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AI-Driven Solutions for a Low-Carbon Transition: Evaluating Effectiveness and Limitations in Climate Change Mitigation

Xinyi Huang[1]

[1] Shenzhen College of International Education, China

Correspondence: Xinyi Huang, Shenzhen College of International Education, Shenzhen 518000, China. Tel: 0086-134-2399-5405. E-mail: s21448.huang@stu.scie.com.cn

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Abstract

Climate change, primarily caused by human activities, poses a significant global challenge. Countries worldwide are integrating efforts to combat climate change through initiatives such as the Paris Agreement and setting targets to reach net-zero emissions by 2050. This paper explores the potential of artificial intelligence (AI) as a promising solution to address climate change, particularly through the analysis of mass data. AI can aid in environmental decision-making processes, optimize renewable energy use, and accelerate the global transition to a low-carbon economy. Using public data from the OECD, the study investigates the effectiveness of AI in promoting a low-carbon economy by examining its impact on greenhouse gas emissions, carbon footprint, investment in research and development, renewable energy production, and recycling rates. The findings suggest that AI has been considerably effective in supporting the growth of renewable energy and recycling while restraining gas emissions and carbon footprint. However, the study also identifies potential limitations, such as the carbon release from AI itself, and suggests further improvements to AI models.

Keywords: low-carbon economy, artificial intelligence, climate change, carbon neutrality, greenhouse effect, renewable energy

1. Introduction

1.1 Introduction of Climate Change

Climate change, identified as the shifts in temperatures and weather patterns by the United Nations (United Nations, n.d.), is a severe challenge faced by the globe, mainly under human activities. This intensity has been officially recognized in the Paris Agreement, a legally binding international treaty enforced on Nov. 4th, 2016 (UNFCCC, n.d.). Countries integrate transparently to control the temperature rise under 2˚C, or even to 1.5˚C. In addition to controlling temperature levels, more and more countries, such as the UK, France, and New Zealand, are committed to reaching net zero emissions by 2050 to prevent the intimidating trend of climate change. Climate change results mainly from human activities, including manufacturing and food production, deforestation, transportation, powering buildings, as well as excessive consumption. These events all give rise to the greenhouse effect, defined as the process by which heat is trapped near the Earth's surface by substances known as "greenhouse gases" (NASA, 2024). The greenhouse gases consist of mainly carbon dioxide (CO2), methane (CH4), and nitrous oxide (N2O), and the whole process of trapping heat causes the planet's average temperature to rise, contributing to the phenomenon of global warming, which later develops as climate change.

1.2 Recognition to Climate Change

While recognizing the threats of climate change towards living organisms and ecosystems including the greenhouse effects and rising sea levels, the United States has set Climate Action as one of the crucial global objectives in the list of 17 sustainable development goals. It is set to motivate countries to contribute to combating climate change through the targets of "strengthening resilience and adaptive capacity to climate-related hazards and natural disasters in all countries" as well as "integrating climate change measures into national policies, strategies, and planning" from the aspects of technological advancements and integration.

1.3 Past Exploration of AI in Tackling Climate Change

When we come to the solutions to climate change, the common answers will be developing renewable energy, reducing unrenewable energy use, including fossil fuels, encouraging vegetarian diets, restoring forests, and reducing plastic bag use. They will all contribute to the control of climate change but may appear with limited use.

While thinking of the new paths of utilizing artificial intelligence (AI), due to the bombarding emergences of Chatbots and virtual assistants, we think of the idea of combining AI with the low-carbon economy more closely and present AI as a promising source to address climate change in this paper, especially through the category of mass data. As suggested by the World Economic Forum, AI aids people's efficiency and accuracy in environmental decision-making processes through the analysis of mass data on areas such as iceberg mapping, deforestation mapping, weather and climate prediction, waste recycling, ocean cleaning, and carbon-emission tracking (World Economic Forum, 2024). At the same time, AI assists in optimizing renewable energy use with advanced cost-effectiveness. Taking solar energy as an example, AI has improved accuracy in solar forecasting by 30%, contributing to cost cuts of generators, on electricity generation (Mortier, 2020).

1.4 Research Hypothesis and Design

In this research, we generally assume that integrating AI into environmental circumstances could accelerate the global transition to a low-carbon economy. The assumption will be tested in our paper to discover whether the present policies and strategies used in different countries have resulted in a positive trend growing toward a low-carbon economy. Following this concept, we will focus on the discussion of AI's technological enhancement in the development of a low-carbon economy, referencing the use of polluting data, including greenhouse gas emissions and carbon footprint, as well as the use of development data, including investment in research and development, renewable energy production, and recycling rate. Through building up a more comprehensive image of the effectiveness of AI in recent years in environmental and energy fields. Throughout the study, based on the public data in OECD, we have discovered that AI is considerably effective, in promoting a low-carbon economy, supporting the growth in renewable energy and recycling rate while restraining the gas emissions and carbon footprint. Nevertheless, we have also found the potential limitations brought by AI, focusing on the carbon release from AI itself, and suggesting further improvements on AI models.

2. Method

Our paper focuses on the study of the extent of effectiveness of AI investment to alleviate greenhouse gas emissions as well as improve renewable energy use.

2.1 Sampling Procedures

In the paper, our research focuses on 34 countries, mainly chosen from European countries, which presents a global scale of AI and energy expenditure. Our sample chose the time interval between 2010 and 2021 to present the change of chosen indicators before and after the Paris Agreement. The whole database is sourced from the OECD (The Organization for Economic Co-operation and Development) Data Explorer.

2.2 Measures and Covariates

There are two dependent variables: greenhouse gas emissions per capita and carbon footprint. Greenhouse gas emissions per capita is an indicator that represents carbon dioxide measured in tons per person (Our World in Data, 2023). Carbon footprint is a measure of the exclusive total amount of carbon dioxide emissions that are directly and indirectly caused by an activity or are accumulated over the life stages of a product (Pertsova, 2007), measured in tons of carbon dioxide per person.

There are three independent variables: investment in R&D, renewable energy, and the recycling rate. Investment in R&D is an expense included in the calculation of net costs to support create creative and systematic work undertaken to increase the stock of knowledge and to use such knowledge and practical experience for devising new or improved products and processes, with the expectation of maintaining or increasing national economic productive capacity or yielding other future benefits (NCSES, 2018), measured in percentage of GDP. Renewable energy is energy derived from natural resources that are replenished at a higher rate than they are consumed (United Nations, n.d.-b), measured in percentage of total energy supply. The recycling rate is the percentage of recyclable materials recycled from waste (Sesotec, 2021), measured in the percentage of treated waste.

2.3 Research Design

By taking the average of the 34 countries for each indicator, we could figure out the average environmental and technical data for each year. Data is presented in tables and line graphs to demonstrate the trend and the change of different indicators when approaching a low-carbon economy and the integration of AI in the global economy. We suppose that AI and technology could bring positive impacts to the low-carbon economy, suggesting a positive relationship in this study.

Table 1. Variable Definitions

Variable name	Definition
Greenhouse gas emissions per capita	An indicator that represents carbon dioxide measured in tons per person.
Carbon footprint	A measure of the exclusive total amount of carbon dioxide emissions that are directly and indirectly caused by an activity or are accumulated over the life stages of a product, measured in tons of carbon dioxide per person.
Investment in R&D	An expense included in the calculation of net costs to support create creative and systematic work undertaken to increase the stock of knowledge and to use such knowledge and practical experience for devising new or improved products and processes, with the expectation of maintaining or increasing national economic productive capacity or yielding other future benefits, measured in percentage of GDP.
Renewable energy	Energy derived from natural resources that are replenished at a higher rate than they are consumed, measured in percentage of total energy supply.
The recycling rate	The percentage of recyclable materials actually recycled from waste, measured in percentage of treated waste.

3. Results

3.1 Statistics and Data Analysis

The set of data, collected from the database in OECD, provides 5 graphs from the five indicators, specifically demonstrated below. It can be analyzed respectively and combined to provide prospective results for the present technological and environmental conditions during the time period of 2010–2021. Generally, from our investigation, we find that research and development have a negative impact on the reduction of gas emissions and carbon footprint. Also, it has a positive impact on renewable energy supply and recycling rate. Apart from the favorable data movements above, there is a counterchange in low carbon economic development, with an unexpected increase in carbon footprint since 2015. In addition to the conclusions above, there are some diverse changes inside these graphs, which are related to each other.

3.2 Adverse Events

As shown in Figure 1, from 2014 to 2018, the average greenhouse gas emissions nearly plateaued, with merely 0.25 tons of decrease in carbon dioxide from 10.37 to 10.15 tons per capita (UNFCCC, 2023). Also, in Figure 3, the average renewable energy in percentage has a limited increase during this period, showing a small rise of 0.84% from 18.47% to 19.31% (OECD, 2016). At the same time, the average carbon footprint has changed during this period. In Figure 2, before 2015, it was consistently decreasing; after reaching the bottom point of 9.28 tons per person, the average carbon footprint started to increase at a lower rate, from 9.28 tons to 9.52 tons per person during 2015-2018 (OECD, 2021). Moreover, the recycling rate, in Figure 4, encountered a change in 2016, changing from the previous approximate rise of 1.09% per year, during 2013-2015, to a much lower annual growth of 0.42%, during 2016-2018 (OECD, 2020). The data reveals the unexpected, buffered trend in environmental improvements under technological developments.

These conditions can be reasonably explained by the lack of sufficient investment in research and development, shown with an inverted U-shape curve in Graph 5, as the average investment in the percentage of GDP first increased from 1.89% to 2.36%, during 2014-2016, but then decreased from 2.36% to 2.15%, during 2016-2018 (OECD, 2020). It acts as a disruption to the continuous smooth trend in gas emissions and inexhaustible energy provision. This can further help to explain the reality of AI causing the reverse impacts on low-carbon economic development, acting as a potential limitation for the utility of AI in the low-carbon economy.

In addition to the inconsistency in the growing trend mentioned above, another unusual pattern observed inside the diagram pinpoints average renewable supply during 2020-2021, undergoing a decrease in percentage from 22.20% to 22.21% (OECD, 2016). The main reason that could explain this reduction is the COVID-19 pandemic. Covid-19 breaks out in 2020. On 5th April 2020, the pandemic was recorded to result in a global lockdown of over 4.2 billion people, causing a massive vacancy in production (IEA, 2020). Apparently, renewable energy production was also affected, due to lower demand for renewable energy consumption, including bioenergy, resulting from lower energy demand in transportation and industrial production (IEA, 2020). At the same time, in addition to demand factors, there are also supply chain disturbances, including delayed energy projects as well as strict hygiene control protocols following COVID-19 controls: For instance, Greece had a 6-month extension for projects due to the online requirements released in mid-2020; Austria had an extension of wind farms construction period by 6 months (IEA, 2020). These factors all contribute to the slower energy construction process.

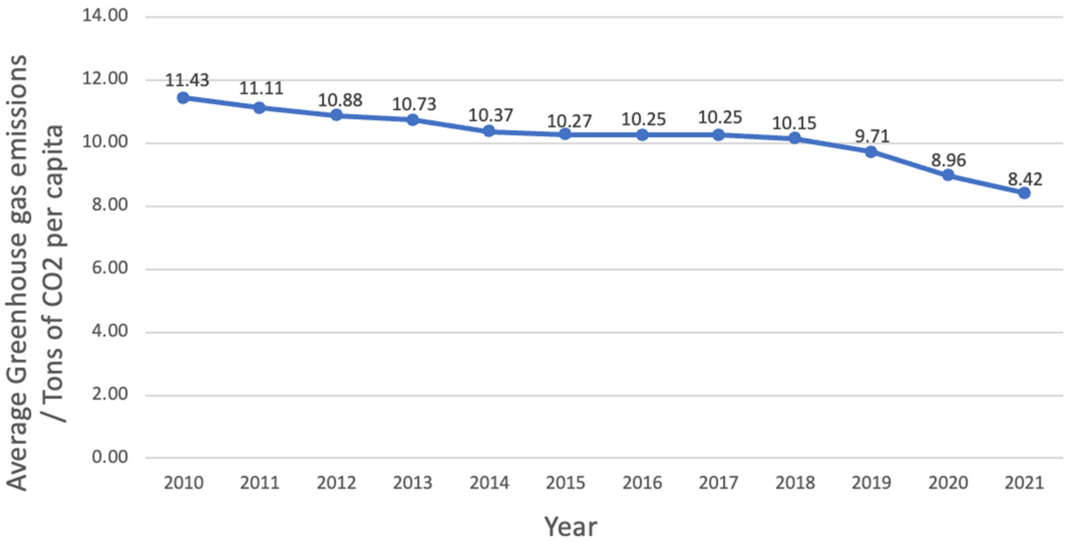

Figure 1. (United Nations, n.d.-b). Annual Average Greenhouse Gas Emissions from: UNFCCC. *National Inventory Submissions 2023*. *UNFCCC*, 2023. The diagram presents the change in average greenhouse gas emissions among the 34 countries in 12 years. The greenhouse gas emissions follow a downward sloping trend from 11.43 tons of carbon dioxide per capita to 8.42 tons of carbon dioxide per capita, declining by a figure of 3.01 tons.

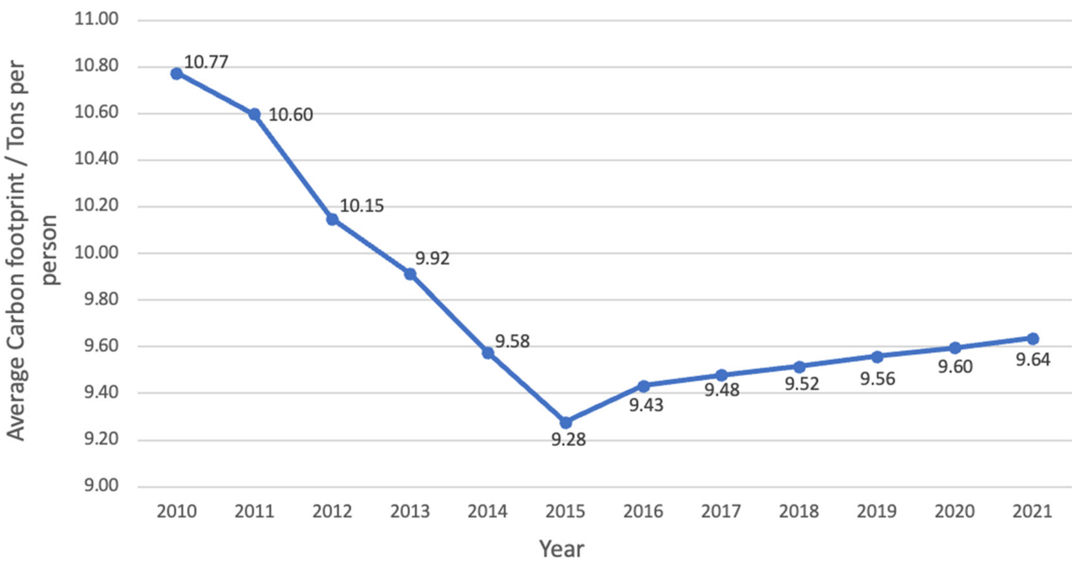

Figure 2. Annual Average Carbon Footprint from: OECD. *Trade in Embodied CO2 Database (TECO2)*. The average carbon footprint per person among the 34 countries follows a downward slopping trend from 10.77 tons per person to 9.64 tons per person, declining by a figure of 1.13 tons. However, the average carbon footprint reached the lowest at 9.28 tons per person in 2015, but in the following years the figure rebounds, increasing by a small amount of 0.36 tons per person.

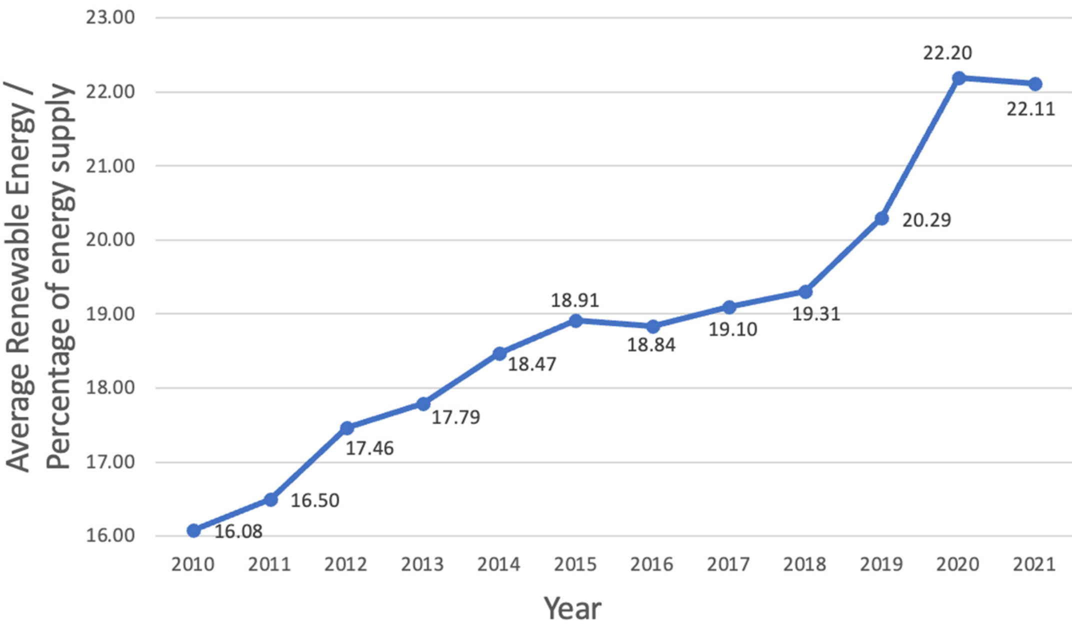

Figure 3. Annual Average Renewable Energy from: OECD. *World energy statistics*. Organisation for *Economic Co-operation and Development,* 2016. Average renewable energy as a percentage among the 34 countries follows an overall upward-slopping trend from 16.08% to 22.11%, increasing by 6.03%. However, there is an exception in that, from 2020 to 2021, the use of average renewable energy decreased by 0.09%, which is low to notice but may be affected by the appearance of COVID-19 on the development of renewable energy productions

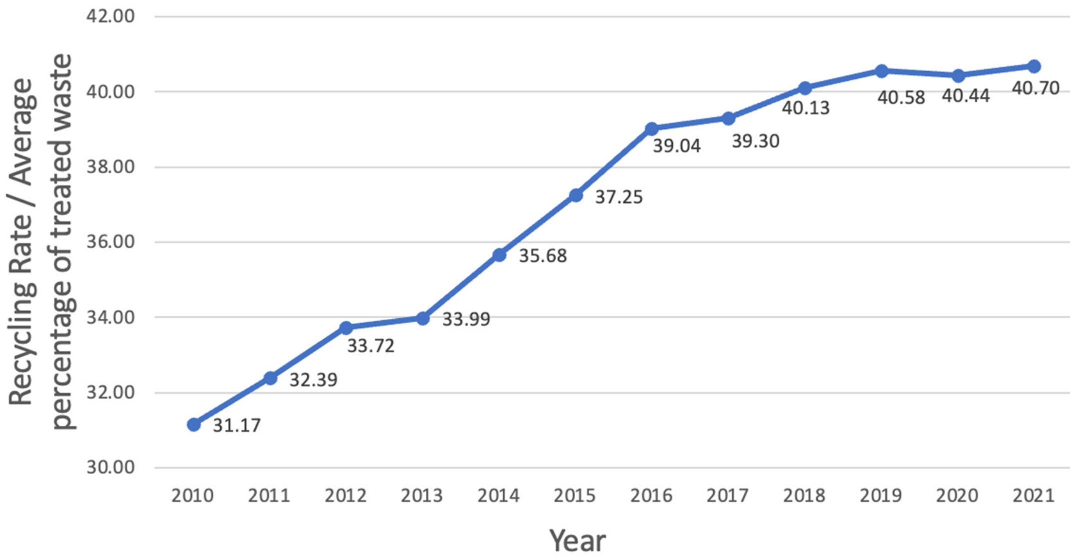

Figure 4. Annual Recycling Rate from: OECD. *How's Life? 2020: Measuring Well-being*. Organisation for *Economic Co-operation and Development*, 2020. The recycling rate as a percentage among the 34 countries follows an upward slopping trend from 31.17% to 40.70%, increasing by a percentage of 9.53%. But the exception of the falling recycling rate in 2020 may be caused by the pandemic, as people around the world were staying at home, resulting in potentially lower efficiency and productivity in treating waste

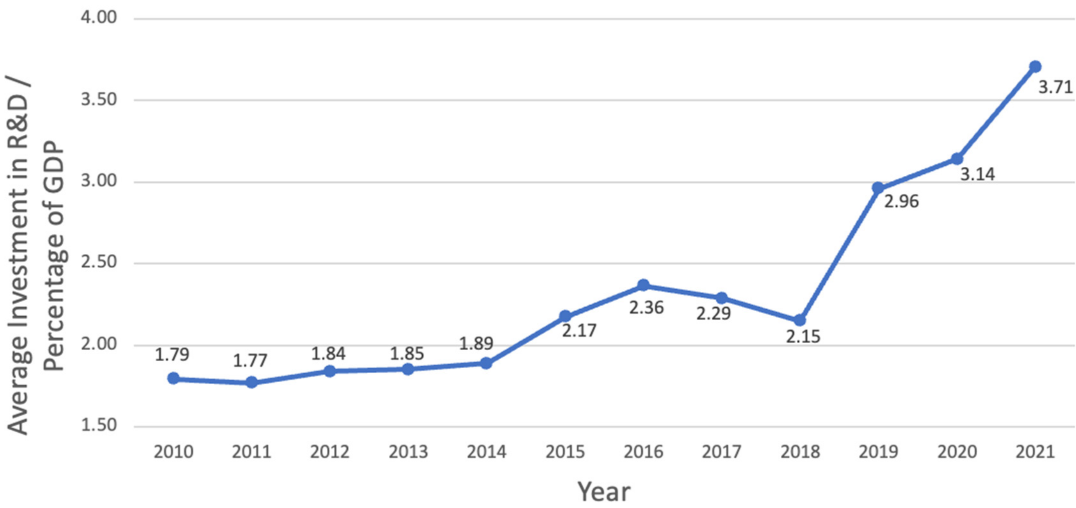

Figure 5. Annual Average Investment in R&D from: OECD. *How's Life? 2020: Measuring Well-being*. Organisation for *Economic Co-operation and Development*, 2020. From 2010 to 2021, the average investment in R&D as a percentage of GDP among the 34 countries follows a general upward-slopping trend from 1.79% to 3.71%, increasing by 2.01%. But between 2016 and 2018, the percentage of investment decreases from 2.36% to 2.15%, by 0.21%.

4. Discussion

A better low-carbon economy is developed under the trend of lower gas emissions and carbon footprint. AI, through research and development, has stood out as an important sector in this form of economic development. Several real adaptations have assisted the gas release, ranging from individuals, and firms, to governments. From a personal perspective, AI can power up personalized carbon footprint Trackers in apps or websites (Imolore, 2023). These trackers can track emissions for different individual activities, including transportation and food consumption, and serve as a nudge for people to carry out environmentally friendly practices (Imolore, 2023). For instance, the myclimate Carbon Tracker could collect and calculate data on carbon emissions in flights with different classes (myclimate, 2023) with rankings and evaluations to identify the suitable goal of carbon reduction. From a manufacturing perspective, the Internet of Things (IoT), which is a paradigm of engaging with networks, can be wielded in microcontrollers to detect real-time emissions, efficiently provide sensor data to monitor energy use, and promote 94.8% to 99.8% of power savings in resource-intensive sectors (Fay et al., 2023). IoT can present as a typical future trending tool for controlling undesirable gas emissions while managing mass data. While it can be presented with low power consumption, it exists as a powerful source for environmental chemical sensing, particularly on carbon dioxide emissions, ranging from external environments to internal home settings. From an institutional perspective, the EPA, or Environmental Protection Agency, for example, could improve its detection of violators of water pollution regulation by over 600% through machine learning during the supervision (Coglianese & Lee, 2024). It can also be further integrated comprehensively with life cycle assessment (LCA) data, including energy consumption, greenhouse gas emissions, and other factors, and supply chain information to create a data-driven model for monitoring and analyzing carbon footprint data through identity the trend in the changes of environmental data statistics to make predictions. These examples, along with more AI inventions and applications, could help to promote a better transition towards a low-carbon economy.

Nevertheless, the rapid development of AI has negatively resulted in the release of extensive carbon emissions. In 2015, numerous breakthroughs in AI contributed to the rise in AI development along with a higher average carbon footprint. Firstly, on December 11th, 2015, OpenAI was created and officially established by Elon Musk and Sam Altman, stressing data collection and generation (Malik, 2023). Secondly, under the release of a wide variety of Atari 26000 games with mere pixels and scores as inputs, DeepRL has established a new standard for AI algorithms while showcasing the power of AI from a practical perspective (European Commission, Joint Research Centre, 2020). Thirdly, artificial intelligence was becoming more mainstream through the development of the AI system of TensorFlow open source by Google, which announced to transit into Alphabet in 2015, including a range of different products, supporting the further development in machine learning (Thompson, 2015). These events contribute to or even determine the rapid evolution of AI, but the trend could also lead to some potential concerns - both environmental and ethical.

From an energy perspective, AI may aggravate climate change. As suggested, innovative technologies have contributed up to 3% of greenhouse gas emissions worldwide (Dolby, 2023). In addition, it is found that training a single AI model can produce carbon dioxide emissions of over 626,000 pounds, equivalent to 52.5 gasoline-powered vehicles annually (Chasan, 2023). This suggests the dominance of AI at present for carbon emissions, adversely contributing to climate change with more gas to trap heat in the atmosphere. In addition, artificial intelligence, in essence, is still computer systems. They can be run as data centers, which may be identified as one of the main usages of AI in the field, but they will need intense cooling, the same as personal computers at home, under tremendous processing. However, the process of cooling down could stress the energy, resulting in further economic and environmental costs as unexpected. At the same time, the application of AI methodologies suggested above may be limited to certain areas, not providing overall benefits in all areas at present, including the utilization of detection framework by researchers of Henderson et al.

From an ethical perspective, the utilization of AI involves ethical concerns. As carbon footprint and other related data are collected, the problem of data privacy and security is involved. Carbon footprint trackers are effective in data collection of the carbon emissions in specific activities in firms, requiring the supervision of the trackers in the transportation and/or production processes, which may be concerning. This may violate the privacy requirements. In the survey conducted by the Pew Research Center in 2019, 79% of Americans were concerned over data use (Auxier et al., 2019), and this concern would also be reflected in the privacy and security of carbon data collection.

Despite the potential side effects of AI in promoting the upbuilding of a low-carbon economy, AI can be adapted into potentially more suitable models to bind in its function of mitigating climate change and carbon emission, which is through the model of deep learning. The definition of this model is "a subset of machine learning and incorporates computational models and algorithms which imitate the architecture of the biological neural networks in brain (artificial neural networks)" (Jakhar & Kaur, 2020). Under deep learning, information could be transmitted through the activation of connected nodes as layers, and this could be categorized into two types of networks to be useful under the environmental background through image recognition and formation — Convolutional neural networks (CNNs) and recurrent neural networks (RNNs). CNNs, consisting of 3 main types of layers: convolutional layer, pooling layer, and full-connected (FC) layer, can more efficiently build up less complex images of the environment through filtering or padding, pattern extraction, as well as the connection of adjacent nodes for quicker transmission between nodes (IBM, 2024b), improving the environmental measurements for emission prediction and other related actions. RNNs, at the time, involves the use of present node information to predict the next word in the next node (IBM, 2024a), which is useful in interpreting people's actions and daily tasks to better identify their actions' relativity to the amount of carbon emission or carbon footprint.

Additionally, we also need to extend from the discussion of the simple and direct unitary relationship between carbon-related factors and financial investment and put our attention on other potential factors. The government policies may be a possible direction that could be explored. The government could include carbon prices, which lead to inflationary price impacts while constraining the release of carbon emissions. Despite its regressive nature as an indirect tax, the government could benefit from higher revenues on further green investments to boost the development of a low-carbon economy (Brand et al., 2023), excluding its original planned spending on renewable energy and R&D. The economic conditions may also affect the ultimate low-carbon transition. As the period chosen undergoes COVID-19 as suggested previously, which can be identified as a global recessionary period, the reduction of greenhouse gas emissions and pollution may be slowed by people's immediate response to maintain their standards of living and health, gearing down the production and development of renewable resources as well as environmental-AI tools for carbon reduction. But at the same time, the immobility of individuals may reduce the carbon release from transports, counteracting the carbon emission and carbon footprint growth. From the study by Ronaghi and Scoresone, the overall carbon dioxide emission has undergone a sharp decline in 2020 (Ronaghi & Scorsone, 2023). Therefore, these omitted factors could appear as influential factors to some extent to affect the trend in developing a low-carbon economy.

Overall, our paper helps prove that technological advancement in AI helps to enable a better transition to the low-carbon economy, revealing a negative relationship between R&D development and greenhouse gas pollution, fulfilling the assumption provided when setting up the study. With this starting point, we could focus more on the research of the effectiveness and functionality of the AI models and technologies in monitoring, analyses, and predictions of environmental and energy data to optimize energy systems and supply chains, transportation, and risk evaluation in extreme weather events, including rising sea-levels, so that the effectiveness of the AI can be identified.

5. Conclusion

This study demonstrates that artificial intelligence (AI) has the potential to be a promising solution in addressing climate change, a significant global challenge primarily caused by human activities. By analyzing mass data, AI can aid in environmental decision-making processes, optimize renewable energy use, and accelerate the global transition to a low-carbon economy. The findings, based on public data from the OECD, suggest that AI has been considerably effective in promoting a low-carbon economy by supporting the growth of renewable energy and recycling while restraining greenhouse gas emissions and carbon footprint. These results align with the efforts of countries worldwide to combat climate change through initiatives such as the Paris Agreement and setting targets to reach net-zero emissions by 2050. However, the study also identifies potential limitations, such as the carbon release from AI itself, highlighting the need for further improvements to AI models to ensure their sustainability and effectiveness in the long term. Future research should focus on developing more energy-efficient AI models and exploring additional applications of AI in mitigating the impacts of climate change.

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