THE PROSPECTIVE OF ARTIFICIAL INTELLIGENCE FOR NET ZERO SUSTAINABILITY: A COMPREHENSIVE REVIEW OF CURRENT EVIDENCE AND FUTURE PROSPECTS

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ABSTRACT

The worldwide limitation to achieve net-zero levels of greenhouse gas emissions by mid-century requires a radical increase in the pace of decarbonization of all sectors of the economy. Machine learning, deep learning, and advanced data analytics, also known as Artificial Intelligence (AI) are becoming an enabling technology that is central and cross-cutting in this transition. The current evidence and future of AI use in achieving net-zero sustainability is comprehensively evaluated in the paper to understand the perspectives on the matter. We summarize and discuss an expanding body of literature and practical case studies of optimisation of energy systems (including grid management and integration into renewable systems), increased industrial efficiency, smart and low-carbon mobility, and transformative climate sciences, carbon capture, and monitoring. The aggregate evidence suggests that AI can greatly decrease emissions, decrease expenditures and speed up innovation in the following important areas. Nevertheless, AI integration is not totally free of serious challenges, such as its own carbon footprint, data accessibility and quality, algorithmic bias, and the necessity to tackle them with a powerful governance and policy system. We conclude that, although AI is not a panacea, it is necessary to implement it strategically and responsibly because it is becoming an indispensable element of timely and efficient and equitable transition to a net-zero future. In order to achieve its potential, it will imply certain research and development priority, better data infrastructure, and cross-disciplinary collaboration between policymakers, industry leaders, and the AI research community to ensure that these powerful tools will be aligned to the greater goal of climate stability at the global level.

INTRODUCTION

The Intergovernmental Panel on Climate Change (IPCC) has been right in its expression of scientific orthodoxy; to ensure that global warming does not exceed 1.5degC above the pre- industrial era, the globe must become net-zero on carbon dioxide (CO2) emissions by around 2050 [1]. This mammoth project demands a systemic restructuring of our energy system, transport system, industrial system, and agriculture, never done before and in such a brief period. Despite the very simple technologies of this transition, which are solar photovoltaics, wind turbines, and batteries are under development, the sheer complexity, scale, and interdependence of the problem brings out a requirement to have more complex instruments to streamline, regulate, to accelerate the process.

Brand into Artificial Intelligence (AI). Artificial intelligence (AI), a broad field of computer science, which entails the creation of intelligent computers that may perform tasks which would have required human cognition, has demonstrated some remarkable abilities insofar as pattern recognition, predictive analytics, optimization of multifaceted systems and autonomous decision-making systems are concerned. The most important sub-field in this regard would be the Machine Learning (ML) that allows systems to learn and improve, and this is not designed to address all the possible situations.

OBJECTIVE

The present paper will contend that AI is a high-priority, cross-cutting facilitator to the achievement of net-zero ambitions, providing a significant tool of efficiency, faster innovation, and handling complexity. The main aim of this review is to generalize the existing evidence of AI implementation into the main industries, predict its future, and new applications, and present a critical analysis of challenges and threats related to it. This paper will enlighten stakeholders in the policymaking process, the industry and scholars on the strategic role of AI in combating the climate and the conditions required to ensure its responsible use. This paper is structured in the following way: Section 2 presents the existing evidence concerning the use of AI in energy, industry, transport, and carbon management. Part 3 is an exploration of future opportunities and new horizons. In section 4, the challenges are critically analyzed such as the footprint of AI itself, as well as the ethical issues.

Lastly, a conclusion and important policy implications are given in Section 5.

METHODOLOGY

Current Evidence: AI in Action for Net Zero

The practical usefulness of AI is being confirmed through more and more real world applications in high-impact domains. The sections below outline the situation of evidence.

Grids and the Management of Energy.

The shift to non-centralized, non-dispatchable, and weather-dependent renewable energy (solar power, wind power) makes the management of electrical grids immensely complex. AI is emerging as one of the most important tools to maintain stability, reliability of the grid and efficiency.

Renewable Energy Forecasting: Renewable intermittency is a significant problem to grid operators that have to balance emerging demand and supply on a real-time basis. The AI models, in particular, deep learning networks, deploy historic weather data, satellite data, and real-time weather prediction to predict solar irradiance and wind energy generation with great accuracy. The most notable of the listed is the DeepMind project of Google that developed an ML model that can estimate the output of a wind farm power 36 hours in advance. This will allow the grid operators to plan energy with less effort and more confidence, reducing the reliance on fossil fuel to supply backup energy. Google argued that such a step raised the value of their wind power by about 20 percent [2].

Smart Grid and Demand-Side Management: The conventional grid is changing to a two- way smart grid. This transformation is centered on AI. The AI algorithms will be able to use smart meter data and IoT data to implement dynamic pricing and demand-response initiatives by analyzing real-time data. As an example, when renewable production is higher and demand is lower, AI can instruct smart appliances (e.g., water heaters, electric vehicle chargers) to use energy, which will absorb surplus clean energy. On the other hand it can encourage low consumption when there is a peak demand. This flattens the demand curve, increases the resilience of the grid and postpones the expensive upgrades of grid infrastructure.

Grid Maintenance and Operations: Predictive maintenance is an AI-based tool that anticipates grid failures in transformers, transmission lines, etc., before they happen taking the sensor data. This will avoid expensive blackouts and enhance safety. In addition, the lines are also controlled by AI optimization algorithms in voltage control and topology optimization to reduce line losses and enhance the overall efficiency of electricity transmission and distribution systems.

Industrial Decarbonization

Industrial sector contributes to the world emissions about a quarter of all the emissions and is regarded as being incredibly hard to decarbonize with the heat demands and the complicated chemical reactions.

- **Process Optimization:** Cement, steel, and chemicals are the energy-intensive industries that apply AI to optimize their production processes. Firms such as Siemens and Bosch have AI applications that adjust the variables of temperature, pressure, and flow rates in real-time. Through constant learning based on the operational data, these systems will be able to determine the best setpoints that will produce the same or even better output using much less energy consumption and reduced greenhouse gas emissions. Using AI to optimise the kiln in a cement plant, as an example, can save the plant 2-5 in fuel consumption, which at scale can equate to significant cost and emission savings.
- **Predictive and Prescriptive Maintenance:** Off of the grid, equipment failure in the industrial domain is predicted by AI-based sensors and analytics. Understanding the anomaly in vibration, temperature, and acoustic data, AI shall be able to strategize the maintenance exactly in time before the sudden unforeseen downtime shall come by and ensure that the specified motors, pumps, and compressors are operating to the full capacity. This will end up destroying the energy wastage and the emissions produced and bring about more productivity.
- **Supply Chain and Logistics Optimization:** AI will be able to optimize complex industrial supply chains, such as the sourcing of raw materials to the final product delivery. This will entail selecting the most effective transportation channels,

minimum inventory to reduce wastes and selecting suppliers with reduced carbon footprint to reduce total emissions of the industrial activities in Scope 3.

Transportation and Mobility.

The transport sector in the world is one of the major contributors to the emission. One of the pillar technologies is AI, which makes its processes electrified, automated, and optimized.

- EV Integration: EV Mass adoption of EVs is a two-sided issue: there is a need to consider the impacts of EVs on the electricity grid and maximize the degree to which they can be helpful to the environment. AI is used to coordinate intelligent charging systems, scheduling charging events to avoid grid overload and to be in sync with periods of high renewable energy generation (i.e. midday with solar). Besides, EVs have their battery management optimized by the use of AI software to extend the battery life and performance, which is another important consideration of the total vehicle lifecycle emissions.
- **Smart Traffic Control:** Traffic congestion is one of the issues that contribute to huge emissions of cars stalling in traffic. Traffic signals control systems based on AI have been implemented in such cities as Pittsburgh and Beijing (e.g., Surtrac). These systems utilize real-time camera and radar information and are dynamically adjusted to change the timing of traffic lights, minimize idling, stop and go traffic and travel time. The independent research of these systems has revealed 25% to 21% reduction in travel duration and 25% to 21% decrease in vehicle emissions [3].
- **Logistics and Fleet Management:** The shipping industry (Maersk), the road delivery industry (UPS and Amazon) involve utilizing AI through complex route and network optimization. The AI algorithms take into account the traffic, weather, topography, and delivery window to decide on the most fuel-efficient routes to be used by their fleets. They also maximize containerization and reduce the amount of empty miles (moving vehicles without a load), which saves a lot of fuel and contributes to a significant decrease in emissions.

Carbon Capture, Utilization, and Storage (CCUS) and Climate Science

CCUS is viewed as an essential technology in hard-to-abate industries, such as heavy industry and aviation. Nonetheless, it is now power-consuming and costly. Artificial intelligence is contributing to the elimination of these challenges.

- **Sorbent Material Discovery:** The most important part of many CCUS technologies is the sorbent material that captures CO 2. It is a lengthy and expensive process to come across new materials, more efficient and less energy-intensive. This is being drastically accelerated by AI and especially by generative models and reinforcement learning. Scientists at colleges such as MIT and Carnegie Mellon have utilized AI to filter through millions of possible metal-organic structures (MOFs) and other nanoporous substances in a few days, which would have required centuries by employing conventional experimental techniques [4]. This AI-in-science is finding very promising sources of capturing CO2 in the air or the industrial flue gases.

- **Climate Modeling and Monitoring:** The dynamic nature of climatic conditions in the earth can only be predicted and understood to mitigate and adjust. AI is increasing the quality of the high-resolution climatic models making them more precise and quicker. In addition, AI applications process satellite data (e.g. ESA Sentinel missions, NASA OCO-2) to measure greenhouse gas emissions, identify methane escapes of oil and gas infrastructure, and trace deforestation with an unprecedented high level of accuracy. This facilitates improved responsibility and specific corrective measures.

Future Prospects and Emerging Applications

There is more potential of AI applications in the future. There are a number of new frontiers that are likely to open up new disruptive ways of reaching net zero.

- **Independent Technology to Climate:** The idea of the self-driving laboratories is emerging. They are AI-controlled robotic platforms that are capable of formulating, designing, and executing experiments on their own and interpreting the findings to guide the following process. The cycle will bring the basic technology innovations such as next-generation perovskite solar cells or other advanced geothermal systems to orders of magnitude faster, as well as new battery electrolytes or green hydrogen catalysts.
- **System-Level Integration and Energy System Planning:** The future net-zero energy system will be a very complex network of electricity, hydrogen, synthetic fuels, and heat. AI will play a key role in managing this complicated system in real-time where it will choose the most cost effective and low-carbon streams of energy conversion, storage, and transfer. Moreover, at a strategic planning level, AI models can enable a policymaker and an investor to simulate thousands of scenarios to find the best paths of investing in the energy infrastructure in the face of deep uncertainty.
- **Precision Agriculture and Land Use Management**: Agriculture, forestry, and other land use are also major contributors to emissions (e.g. m methane form livestock, nitrous oxide form fertilizers, CO2 form deforestation). Precision agriculture is possible with the help of AI, satellite imagery, drones, and IoT sensors. This enables the use of water, fertilizers, and pesticides which are highly calized and this significantly reduces the amount of input used and the emissions created. The optimization of the reforestation projects can also be done through AI, which will help to find the best planting sites and the type of plants that will capture carbon the most.
- **Circular Economy and Waste**

Management: AI can be used to optimize the flow of waste to the recycling plant by improving waste sorting using computer vision, to discover the best way of disassembling products and remaking them, and anticipate the quality of materials to recycle. This conserves on the production of virgin materials which is energy intensive.

- **More Flexible Climate Risk Assessment:** In the case of adaptation finance, and resilience planning, AI can be applied to create hyper-localized climate risk models to assess the physical risk of climate change (flooding, wildfires, droughts) to particular assets, supply chains, and communities and make more targeted and effective investments in adaptation.

Challenges and Risks

Challenges

The use of AI to the net-zero journey is not a panacea. There are a number of major challenges and risks that should be proactively handled so that benefits of the same can be achieved in a fair and sustainable manner.

- **Auto Carbon Footprint of AI:** It is a big number of computational resources to run and train large AI models. It was estimated that training a single large natural language processing model such as GPT-3 to use hundreds of megawatt-hours of electricity which could produce hundreds of tons of CO2 equivalent depending on the source of the data center data [5]. This poses a possible paradox in the fight against climate change in which AI may be used to fight climate change. This needs mitigation on a multi-pronged basis; by designing AI algorithms that are more computationally efficient (e.g., TinyML), hardware that is specialized and energy-efficient, and data centers powered by 100 percent renewable energy. The idea of green AI is becoming quite popular, with the focus on creating the models that are highly-performing with reduced computational overhead. [6]
- **Data Quality and Availability:** accessibility and quality of data are the main precondition of the successful work of AI. In most of the industries that are very essential in terms of net-zero transition like heavy industry, built environment, and supply chains, data is typically isolated, confidential, inconsistent, or even non-existent. The absence of standardized forms and the fear of commercial privacy also contribute to the inability to build the large and high-quality datasets required to use to train an effective AI model. It is necessary to initiate the development of open-data systems of non-sensitive climate- related information.
- **Algorithms Bias and Equity Concerns:** AI algorithms have the potential to reproduce and increase the existing biases in the society when they are trained on faulty or unrepresentative information. This may cause unfair results in a climatic context. To take a specific example, an AI model to optimize EV charging infrastructure may give priority to the affluent neighborhoods that have a large number of cars, which will

increase transport inequalities. Equally, climate risk models may fail to recognize vulnerable communities in the underserved population because of insufficient information. Fairness, transparency, and equity in climate AI applications is an essential ethical concern demanding a variety of data and multidisciplinary teams.

Risks

Governance, Trust, and Explainability: It is a barrier to adoption because the logic behind a decision is not as easy to understand with certain complex AI models, sometimes known as the black box. Operators find it difficult to lose control to an inexplicable system. Training the explainable AI (XAI) methods and ensuring proper accountability and regulatory frameworks of the AI-assisted or autonomous decisions is an essential step to gaining trust and its safe operation.

Cost and the Digital Divide: The first investment, AI infrastructure and software, and special talent may be prohibitive, especially on small and medium-sized enterprises (SMEs) and in developing countries. This may lead to the development of a so-called digital divide in climate action in which the richest entities will be able to purchase the AI tools that reduce the price and increase the speed of decarbonization. These transformative technologies should be provided to the world through international cooperation and capacity-building programs.

POLICY IMPLICATIONS

The overall evidence that has been combined in this review is a strong argument: Artificial Intelligence has the potential to be transformative in the world making a faster switch towards a net-zero economy. It is a strong lever, both in maximizing the effectiveness of already existing systems and infrastructures, and in finding and implementing breakthrough clean technologies by leaps and bounds. The existing uses in energy, industry and transport are already providing quantifiable results in terms of emission cuts and cost savings and the future perspectives in climate science and material discovery are expected to establish new frontiers in combating climate change.

It is, however, most important to note that AI is not a solution, but a tool. Its effect is determined by the motive of its human makers and paradigms in which it is implemented. The problems are not easy- the AI computational foot print, data gaps, risks of bias, and governance gaps have to be treated in a serious and immediate manner. [7]

CONCLUSION

To effectively and ethically tap the potential of AI in a net-zero future, the multi-stakeholder effort must be coordinated. Our recommendations of policies and action plans are as follows:

- **Focused R&D and Public Investment:** Governments, collaborating with the non- government sector, must massively augment the financing of R&D of the "Climate AI. This involves studies on energy efficient AI (Green AI), solutions to sectors difficult to abate, and open source tools and benchmarking to the community.
- **Develop Data Ecosystems:** The

creation of secure and standardized platforms to share climate-relevant information (anonymized energy data, material properties, satellite data) should be incentivized or compelled by policymakers. This will create innovation and the equalizing of the playing field to smaller players.

- **Establish Standards, Rules and Ethics:** The international regulatory bodies and those in the country should establish standards to gauge and report the environmental impact of AI systems. Moreover, ethical, fair, and transparent recommendations regarding the utilization of AI in climate-critical applications are to be set to develop the trust of the population and avoid any harm.
- **Build Capacity and Bridge Digital divide:** Invest to create education and training programs to create a workforce with skills in the sustainability and AI disciplines. The international support and knowledge-sharing initiatives should be strengthened such that the developing nations would be able to use AI to their benefit to pursue climate- resilience and clean developmental paths.
- **Encourage Cross-Sectoral Cooperation:** Organize forums and innovation competitions that include AI specialists, climate scientists, engineers, industry leaders, policymakers and civil society. To deal with the climate crisis, it is necessary to disintegrate the classic silos. [8]

To sum up, the way towards having a net zero is not easy, but the supporting, accountable, and fair process of integrating Artificial Intelligence offers a vital and possibly essential tool to have this change more streamlined, more affordable, and quicker. It is within our capability to manage the most potent general-purpose technology of our generation to support the most urgent mission of our time: to ensure the future generations live in a sustainable and habitable planet.

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