimal or even harmful outcomes. Policymakers may be tempted to depend excessively on AI for its efficiency and predictive capabilities, overlooking the nuanced judgment and contextual understanding that human decision-makers bring to the table. This overreliance can lead to policies that fail to consider local contexts, cultural dynamics, or unintended consequences [23]. For example, an AI model optimizing energy distribution might prioritize efficiency over equity, inadvertently disadvantaging vulnerable communities.

To mitigate this risk, AI systems must be complemented by robust human oversight, ensuring that technological insights are balanced with ethical and contextual considerations. The potential exclusion of marginalized groups in AI-driven policy frameworks presents a significant barrier to achieving energy justice. AI models often reflect the perspectives and priorities of those involved in their design and deployment, which may not encompass the perspectives of underrepresented or disadvantaged communities. This exclusion can result in policies that fail to address the unique needs and challenges faced by these groups [31]. For example, rural or low-income communities may be overlooked in energy infrastructure planning if their data is not adequately represented in AI systems. To counteract this exclusion, it is essential to incorporate participatory approaches that engage diverse stakeholders in the design and implementation of AI-driven policies. Ensuring that marginalized voices are heard and represented can help create more inclusive and equitable energy policies.

Beyond the technical and ethical risks outlined above, the implications of AI-driven energy policymaking for social welfare policy merit closer scrutiny. If algorithmic biases and exclusions go unaddressed, AI may inadvertently reinforce structural inequalities that extend far beyond energy systems, affecting access to housing, health services, education, and income support. Social welfare policies, which aim to mitigate these inequalities, risk being undermined if energy-related interventions—such as subsidy allocation or dynamic pricing—fail to reach the most vulnerable populations [32]. Conversely, when designed inclusively and transparently, AI-supported energy policies can serve as powerful instruments to enhance social protection frameworks by informing targeted welfare interventions, reducing energy poverty, and promoting inter sectoral equity [33], [34]. Therefore, aligning AI applications with the principles of social welfare not only strengthens the legitimacy and impact of energy governance but also helps build more resilient and just societies.

3.3. Strategies for Using AI for Energy Justice (Answering RQ3)

Ensuring that datasets used for AI model training and analysis represent diverse communities and their unique energy needs is a foundational step in promoting energy justice. Data biases can arise when underrepresented groups, such as rural populations, low-income households, or Indigenous communities, are excluded from datasets, leading to AI-driven policies that fail to address their needs. Inclusive data practices involve collecting and integrating data from diverse demographic, geographic, and socioeconomic contexts [26]. For instance, incorporating localized data on energy access, consumption patterns, and affordability can help AI models identify and address disparities in energy distribution. Policymakers and developers must also establish mechanisms to continually update and refine datasets, ensuring that AI-driven policies remain equitable and responsive to diverse needs as societal and energy dynamics evolve. The complexity of AI systems often renders their decision-making processes opaque, which can hinder policymakers' ability to understand and build public trust. To overcome this challenge, developing AI models with precise and interpretable outputs is essential. Explainable AI systems provide stakeholders with insights into how decisions are made, enabling them to evaluate the rationale behind policy recommendations and ensure that these recommendations align with energy justice principles [35]. For example, when an AI system suggests prioritizing certain regions for renewable energy projects, it should provide clear reasoning based on data analysis and the criteria used in the decision-making process. Enhancing transparency fosters trust and empowers policymakers to make informed decisions, adjusting AI recommendations as needed to address equity concerns.

AI technologies can facilitate participatory policymaking by enabling the active involvement of marginalized communities in the policy development process. Traditional policy frameworks often exclude underrepresented groups, leading to decisions that fail to address their specific challenges [36]. AI-driven tools, such as natural language processing and sentiment analysis, can analyse feedback from diverse stakeholders, ensuring that their voices are considered in energy policy discussions [37]. Additionally, AI can support virtual platforms and digital forums that bring communities together to share insights and co-create solutions. For example, rural communities could use AI-supported participatory methods to highlight local energy needs and propose region-specific interventions. By incorporating these perspectives, policymakers can develop more inclusive and equitable energy policies that resonate with the lived experiences of all stakeholders. Embedding justice and fairness principles in AI design is crucial for aligning these technologies with the objectives of energy justice. Ethical AI development involves proactively addressing potential biases, ensuring accountability, and prioritizing the equitable distribution of energy resources. This study specifically considers the role of several AI techniques in policy design, including supervised learning for demand forecasting, classification algorithms for social vulnerability mapping, natural language processing (NLP) for stakeholder sentiment analysis, and reinforcement learning for real-time grid optimization. To mitigate algorithmic bias, the proposed framework prioritizes fairness-aware algorithm design, stakeholder-inclusive training data, regular auditing mechanisms, and the utilization of explainable AI to ensure transparent decision-making processes. These measures are crucial for mitigating the risk of reinforcing existing inequalities and ensuring equitable policy outcomes.

This includes designing algorithms that explicitly consider social equity and environmental sustainability as key parameters [38]. For instance, AI models can be programmed to prioritize investments in regions with high energy poverty or to favour renewable energy projects that benefit underserved populations. Developers must also adhere to ethical guidelines and industry standards, collaborating with experts in social justice, environmental policy, and technology to create AI systems that uphold these values. Ethical AI design mitigates risks and ensures that AI serves as a tool for advancing justice and fairness in energy systems.

In parallel with technical and ethical strategies, aligning AI applications with social welfare policy frameworks can further strengthen their capacity to promote energy justice. AI-driven tools that inform energy pricing, subsidy targeting, and infrastructure investments can directly support the aims of social welfare by reducing household energy burdens and improving living conditions [39]. For instance, integrating energy data with social policy indicators allows AI systems to identify households at the intersection of energy poverty and broader social vulnerability, enabling cross-sectoral interventions that combine energy assistance with housing, healthcare, or income support programs [40]. Such integrative approaches enhance the responsiveness and equity of both energy and welfare systems, making AI not just a technological enabler but a strategic asset in building inclusive social protection infrastructures. The process of integrating AI into energy justice frameworks requires a series of intentional and interconnected steps that prioritize inclusivity, transparency, and ethical design. As illustrated in Figure 4, this study proposes a strategic pathway that begins with inclusive data practices and progresses toward the alignment of AI systems with social welfare policies, ultimately aiming to achieve equitable and inclusive energy governance.

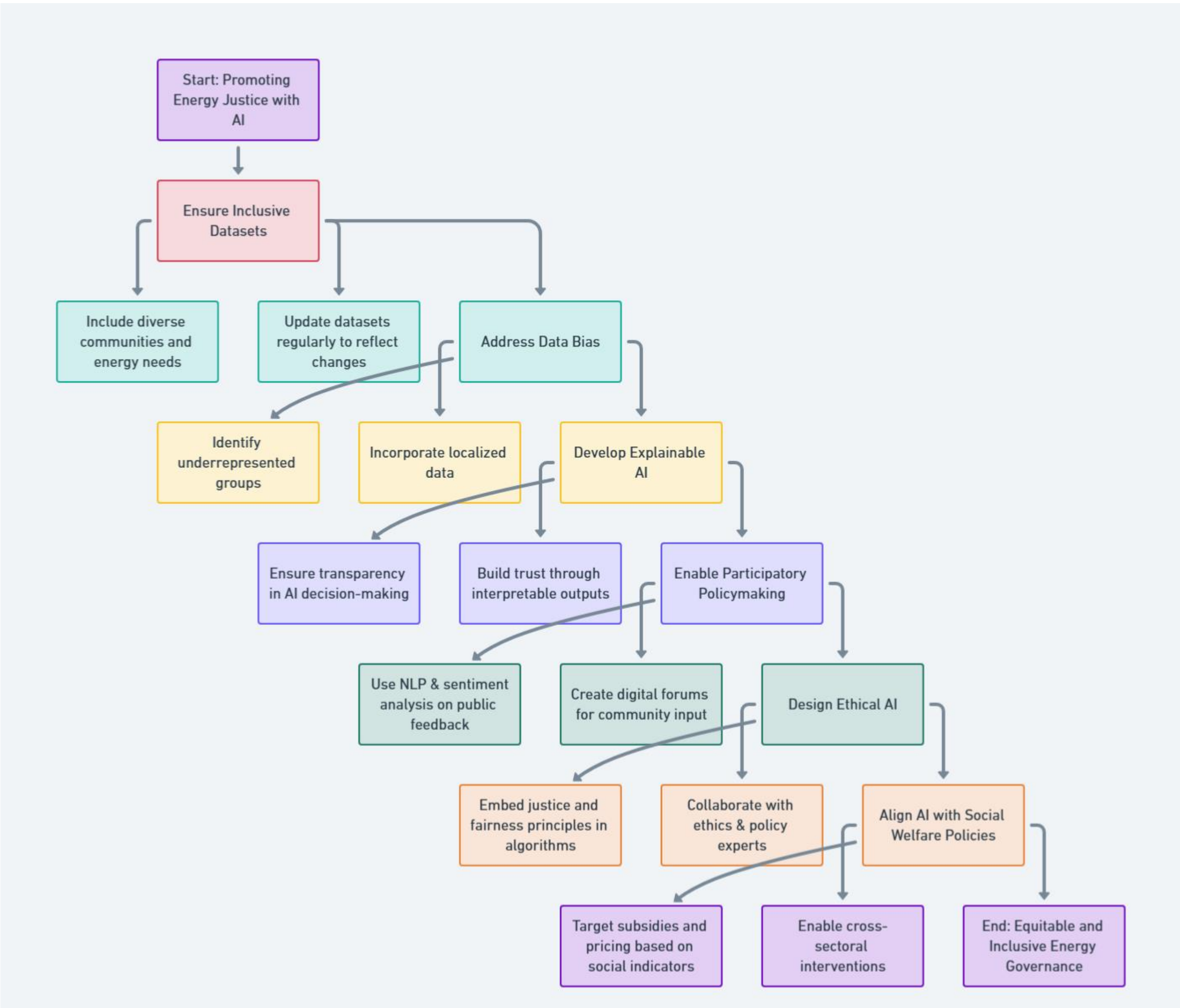

Fig. 4. AI for energy justice flowchart.

4. Discussion

AI holds significant transformative potential in shaping energy policies by enhancing policy modelling, forecasting, and implementation processes. Through advanced simulation tools, AI enables policymakers to anticipate the outcomes of proposed energy policies under various socio-economic and environmental scenarios. For instance, machine learning algorithms can identify optimal renewable energy deployment strategies by analysing resource availability, cost factors, and energy demands [41]. AI-driven forecasting models offer accurate predictions of energy consumption trends, enabling policymakers to design proactive strategies that meet future energy needs. Moreover, AI can streamline policy implementation by automating complex processes, such as optimizing energy resource allocation or monitoring compliance with regulatory frameworks [42]. The implications of AI-driven energy justice extend beyond the energy sector itself. As energy access is a core social determinant, equitable energy policies can shape broader social welfare systems. AI-based interventions that reduce energy poverty or improve access can ultimately contribute to more effective and just social welfare policies.

However, realizing AI's full potential requires robust integration with human expertise to ensure the ethical and equitable application of its capabilities. Despite its transformative potential [43], AI poses challenges related to bias, transparency, and accountability that can undermine equitable policymaking. Algorithmic biases, often stemming from incomplete or unrepresentative datasets, risk perpetuating existing disparities in energy access and resource allocation. For example, AI models trained on data from urban areas may fail to address the specific needs of rural or marginalized communities. Transparency issues further complicate trust in AI-driven decisions, as the opaque nature of some algorithms can leave stakeholders unclear about how policy recommendations are generated. This lack of clarity can erode public trust and prevent stakeholder engagement. Additionally, overreliance on AI without adequate human oversight raises concerns about accountability, as policymakers may deflect responsibility for unfair or ineffective decisions onto AI systems. Addressing these challenges requires greater emphasis on explainable AI, inclusive data practices, and clearly defined accountability mechanisms in the policy process.

Strategies proposed for using AI to promote energy justice carry significant practical implications for achieving equitable energy policies. Inclusive data practices, for instance, ensure that AI models account for the needs of diverse communities, reducing disparities in energy distribution. Transparency and explainability initiatives foster trust and empower policymakers to make informed decisions, thereby promoting accountability. Participatory policymaking, enabled by AI tools, enhances inclusivity by incorporating the perspectives of marginalized groups into energy policy development. Ethical AI development ensures that fairness and justice principles are embedded in algorithmic design, aligning AI applications with broader energy justice goals. Together, these strategies form a framework for leveraging AI to promote equity, sustainability, and inclusivity in energy systems [44], [45].

The integration of AI within Smart Grid infrastructures enhances its capacity to deliver equitable energy solutions. Smart Grids enable high-frequency, bidirectional communication across energy networks, allowing AI to dynamically manage grid stress, forecast outages, and support time-sensitive interventions such as rolling subsidies or emergency load management. These systems transform AI from a passive policy support tool into an active agent for delivering real-time energy justice. When combined with ethical design and participatory oversight, AI-powered Smart Grids hold the potential to democratize energy access and reinforce social protection frameworks in a technologically resilient manner [15], [16], [20]. However, their successful implementation requires collaboration among policymakers, AI developers, and community stakeholders, underscoring the need for interdisciplinary and participatory approaches to energy policymaking. AI plays a dual role in energy justice, acting as both an enabler of progress and a potential barrier to equity. Firstly, AI offers tools for optimizing energy systems, enhancing efficiency, and expanding access to renewable energy resources [46]. For example, AI-driven simulations and predictive models can inform policies that reduce energy poverty and promote equitable distribution. On the other hand, uncritical reliance on AI risks perpetuating systemic inequities. Algorithmic biases and opaque decision-making processes can marginalize underserved communities, preventing them from accessing energy resources. Striking a balance between these roles requires a critical understanding of AI's limitations and the proactive implementation of measures to mitigate potential harms. Policymakers and AI developers must collaborate to ensure that these technologies align with principles of fairness, inclusivity, and transparency, safeguarding energy justice as a fundamental outcome.

The findings of this study align closely with several Sustainable Development Goals (SDGs), particularly SDG 7 (Affordable and Clean Energy), SDG 10 (Reduced Inequalities), and SDG 13 (Climate Action). AI-driven energy policies can directly contribute to achieving Sustainable Development Goal 7 (SDG 7) by improving access to affordable, reliable, and sustainable energy for all. Through inclusive data practices and participatory approaches, AI can address disparities in energy access, supporting SDG 10 by reducing inequalities within and among nations. Furthermore, AI applications in energy resource optimization and demand forecasting can bolster climate action under SDG 13, reducing greenhouse gas emissions and supporting global climate commitments. By using AI responsibly, stakeholders can ensure that energy justice becomes an integral part of achieving these SDG targets, fostering a sustainable and equitable future. Integration of AI into energy policymaking has significant implications for governance and policy design. Policymakers must strike a balance between the drive for AI innovation and the need to uphold fairness and equity in energy systems. Transparent governance frameworks are crucial for ensuring accountability and fostering stakeholder trust in AI-driven decisions. For example, establishing guidelines for the ethical use of AI and incorporating mechanisms for public oversight can enhance legitimacy and prevent misuse. Additionally, AI must be viewed as a complement to, rather than a substitute for, human judgment. Maintaining critical human oversight ensures that AI tools enhance decision-making without undermining democratic principles or excluding marginalized voices. Policymakers should also prioritize capacity-building initiatives, equipping stakeholders with the necessary skills to effectively engage with AI technologies. By fostering a collaborative and equitable approach, governance systems can maximize the potential of AI while safeguarding the principles of energy justice.

Moreover, the integration of AI into energy policymaking presents critical opportunities for advancing social welfare policy goals. Equitable energy access is not only a matter of technical distribution but also a fundamental component of broader social protection systems. By incorporating social indicators—such as income level, health vulnerability, or housing quality—into AI-driven energy planning, policymakers can design interventions that simultaneously alleviate energy poverty and strengthen welfare infrastructures. For example, AI tools that guide targeted subsidies or energy retrofitting programs for low-income households can significantly reduce household burdens and improve living standards. These cross-sectoral applications position AI as a strategic enabler of social equity, aligning energy justice initiatives with national and local social welfare agendas. Thus, future-oriented energy governance must consider AI not only as a technological solution but also as a policy instrument to reinforce inclusive and resilient welfare systems.

5. Conclusion

This study highlights the transformative potential of AI in advancing energy justice through its diverse applications in policy modelling, demand forecasting, and resource optimization. At the same time, it highlights significant challenges, including algorithmic bias, a lack of transparency, and the risk of marginalizing underrepresented communities. Strategies such as inclusive data practices, participatory policymaking, and ethical AI development have been proposed to address these challenges and ensure that AI-driven policies align with the principles of energy justice. The study offers novel insights into how AI can be effectively integrated into policymaking to tackle energy inequities. Identifying both the enabling potential and inherent risks of AI contributes to the growing body of knowledge on the intersection of technology and justice in the energy sector. The findings underscore the importance of adopting a balanced approach to utilizing AI for achieving equitable and sustainable energy policy outcomes.

Policymakers, researchers, and AI developers are encouraged to prioritize energy justice in AI-driven policy initiatives. This involves creating transparent, inclusive, and participatory frameworks that actively engage marginalized communities and address systemic inequities. Collaboration among stakeholders is crucial to ensure that AI innovations are directed toward achieving equitable outcomes and aligning with global sustainability goals. Future research should focus on the real-world application of AI-driven policy frameworks and assess their long-term impacts on energy justice. Investigating case studies and pilot projects will provide valuable insights into the practical challenges and opportunities of implementing AI in diverse socio-economic and cultural contexts. Moreover, further exploration is needed to refine strategies for mitigating risks and maximizing the benefits of AI in promoting equitable and sustainable energy systems. These efforts will be crucial for advancing the role of AI as a tool for achieving global energy justice. In addition to advancing energy justice, the responsible use of AI in policy design has the potential to reinforce broader social welfare objectives. By linking energy access data with indicators of social vulnerability, AI-driven frameworks can inform more responsive and integrated welfare policies—ranging from targeted subsidies to energy-efficient housing and public health interventions. This convergence underscores the necessity of framing AI not only as a technical enabler but also as a policy tool that can strengthen social protection systems and address structural inequalities. Future policy and research efforts should, therefore, explore the synergies between AI-based energy justice initiatives and inclusive welfare strategies to build more equitable and resilient societies.

Implications for Global Practice

Policymakers around the world are encouraged to establish actionable guidelines for the adoption of AI in energy policy design that prioritizes transparency, inclusivity, and equity. Ensuring that AI systems used in energy policy are transparent will increase public trust and accountability, while inclusive data practices will prevent the marginalization of underserved communities. Policymakers should establish regulatory frameworks that promote the ethical use of AI, ensure broad stakeholder engagement, and prevent discriminatory outcomes. It is essential to balance AI innovation with fundamental principles of fairness, ensuring that AI technologies advance energy justice goals across diverse socio-economic and cultural contexts. Practitioners, including energy experts, consultants, and technology developers, should be equipped with clear strategies for deploying AI tools that align with the principles of justice and equity. They must focus on ensuring that AI applications in energy policy address historical inequities and work towards reducing disparities in energy access. By integrating participatory approaches and engaging marginalized groups, practitioners can ensure that AI-driven solutions reflect the needs and perspectives of all communities. Additionally, practitioners should prioritize developing AI models that are interpretable, ensuring that energy policies are not just efficient but also fair and responsive to public concerns. Researchers have a critical role in identifying gaps in the field of AI-driven policymaking for energy justice. Future research should focus on real-world case studies that test the effectiveness of AI tools in addressing energy inequities, particularly in marginalized or underserved regions. Identifying potential risks associated with AI implementation and developing strategies to mitigate biases and ensure inclusivity will be crucial. Furthermore, research should investigate how AI can be utilized to facilitate long-term, sustainable policy changes that align with global goals, such as the Sustainable Development Goals (SDGs). By addressing these research gaps, scholars can help advance the role of AI in achieving equitable and just energy systems globally. In the context of global policymaking, AI applications in energy justice should be strategically aligned with national and local social welfare agendas. Policymakers are encouraged to integrate energy data with welfare indicators to design cross-sectoral interventions—such as energy subsidies tied to housing conditions or renewable infrastructure investments targeted at health-vulnerable populations. Practitioners should explore synergies between energy systems and social protection mechanisms, ensuring that AI tools address the complex realities of energy poverty as part of broader welfare challenges. For researchers, this calls for a deeper investigation into how AI-supported energy interventions can reinforce the effectiveness of welfare delivery systems, particularly in underserved regions. Embedding social welfare perspectives into AI-driven policy frameworks will not only improve inclusivity but also enhance the resilience of both energy and welfare infrastructures worldwide.

References

[1] K. Iwińska, A. Lis, and K. Mączka, "From framework to boundary object? Reviewing gaps and critical trends in global energy justice research," Energy Research & Social Science, vol. 79, p. 102191, Sep. 2021, doi: 10.1016/j.erss.2021.102191.

[2] M. Apergi et al., "An energy justice index for the energy transition in the global South," Renewable and Sustainable Energy Reviews, vol. 192, p. 114238, Mar. 2024, doi: 10.1016/j.rser.2023.114238.

[3] T. Ahmad et al., "Artificial intelligence in sustainable energy industry: Status Quo, challenges and opportunities," Journal of Cleaner Production, vol. 289, p. 125834, Mar. 2021, doi: 10.1016/j.jclepro.2021.125834.

[4] L. Tian, X. Li, C.-W. Lee, and C. Spulbăr, "Investigating the asymmetric impact of artificial intelligence on renewable energy under climate policy uncertainty," Energy Economics, vol. 137, p. 107809, Sep. 2024, doi: 10.1016/j.eneco.2024.107809.

[5] Commonwealth, "The Commonwealth Secretariat and Intel launches StrategusAI — an AI-driven policy toolkit for Commonwealth policymakers," Commonwealth. Accessed: Jan. 03, 2025. [Online]. Available: https://thecommonwealth.org/news/commonwealth-secretariat-and-intel-launches-strategusai-ai-driven-policy-toolkit-commonwealth

[6] X. Wen, Q. Shen, W. Zheng, and H. Zhang, "AI-Driven Solar Energy Generation and Smart Grid Integration A Holistic Approach to Enhancing Renewable Energy Efficiency," International Journal of Innovative Research in Engineering and Management, vol. 11, no. 4, Art. no. 4, Aug. 2024.

[7] M. A. Salamkar and J. Immaneni, "Data Governance: AI applications in ensuring compliance and data quality standards," Journal of AI-Assisted Scientific Discovery, vol. 4, no. 1, Art. no. 1, May 2024.

[8] X. Wen, Q. Shen, W. Zheng, and H. Zhang, "AI-Driven Solar Energy Generation and Smart Grid Integration A Holistic Approach to Enhancing Renewable Energy Efficiency," IJIREM, vol. 11, no. 4, pp. 55–66, Aug. 2024, doi: 10.55524/ijirem.2024.11.4.8.

[9] M. El Zein and G. Gebresenbet, "Digitalization in the Renewable Energy Sector," Energies, vol. 17, no. 9, p. 1985, Apr. 2024, doi: 10.3390/en17091985.

[10] R. E. Stevens, D. L. Loudon, H. Cole, and B. Wrenn, Concise Encyclopedia of Church and Religious Organization Marketing. Routledge, 2013.

[11] V. Clarke and V. Braun, "Thematic analysis," The Journal of Positive Psychology, vol. 12, no. 3, pp. 297–298, May 2017, doi: 10.1080/17439760.2016.1262613.

[12] M. A. R. Estrada, D. Park, and M. Staniewski, "Artificial Intelligence (AI) can change the way of doing policy modelling," Journal of Policy Modeling, vol. 45, no. 6, pp. 1099–1112, Nov. 2023, doi: 10.1016/j.jpolmod.2023.11.005.

[13] G. F. Gemechu, X. Rui, and H. Lu, "Wetland Change Mapping Using Machine Learning Algorithms, and Their Link with Climate Variation and Economic Growth: A Case Study of Guangling County, China," Sustainability, vol. 14, no. 1, Art. no. 1, Jan. 2022, doi: 10.3390/su14010439.

[14] P. Boza and T. Evgeniou, "Artificial intelligence to support the integration of variable renewable energy sources to the power system," Applied Energy, vol. 290, p. 116754, May 2021, doi: 10.1016/j.apenergy.2021.116754.

[15] IRENA, "Energy transition outlook." Accessed: Jan. 03, 2025. [Online]. Available: https://www.irena.org/Energy-Transition/Outlook

[16] IEA, "Net Zero by 2050 – Analysis," IEA. Accessed: Jan. 03, 2025. [Online]. Available: https://www.iea.org/reports/net-zero-by-2050

[17] M. George, K. O'Regan, and A. Holst, "Digital technologies can cut global emissions by 20%. Here's how," World Economic Forum. Accessed: Jan. 03, 2025. [Online]. Available: https://www.weforum.org/stories/2022/05/how-digital-solutions-can-reduce-global-emissions/

[18] H. R. O. Rocha, I. H. Honorato, R. Fiorotti, W. C. Celeste, L. J. Silvestre, and J. A. L. Silva, "An Artificial Intelligence based scheduling algorithm for demand-side energy management in Smart Homes," Applied Energy, vol. 282, p. 116145, Jan. 2021, doi: 10.1016/j.apenergy.2020.116145.

[19] K. You, Q. K. Qian, W. Cai, X. Wang, and H. Visscher, "Subsidy allocation for residential building energy retrofit: A perspective of families' incomes," Sustainable Cities and Society, vol. 104, p. 105317, May 2024, doi: 10.1016/j.scs.2024.105317.

[20] J. Mello, C. De Lorenzo, Fco. A. Campos, and J. Villar, "Pricing and Simulating Energy Transactions in Energy

Communities," Energies, vol. 16, no. 4, p. 1949, Feb. 2023, doi: 10.3390/en16041949.

[21] H. R. O. Rocha, I. H. Honorato, R. Fiorotti, W. C. Celeste, L. J. Silvestre, and J. A. L. Silva, "An Artificial Intelligence based scheduling algorithm for demand-side energy management in Smart Homes," Applied Energy, vol. 282, p. 116145, Jan. 2021, doi: 10.1016/j.apenergy.2020.116145.

[22] Z. Allal, H. N. Noura, O. Salman, and K. Chahine, "Machine learning solutions for renewable energy systems: Applications, challenges, limitations, and future directions," Journal of Environmental Management, vol. 354, p. 120392, Mar. 2024, doi: 10.1016/j.jenvman.2024.120392.

[23] P. Boza and T. Evgeniou, "Artificial intelligence to support the integration of variable renewable energy sources to the power system," Applied Energy, vol. 290, p. 116754, May 2021, doi: 10.1016/j.apenergy.2021.116754.

[24] T. Ding, H. Li, L. Liu, and K. Feng, "An inquiry into the nexus between artificial intelligence and energy poverty in the light of global evidence," Energy Economics, vol. 136, p. 107748, Aug. 2024, doi: 10.1016/j.eneco.2024.107748.

[25] Y. Wang et al., "The impact of energy poverty on the health and welfare of the middle-aged and older adults," Front. Public Health, vol. 12, p. 1404014, Aug. 2024, doi: 10.3389/fpubh.2024.1404014.

[26] C.-C. Lee and Z. Yuan, "Impact of energy poverty on public health: A non-linear study from an international perspective," World Development, vol. 174, p. 106444, Feb. 2024, doi: 10.1016/j.worlddev.2023.106444.

[27] E. İpek and Ö. İpek, "Energy poverty and health in Turkey: Evidence from Longitudinal data," Renewable and Sustainable Energy Reviews, vol. 203, p. 114777, Oct. 2024, doi: 10.1016/j.rser.2024.114777.

[28] Y. Fan, T. Döring, S. Li, X. Zhang, M. Fang, and Y. Yu, "Energy poverty and public health vulnerability: A multi-country analysis," Sustainable Development, vol. 32, no. 5, pp. 5161–5180, Oct. 2024, doi: 10.1002/sd.2965.

[29] U. Peters, "Algorithmic Political Bias in Artificial Intelligence Systems," Philos. Technol., vol. 35, no. 2, p. 25, Mar. 2022, doi: 10.1007/s13347-022-00512-8.

[30] Statista, "Trust and acceptance of AI worldwide 2022," Statista. Accessed: Jan. 03, 2025. [Online]. Available: https://www.statista.com/statistics/1369185/trust-and-acceptance-of-ai-worldwide/

[31] A. Willie, "AI and Social Justice: Addressing the Impact of AI on Marginalized Communities and Fostering Inclusivity", [Online]. Available: https://www.researchgate.net/profile/Alan-Willie/publication/387364148_AI_and_Social_Justice_Addressing_the_Impact_of_AI_on_Marginalized_Communities_and_Fostering_Inclusivity/links/676a6cd1e74ca64e1f26de40/AI-and-Social-Justice-Addressing-the-Impact-of-AI-on-Marginalized-Communities-and-Fostering-Inclusivity.pdf

[32] T. M. Croon, J. S. C. M. Hoekstra, and U. Dubois, "Energy poverty alleviation by social housing providers: A qualitative investigation of targeted interventions in France, England, and the Netherlands," Energy Policy, vol. 192, p. 114247, Sep. 2024, doi: 10.1016/j.enpol.2024.114247.

[33] B. Costa Ruiz, R. Lucas, and M. Ferrando Garcia, "Contributing to healthier populations by reducing energy poverty via innovative financial models," European Journal of Public Health, vol. 34, no. Supplement_3, p. ckae144.1371, Nov. 2024, doi: 10.1093/eurpub/ckae144.1371.

[34] P. Boostani, G. Pellegrini-Masini, and J. Klein, "The Role of Community Energy Schemes in Reducing Energy Poverty and Promoting Social Inclusion: A Systematic Literature Review," Energies, vol. 17, no. 13, p. 3232, Jul. 2024, doi: 10.3390/en17133232.

[35] D. Shin, "The effects of explainability and causability on perception, trust, and acceptance: Implications for explainable AI," International Journal of Human-Computer Studies, vol. 146, p. 102551, Feb. 2021, doi: 10.1016/j.ijhcs.2020.102551.

[36] M. Shahvaroughi Farahani and G. Ghasemi, "Artificial Intelligence and Inequality: Challenges and Opportunities," Qeios, Feb. 2024, doi: 10.32388/7HWUZ2.

[37] M. Lafi, B. Hawashin, and S. AlZu' bi, "Eliciting Requirements from Stakeholders' Responses Using Natural Language Processing," Computer Modeling in Engineering & Sciences, vol. 127, no. 1, pp. 99–116, Apr. 2021, doi: 10.32604/cmes.2021.013026.

[38] D. Jayasutha, R. V. Prabhu, S. M. Sassirekha, K. Maithili, P. Girija, and R. S. Subramanian, "Exploring the Intersection of Sustainable Energy, AI, and Ethical Considerations," in AI Applications for Clean Energy and Sustainability, IGI Global Scientific Publishing, 2024, pp. 139–160. doi: 10.4018/979-8-3693-6567-0.ch008.

[39] M. Noorman, B. Espinosa Apráez, and S. Lavrijssen, "AI and Energy Justice," Energies, vol. 16, no. 5, p. 2110, Feb. 2023, doi: 10.3390/en16052110.

[40] E. Kalfountzou, C. Tourkolias, S. Mirasgedis, and D. Damigos, "Identifying Energy-Poor Households with Publicly Available Information: Promising Practices and Lessons Learned from the Athens Urban Area, Greece," Energies, vol. 17, no. 4, p. 919, Feb. 2024, doi: 10.3390/en17040919.

[41] Z. Allal, H. N. Noura, O. Salman, and K. Chahine, "Machine learning solutions for renewable energy systems: Applications, challenges, limitations, and future directions," Journal of Environmental Management, vol. 354, p. 120392, Mar. 2024, doi: 10.1016/j.jenvman.2024.120392.

[42] R. Urbanowicz, R. Zhang, Y. Cui, and P. Suri, "Streamline: A Simple, Transparent, End-To-End Automated Machine Learning Pipeline Facilitating Data Analysis and Algorithm Comparison," in Genetic Programming Theory and Practice XIX, L. Trujillo, S. M. Winkler, S. Silva, and W. Banzhaf, Eds., Singapore: Springer Nature, 2023, pp. 201–231. doi: 10.1007/978-981-19-8460-0_9.

[43] R. Gruetzemacher and J. Whittlestone, "The transformative potential of artificial intelligence," Futures, vol. 135, p. 102884, Jan. 2022, doi: 10.1016/j.futures.2021.102884.

[44] D. W. Joyce, A. Kormilitzin, K. A. Smith, and A. Cipriani, "Explainable artificial intelligence for mental health through transparency and interpretability for understandability," npj Digit. Med., vol. 6, no. 1, pp. 1–7, Jan. 2023, doi: 10.1038/s41746-023-00751-9.

[45] J. L. Mathieu, "Algorithms for Energy Justice," in Women in Power: Research and Development Advances in Electric Power Systems, J. S. Tietjen, M. D. Ilic, L. Bertling Tjernberg, and N. N. Schulz, Eds., Cham: Springer International Publishing, 2023, pp. 67–83. doi: 10.1007/978-3-031-29724-3_4.

[46] A. Entezari, A. Aslani, R. Zahedi, and Y. Noorollahi, "Artificial intelligence and machine learning in energy systems: A bibliographic perspective," Energy Strategy Reviews, vol. 45, p. 101017, Jan. 2023, doi: 10.1016/j.esr.2022.101017.