Gondwana Research 139 (2025) 43–72

Contents lists available at ScienceDirect

Gondwana Research

journal homepage: www.elsevier.com/locate/gr

Global progress towards the Coal: Tracking coal reserves, coal prices, electricity from coal, carbon emissions and coal phase-out

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ARTICLE INFO

Handling Editor: Minu Treesa Abraham

Keywords:
Global coal reserves
Coal prices
Coal energy
Carbon emissions
Coal phase-out

ABSTRACT

Coal remains a significant energy source globally, with the United States holding a substantial portion of the world's coal reserves but it creates the dangerous effects of global warming. Despite its abundance, questions arise regarding the accessibility and environmental impact of coal reserves. Therefore, this research forecasted the future of coal reserves, coal prices, electricity from coal, carbon emissions and coal phase-out targets globally using the SARIMAX Python® model for the study period 2023 to 2050 by using the economic data from the year 1980 to 2022. It is found that, the global coal reserve capacity is 1.07 trillion tons with an average coal prices vary with region to region, ranging from US $130 per tone to US $206 per tone until 2050. The global production of electricity from coal will also increase from 10415.49 TWh in 2023 to 13316.57 TWh until 2040 and 15243.36 TWh until 2050 which ultimately enhances the production of carbon emissions, increases from 157,768 billion metric tons in 2023 to 188,535 billion metric tons until 2040 and 215,077 billion metric tons until 2050. Furthermore, this study undertakes and presented the country wise examination of coal phase out and it is found that in many countries 75% of coal will phase out by 2030 and 100% by 2040 for meeting the Intergovernmental Panel on Climate Change (IPCC) 1.5 ^{0}C targets. Therefore there is a dire need to shift towards cleaner energy sources, leading to a decline in coal-fired power generation and a trend towards coal phase-out.

1. Introduction

The majority of carbon emissions are produced due to the burning of fossil fuel (Paraschiv and Paraschiv, 2020). As a result, global warming would climb slightly more than half now to around 3/4th by the year 2100, and also that the average global surface temperature will be elevated more in the twenty-first century than in any other century in the previous 1000 years (Chishti et al., 2021). Carbon emissions are taken up around 0.03 % of the earth's atmosphere, but due to fossil fuel consumption and deforestation, it has increased by about 49 % since preindustrial times (Smith et al., 2021). The combustion of fossil fuels releases approximately 34.8 Giga tons of carbon emissions into the atmosphere every year. The global average carbon content in the atmosphere has increased from approximately 277 parts per million (ppm) in 1750 to 414 ppm in 2020 (Wang et al., 2022). According to study (Zhu et al., 2021), increased carbon emissions into the atmosphere will raise the earth's surface temperature by 1.5 ^{0}C to 4 ^{0}C during the next 30 to 40 years. Most poor countries emit 0.6 to 0.9 tons of carbon emissions per person per year. Emerging countries have increased carbon emissions at a far faster rate than developed countries in recent decades (Bruckner et al., 2022). Because of greater quantity of carbon emissions, the world environment absorbs higher heat energy, resulting in higher global temperatures. This increase in atmospheric temperature is concerning because even a few degrees of warming would have harsh geographic consequences, including such droughts, soil degradation, crop growth pattern changes, vegetative production with increased desertification, and polar ice melting (Raza et al., 2022).

On the other hand, energy from fossil fuel sources is essential for the

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https://doi.org/10.1016/j.gr.2024.11.007
Received 11 April 2024; Received in revised form 19 October 2024; Accepted 4 November 2024
Available online 2 December 2024

growth of industry, government, and transportation. It is the catalyst for economic development and growth (Tawiah et al., 2021). Major advancements in civilization have always been accompanied by rising energy use throughout human history. Hence, combustion transforms coal into usable thermal energy, but it is also a process that causes the most environmental and health problems (Ma et al., 2019). Carbon dioxide (CO_2), sulphur oxides (SO_x), nitrogen oxides (NO_x), chlorofluorocarbons (CFCs), various traces of gases, and airborne inorganic particles like fly ash and suspended particulate matter are emitted primarily by coal combustion at thermal power plants (Li et al., 2020). Although carbon emissions are produced in combustion is not technically polluted (it is a natural result of all combustion), but its impact on global warming is of major concern (Wang et al., 2021). CO_2 is a stable molecule with an average residence time of less than 10 years, like 3 years in the troposphere, despite having a contact time in the atmosphere of more than 100 years, and its current presence in the atmosphere is increasing at an astonishing rate of 0.4 % per year. The average residence time in the troposphere refers to the number of years a molecule exists in the troposphere before it is reused by another biological mechanism on the ground or breaks apart in the stratosphere (Han et al., 2024).

We focus on coal as a key source of energy in this article, as well as new technologies that will allow coal to be utilized in power generation with little or no carbon buildup in the atmosphere. The challenge of continually growing carbon levels in the environment necessitates solutions that will allow for greater levels of sustainable electricity generation. Over the last few years, there has been a growing consensus that extra carbon emissions will produce a dramatic shift in climate with far-reaching consequences of variety of human activities. The majority of projections, however, are based on complicated climate models that are still unable to properly describe all of the physical forces that combine to cause climate change. As a result, there is still a great deal of ambiguity (Raza et al., 2023). Since the beginning of the nineteenth century, the quantity of atmospheric carbon emissions has risen substantially. The increase recorded during the last 40 years (from 315 ppm to 360 ppm) accounts for more than 50 % of the total increase during the last two centuries (Zhou et al., 2021). The widespread opinion is that human actions, especially the burning of fossil fuels, are to blame for the increase in carbon levels in the atmosphere. It has been pointed out that the rate of increase closely tracks the growth in the generation of carbon from cement production (Sousa and Bogas, 2021). At present, about 60 % of the CO_2 thus generated remains in the atmosphere. Further, It has also been demonstrated that changes in atmospheric carbon emissions are accompanied by a comparable decline in atmospheric oxygen levels, implying that combustion activities, rather than natural processes are to blame, for example, a decrease in the rate of photosynthesis, which would also increase CO_2 levels (Erdoğan et al., 2020). In this regards, "Plan of Action" formulated at the G8 Summit at Gleneagles in July 2005, Leaders stated: we will support efforts to make electricity generation from coal and other fossil fuels in terms of clean, green and sustainable way. This commitment provided the impetus for identifying the most promising advances that would increase coal-fired power plant efficiency (Raza et al., 2022). Efficiency is a critical performance criterion in coal-fired power generation. Raising efficiency reduces carbon emissions, with a one point margin increase in total efficiency resulting in 3 % reduction in carbon emissions (Li, 2021).

The advancement of extremely efficient supercritical (SC) and ultra-supercritical (USC) pulverized coalfired (PC) technology has made significant progress on bituminous coals, USC plants operating at saturated steam temperatures of 600 °C to 620 °C and pressures of over 25 MPa (250 bar) in some areas of the world reach design efficiencies of 45 % to 46 % (LHV, net). The capacity of such facilities has risen to 1100 MW per unit (Seo et al., 2021). In the next 10 to 15 years, if continued material advances succeed, the effectiveness of the finest PC plants might approach 50 % (LHV, net) (Zhou et al., 2023). Effective policies must be put in place to speed up the development of such technologies to the testing and implementation stages. At the same time, progress is being made in the development of circulating fluidized bed combustion (CFBC) plants. These can better utilize low-rank fuels, and result in lower carbon emissions of conventional pollutants. In 2009, the first supercritical CFBC plant, with a capacity of 460 MW, was built in Lagisza, Poland, although plans for larger units are now being developed. There will be a considerable market for CFBC in the future, notably for lower quality coals, high sulphur coals, and biomass. The successful functioning of the Lagisza supercritical unit should pave the door for similar units to be built in other nations, notably China (Chen et al., 2023). In the globe of integrated gasification combined cycle (IGCC) power production, there are only six coal-fired facilities. Nonetheless, a modest number of new projects have been launched throughout the world, all of which are in various stages of development (Giuliano et al., 2018). If IGCC is to be extensively used, certain urgent problems must be addressed, including as lowering the cost and increasing the availability of the technology. Different supplier groups have been made to solve the problems and provide a viable alternative to IGCC units (Wu et al., 2020). Around 45 % of the world's coal has an excessive moisture or ash content, there is a pressing need to create coal drying systems that are less energy demanding. While coal drying projects in Australia, Germany, and the United States are underway, it is crucial to expedite these efforts into large-scale integrated demonstrations (Fan and Ma, 2018). To lower the amount of ash and sulphur in coal, there is a comparable need to create less energy and water demanding coal beneficiation processes. If more effective coal drying and beneficiation technologies can be developed, low rank coals will be used more widely in both USC pulverized coal and IGCC applications (Coenen et al., 2018).

Carbon capture and storage (CCS) is a topic that will have a substantial influence on both present and future facilities (Wilberforce et al., 2019). Retrofitting PC or CFBC units with carbon collection at the current state of technology will result in a decrement of up to 10 %. Despite the existence of the concept of "CCS ready", many existing PC plants may be deemed unsuitable for retrofitting with carbon collecting owing to inefficient units (Meng et al., 2024). Carbon collection retrofit is projected to be more beneficial for plants with high baseline efficiency in general. If 40 % efficiency was used as a cutoff for retrofitting with carbon capture, only around 10 % of the world's present coal-fired capacity could be retrofitted with CCS. This estimate assumes that retrofitting these facilities is feasible and are suitable for geological storage sites for collected carbon (Runsheng et al., 2023). Oxyfuel technology is emerging in parallel for carbon capture, and may theoretically be utilized with both PC and CFBC units (Yadav and Mondal, 2022). One problem of special relevance in the selection of IGCC, PC, and CFBC is the mechanism for selecting new power plants. Even though there are various plans for more commercial demonstrations of IGCC, and several are already being built, pulverized coal plants from SC and USC continue to dominate new plant orders. Only if the coproduction of electricity and chemicals can be shown economically will IGCC, with or without CCS, be able to reach the market on a wide scale (Melendo et al., 2023). The impediments to wider demonstration and effective implementation of technologies, as well as key R&D needs for all of these technological advances, should have been identified. Progress in carbon emissions and fuel for coal-fired power generation is expected to increase steadily through 2020 and beyond, if the energy efficiency measures were not incorporated (Shi et al., 2019). Clean coal transition through efficient technology is conceivable around the globe with sufficient policy as shown in Fig. 1 (Li et al., 2022).

The significance of coal in the context of clean energy and the targets set by the IPCC is critical, as coal remains the most carbon-intensive fossil fuel and a major contributor to global carbon emissions (Liu et al., 2024). The IPCC's latest assessments emphasize the urgent need for a rapid transition away from coal to meet global climate goals, particularly the aim to limit global warming to 1.5 ^{0}C. Coal accounts for approximately 26 % of primary energy needs and 37 % of electricity

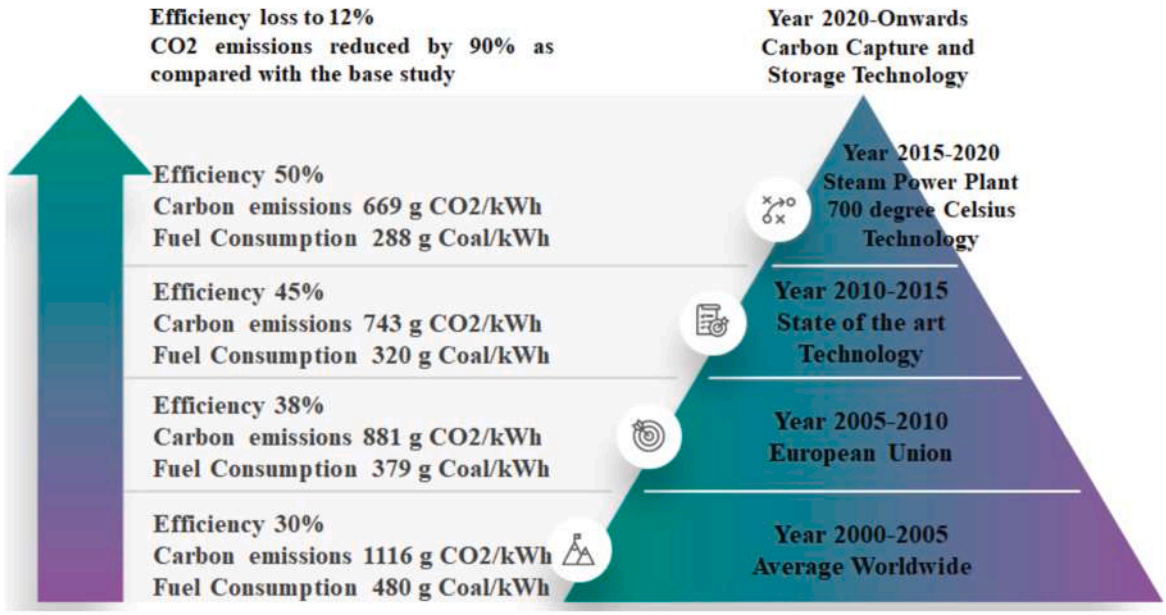


Fig. 1. Improvement in efficiency causes reduction in CO_2 emissions (Li et al., 2022).

generation worldwide by 2023, making it a significant player in the global energy landscape. However, burning coal through traditional technologies produces over 15 billion tons of carbon emissions annually, which is a major driver of climate change (Wang et al., 2024). The IPCC has indicated that to align with the 1.5 °C target, coal use must decline dramatically by nearly 75 % by 2030 and by up to 97 % by 2050. But none of the study has focused on the relationship between clean coal energy production and coal phase out in each country when needed around the globe for stabilizing economy. However, this study identify the path for global progress towards the coal, tracking coal reserves, coal prices, electricity from coal using high efficient technologies like SC, USC, PC, CFBC, IGCC and CCS, production of carbon emissions from coal and coal phase out statistics in each country and suggested the immediate action for coal-dependent countries around the globe.

Hence this research is conducted to track the global progress towards the coal and answer the following question:

1. How much global coal reserves are available (country wise)?
2. What are the coal exploitation and coal use prices?
3. How much electricity is generated from coal in past and how much in the future using the efficient and emerging technologies?
4. What should be the future intensity of carbon emissions? and finally,
5. When coal will be phase out around the globe?

Global progress towards the coal utilization is identified in this research over the period 2023 to 2024 by considering the past data from 1980 to 2022. The coal reserves in 2023 are primarily concentrated in a few countries, with the top five holding around 75 % of the total reserves including United States have 22 % reserves followed by Russia 15 %, Australia 14 %, China 14 % and India 11 %. But on the other hand, China utilized greater coal around 50.5 % of global coal consumption followed by India 11.3 %, United States 8.5 %, Germany 3 % and Russia 2.7 %. Furthermore, Indonesia dominate in both coal exploitation and exports to other countries around 516.7 million tons in 2023 followed by Australia 401.3 million tons, Russia 242.6 million tons, United States 85.9 million tons, South Africa 83.1 million tons, Colombia 62.3 million tons, Kazakhstan 41.1 million tons, Canada 31.8 million tons, Mongolia 21.5 million short tons, and Netherlands 17.6 million tons. Coal accounts for just over one-third of global electricity generation, making it the most carbon-intensive fossil fuel in use today. Despite a gradual decline in some regions, coal-fired power generation saw resurgence in 2022, driven by high gas prices and extreme weather conditions. As of late 2023, 84 countries have pledged to phase out coal or refrain from developing new unabated coal plants, representing about 30 % of current coal consumption for electricity generation. However, countries like China and India, which together account for two-thirds of global coal power generation, continue to expand their coal capacity to meet rising electricity demand. Some countries are successfully phasing out coal faster than others and some countries are developing and implementing new technologies such as like SC, USC, PC, CFBC, IGCC and CCS systems to enhance the efficiency of coal power generation and reduce the carbon emissions to a greater extent. Hence, the transition away from coal is critical for achieving global climate targets. While many nations are making strides toward reducing their coal dependency, the pace and extent of these changes vary significantly across different regions. Continued investment in renewable energy and carbon capture technologies will be essential to facilitate this transition while meeting growing energy demands.

Hence, SARIMAX Python® is developed for this study and considered the past data from the year 1980 to 2022 and forecasted the future parameters from 2023 to 2050. The past assumptions are based on the major economic indicators like the historical coal supply and demand dynamics, coal electricity with carbon emissions, geopolitical events, environmental regulations, trade volumes, natural disaster and market trend with low carbon policy changes through efficient technologies. The model automatically forecast the future based on the latest economic sentiment. The proposed method has greater reliability of the time series predictions using economic strategies for global coal that allows for more informed decision-making in an ever-changing market landscape. The study adopted in this paper would help to realize the future coal consequences and provides sustainable option to policy makers in various countries around the globe for reduction or no production of carbon emissions in the atmosphere.

2. Research Methodology

In this section, the research flow diagram along with clean coal transition framework is presented. Further, the input data and system simulation techniques using the SARIMAX Python® model are described in detail.

2.1. Research method

Fig. 2 depicts the research flow diagram for this proposed study, while Fig. 3 depicts the model framework for a clean coal transition using efficient technologies.

In this study, SARIMAX Python® is developed and considered the past data from the year 1980 to 2022 and forecasted the future parameters from 2023 to 2050. The past assumptions are based on the major economic indicators like the historical coal supply and demand dynamics, coal electricity with carbon emissions, geopolitical events, environmental regulations, trade volumes, natural disaster and market trend with low carbon policy changes through clean coal efficient technologies. Clean coal efficient technologies offer promising pathways to reduce carbon emissions from coal-fired power generation, their effectiveness is contingent upon overcoming economic and technical challenges. The transition towards renewable energy sources is vital for long-term sustainability, but clean coal efficient technologies like circulating fluidized bed combustion technology with carbon capture and storage (CFBC-CCS), integrated gasification combined cycle with carbon capture and storage (IGCC-CCS), supercritical pulverized coal fired technology with carbon capture and storage (SCPC-CCS) and ultra-supercritical pulverized coal fired technology with carbon capture and storage (USCPC-CCS) may play a transitional role in regions heavily reliant on coal until and unless the coal will phase out. The integration of these clean coal efficient technologies into broader energy strategies will be crucial for meeting IPCC 1.5 ^{0}C climate targets and reducing the environmental impact of coal usage globally.

2.2. Input data for system simulation

We use data from "Our World in Data" January 2022 edition on coal that was between 1980 and 2022 (Global Change Data Lab., 2024) to forecast future energy potential, carbon emissions coal prices, and coal phase statistics of various countries around the globe. The past assumptions are based on the major economic indicators like the historical coal supply and demand dynamics, coal electricity with carbon emissions, geopolitical events, environmental regulations, trade volumes, natural disaster and market trend with low carbon policy changes through clean coal efficient technologies. Fig. 4 shows the capacity of the coal at each level including proposed, in construction, operational and also retired (Raza et al., 2022). We modify parameters on which policymakers may have some control in the analysis. We change the expected lifespan of coal-fired power plant units (30, 35, and 40 years), the rate at which planned units are discarded (attrition rate), and unit capacity utilization (capacity factor) (Rocha et al., 2021). Similarly, the efficiency of power transmission infrastructure and demand for coal power affect the use of coal-fired power plants, both of these elements are impacted by politicians' and government regulators' actions in tightly regulated developing and underdeveloped nation (Khan et al., 2023).

At the national level (country wise), we construct attrition rates based on current patterns in the country's power industry, which we then raise and lower by 10 % (Zheng et al., 2020). We also employ country-specific capacity factors derived from research on coal-intensive countries utilization rates. It's worth noting that we use the mean commissioning year in each nation and also we kept the technical characteristics of coal-fired power plants unchanged. These are the heating rate and emission levels. These two factors that are mostly not considered by policymakers so immediate control yet are needed to estimate accurate carbon emissions (Debiagi et al., 2022). We assume that new additional plants will be added where high quantity coal capacity is available and no additional plants will be added to the pipeline in major carbon emitting countries in the future. Coal is mainly made up of carbon. During the combustion of coal, carbon reacts with oxygen present in the air to release CO_2 and energy. The reaction is given in Eqn. (1) (Raza et al., 2022):

$$C(s) + O_2(g) = CO_2(g) + Energy \tag{1}$$

We forecast CO_2 emissions using a variety of realistic assumptions in

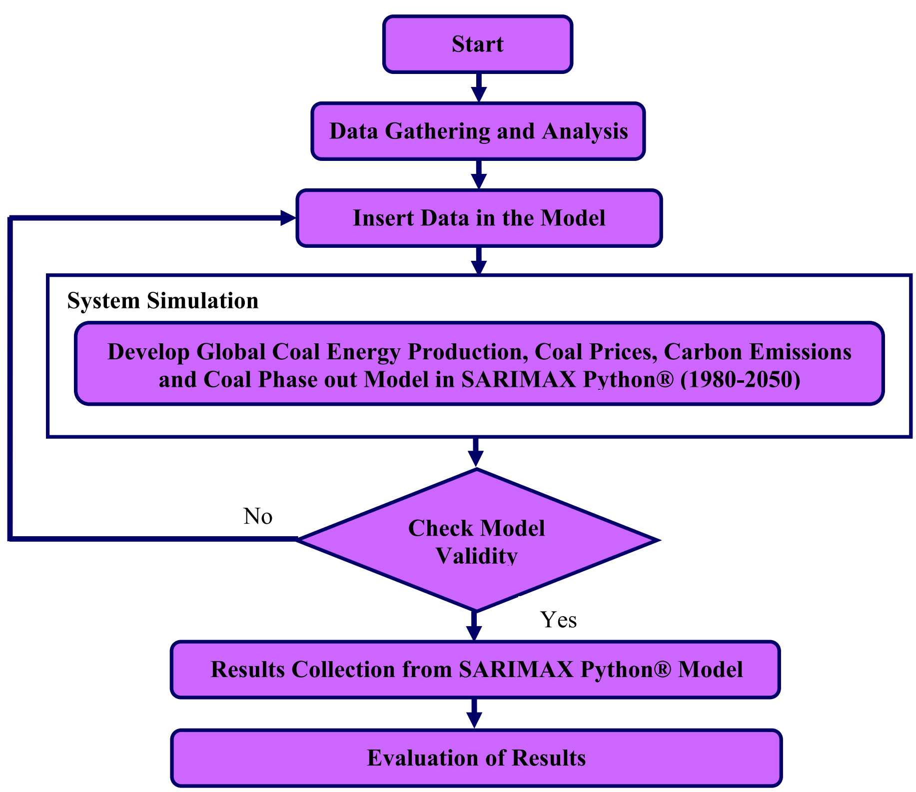


Fig. 2. Study methodological flow diagram.

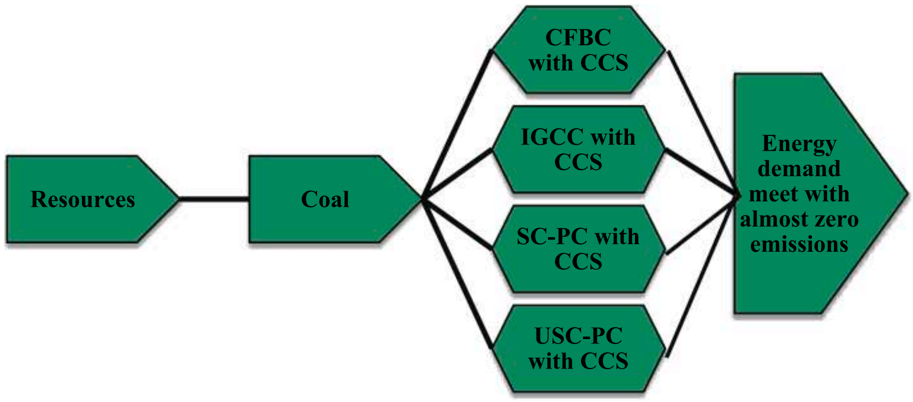


Fig. 3. Study framework for global clean coal transition.

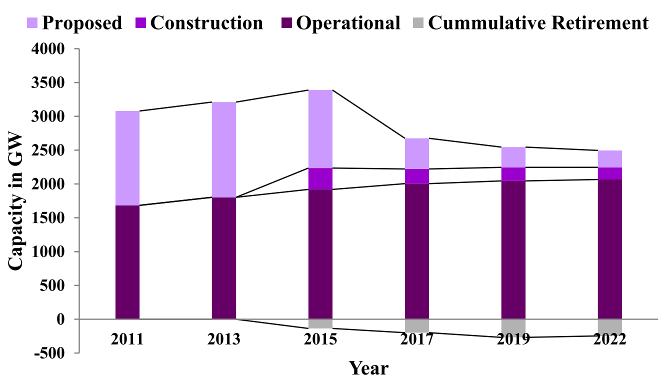


Fig. 4. Proposed, in construction, operational and retirement capacity of coal plants (Zhao and Alexandroff, 2019).

addition to effective capacity. CO_2 emissions formula is given in Eqn. (2) (Ren and Long, 2021); (Raza et al., 2023):

$$AnnualCO_2\,(\mathrm{Mt}) = Capacity \times CapacityFactor \times HeatRate \times EmissionFactor \quad (2)$$

Heat rates range from 7528 Btu/kWh to 8921 Btu/kWh, with CO_2 emissions ranging from 216.3 to 227.4 lbs CO_2 per million Btu (for lignite/anthracite or brown coal) (Qader et al., 2021); (Raza et al., 2024). We utilize the averages of these ranges in the ensuing studies since they are technical issues that policymakers cannot readily change. The price for coal is forecasted using the Eqn. (3) (Zhang et al., 2020):

$$P(t) = f(P_{t-1,}.....................P_{t-d}) \quad (3)$$

where, "P" is the price of coal forecasting, "f" is the function, and "t" represents the time.

We use past data from 1980 to 2022 and forecast from 2023 to 2050, we estimate global coal energy potential, coal prices, carbon emissions and coal phase out around the globe. Let's start with the capacity of operating coal-fired power plants in 2021. We then look at the commissioning years for the plants that are currently active, and we project retirements based on a 35-year lifespan. Next, we use the "SARIMAX Python®" technique to forecast entrance timeframes for plants that have been announced, pre-allowed, permitted, or are now under construction: Plants that have been announced have a 10-year entrance period, plants that have been pre-permitted have a 7-year entry period, plants that have been permitted have a 4-year entry period, and plants that are under construction have a one-year admission period. This study (Rocha et al., 2021) utilized a similar schedule, assuming that announced units will come online in 2029 (9 years), and pre-permitted units in 2027 (7 years), Units will be approved in 2026 (6 years), and units will be under construction in 2024 (4 years). Our timetable should produce significantly higher forecasts for future coal consumption due to more aggressive assumptions regarding approved units and units under development.

2.3. SARIMAX Python® model Description

The SARIMAX Python® model is a powerful tool used for energy forecasting (Elshabrawy et al., 2023). It employs a Seasonal autoregressive integrated moving average model with exogenous variables to predict future values in a time-series, specifically in the context of energy consumption (Elshewey et al., 2022). This model is designed to handle the complexities of time-series data, incorporating seasonal patterns and external factors that can influence energy demand or production (Fiskin et al., 2022). Studies and frameworks like those presented in the provided sources demonstrate the effectiveness of SARIMAX Python® in forecasting electricity demand, solar PV power output, and day-ahead electricity price (Sarang et al., 2024). By utilizing statistical approaches and advanced modeling techniques, SARIMAX Python® can provide accurate predictions that are crucial for energy planning, management, and decision-making. The SARIMAX Python® model, as discussed in the sources, is particularly valuable for its ability to account for seasonality, auto-regression, and exogenous variables, making it a comprehensive tool for energy forecasting. It is essential in the energy sector for optimizing resource allocation, improving grid stability, and enhancing overall operational efficiency (Alharbi and Csala, 2022).

The SARIMAX Python® model with external variables, called SARIMAX (p,d,q) (P,D,Q)S (b), where "b" is the vector of external variables. The external variables can be modeled by multi linear regression which is expressed in Eqn. (4) (Saranj and Zolfaghari, 2022):

$$f(x) = a_0 + a_1 b_{1,t} + a_2 b_{2,t} + \cdots + a_y b_{y,t} + z_t \quad (4)$$

where, $b_{1,t}, b_{2,t} \cdots b_{y,t}$ is observation of y number of external variables corresponding to the dependent variables f(x); $f(x); a_{0,} a_1, a_2, \cdots, a_y$ are the regression coefficient of external variables; z_t is a stochastic residual i.e the residual series that is independent of input series. The residual series z_t can be represented in the form of ARIMA model as given in Eqn. (5) (Sheshadri, 2020):

$$z_t = \frac{\Omega_q(b)\Omega_q(b^s)}{\Phi_p(b)\Phi_p(b^s)(1-b)^d(1-b^s)^D} \times \omega_t \quad (5)$$

where, $\Omega_q(b)$ is the moving average operator of q order, $\Omega_q(b^s)$ is the seasonal moving average operator of q order, $\Phi_p(b)$ is the autoregressive operator of p order, $\Phi_p(b^s)$ is the seasonal autoregressive operator of p order, $(1-b)^d$ is the differencing operator of order d to remove non-seasonal stationarity, $(1-b^s)^D$ is the seasonal differencing operator of order D, and ω_t is the residual error in SARIMA model. The SARIMAX Python® model Eqn. can be obtained by substituting Eqn. (5) in Eqn. (4) (Hadri et al., 2021).

$$f(x) = a_0 + a_1 b_{1,t} + a_2 b_{2,t} + \cdots + a_y b_{y,t} + \left(\frac{\Omega_q(b)\Omega_q(b^s)}{\Phi_p(b)\Phi_p(b^s)(1-b)^d(1-b^s)^D} \times \omega_t\right) \quad (6)$$

In this case of model, the regression coefficient can be interpreted as in usual and easier way. To choose the optimal order of a SARIMAX Python® model for energy forecasting, several key steps are involved as outlined in the provided sources (Ahn and Hur, 2023; Almaleck et al., 2024; Rehan et al., 2023):

1. The SARIMAX Python® model involves two types of orders – the (p, d, q) order for the time series and the (P, D, Q, M) seasonal order for the seasonal component of the time series. These parameters represent the autoregressive, differencing, and moving-average components, both for the non-seasonal and seasonal parts of the model
2. The selection of the optimal SARIMAX Python® model involves tuning these parameters to achieve the best fit for the data. This process includes evaluating different model configurations based on criteria like Akaike Information Criterion (AIC) and Bayesian Information Criterion (BIC).
3. Metrics like Mean Absolute Error (MAE) and Mean Absolute Percentage Error (MAPE) are commonly used to compare the performance of different SARIMAX Python® models. These metrics help assess the accuracy of the models in predicting energy consumption or production.
4. It is crucial to validate the chosen SARIMAX Python® model by comparing its forecasted values with actual data. This validation step helps ensure the reliability and effectiveness of the model for energy forecasting

By following these steps, analysts and researchers can effectively determine the optimal order of a SARIMAX Python® model for energy forecasting, considering both the non-seasonal and seasonal components of the time series data.

3. Comprehensive results and discussions

3.1. Global coal reserve

Global coal power capacity stood at 2,121 GW in 2023, with 2,435 coal-fired power plants operating worldwide. This capacity has grown by 10 % since 2015, despite some countries reducing their planned coal power (Raza et al., 2023). To align with climate goals of IPCC, all existing coal plants need to be retired by 2030 in the wealthiest nations and by 2040 globally (Mahmood et al., 2024). The International Energy Agency (IEA) suggests that 100 GW of coal power must be retired annually for the next 17 years to achieve this goal. Despite the increasing coal capacity, there are signs of progress, with a significant decrease in the pipeline of new coal plants under construction or proposed since 2015 (Mahmood et al., 2024). The countries with the highest coal power capacity is China, which has the highest installed capacity of coal power plants globally, and India, which has the second most coal power plants in the world. Additionally, the United States has a significant number of coal power plants, ranking third in terms of active coal power plants. These countries have substantial coal power capacity, contributing significantly to global coal energy production and consumption. The world capacity for coal reserves are 1.07 trillion tons. However, region wise coal capacity is shown in Fig. 5.

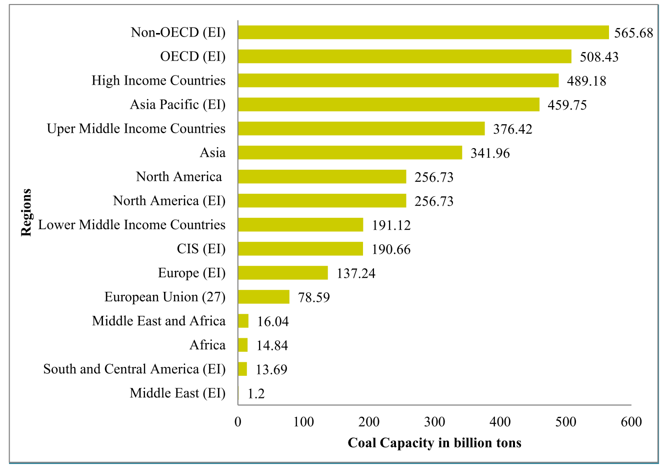


Fig. 5. Global coal capacity.

The global coal capacity has seen significant developments in recent years. In 2023, the operating coal power capacity globally reached 2,095 GW, showing a growth of 9 % since the Paris Agreement in 2015. Despite this growth, there have been notable retirements of old coal plants, with 280 GW being retired, while 458 GW of new plants were added, resulting in a net addition of 178 GW. The expected growth of coal capacity has been reduced due to numerous cancellations, with projects under development declining by 937 GW since 2015. New coal plants are still being built and planned across 38 countries, potentially increasing total coal capacity in the coming years. The share of total electricity generated by coal globally continues to decrease, with coal power generation growing by 11 % compared to a 21 % increase in global electricity demand since 2015. Policy progress has been made towards coal phase out and finance, with commitments from national and subnational governments, the G7, and China to stop financing overseas coal projects. Despite these efforts, coal power emissions are still growing globally, albeit at a slower rate. To align with a 1.5 °C pathway, global coal power generation needs to decline significantly by 2025 and 2030, requiring the closure of older plants, canceling new projects, and increasing renewable energy capacity substantially. The global coal transition has been delayed, especially since 2021, due to various challenges like energy security concerns, economic recovery post-pandemic, and the influence of powerful stakeholders in the coal industry. Successful project-level transition cases demonstrate the feasibility and benefits of a rapid and just coal phase out with strong policy support, finance, and stakeholder engagement.

3.2. Coal prices

Coal prices are forecasted as shown in Fig. 6 from 2022 to 2050 based upon the past data taken from 1980 to 2022. Coal prices in Asian markets have shown fluctuations based on various factors. In recent months, Asia's seaborne imports of thermal coal have experienced changes. In January 2023 Asia's imports of thermal coal fell to 77.65 million metric tons, a 5 % decrease from the record levels in December 2022. Despite this decline, China's imports were still 34 % higher than the previous year, driven by increased demand for thermal generation due to lower hydropower output and cost advantages over domestic coal. In China the price for unit tone coal will also be increased from $137.11 in 2022 to $169.49 until 2040 and to $224.73 until 2050. India also saw a decline in imports for the third consecutive month but experienced a 27.2 % rise compared to the previous year. Japan and South Korea, on the other hand, showed strong demand for thermal coal. In Japan, coal is used for cooking, electricity and spot steam. The price for cooking coal will be increased from $126.36 in 2022 to $171.98 and then reduces to $113.64 until 2050 (Khan et al., 2024). The price for coal used for electricity will be $136.027 until 2040 and then reduces to $175.53 until

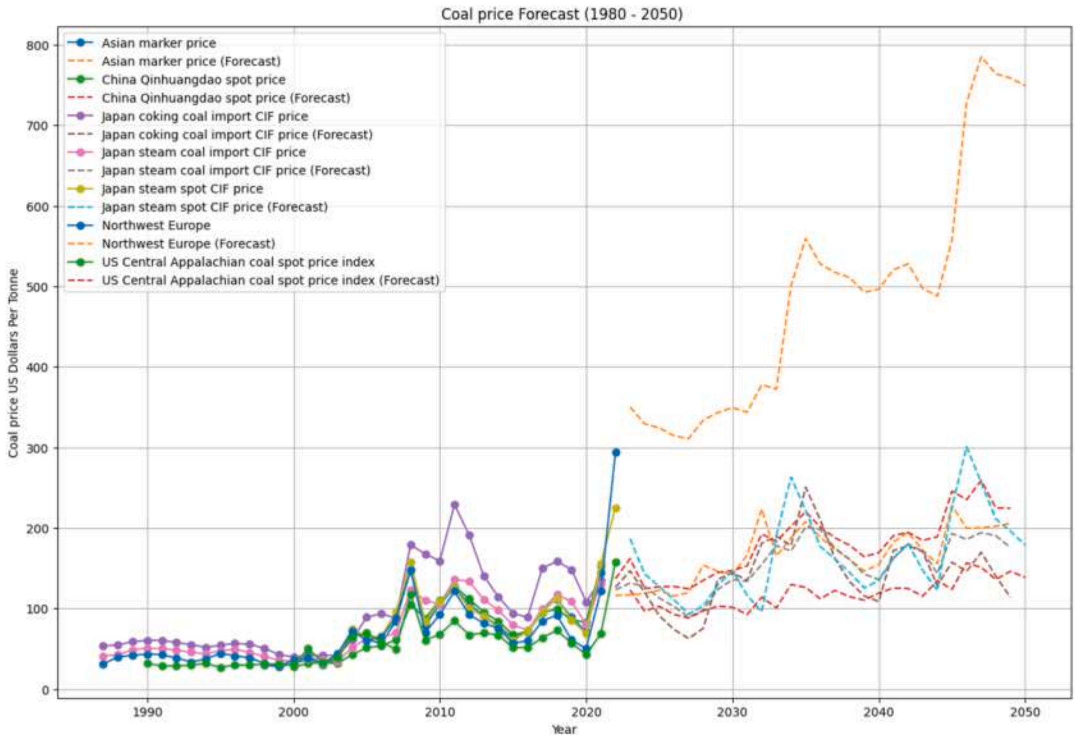


Fig. 6. Global coal prices from 1990 to 2050.

2050 which was $123.26 in 2022. The price for coal steam spot will be decreased from $186.99 in 2022 and to $131.58 until 2040 and then suddenly increased to $180.33 until 2050. Looking ahead, India is expected to witness a decrease in thermal coal imports for the first time since the pandemic, with estimates suggesting a 3–6 % drop in imports due to rising domestic production and high inventories. In Asian countries the price for unit tone of coal will be $154.99 until 2040 and $206.011 until 2050 which was $116.50 in 2022. Overall, coal prices in Asian markets have been influenced by a combination of factors such as supply and demand dynamics, changes in import volumes, and regional economic conditions.

Global coal prices experienced significant fluctuations and reached record levels in recent years due to various factors impacting the market. In 2022, coal prices surged to unprecedented highs driven by soaring global demand, supply shortages, and geopolitical events like Russia's invasion of Ukraine. The turmoil in the coal spot market influenced forward prices, with expectations shifting towards higher long-term prices. Despite the high prices, there was a decline in global met coal consumption in 2022. The United States saw a rise in coal costs delivered to power plants, but prices started to fall by May 2023, nearing pre-crisis levels. China's import price spread narrowed due to high domestic production and a return to Australian coal, impacting the dynamics of domestic versus imported coal prices. Looking ahead, average annual coal prices are forecasted to decrease in 2023 compared to 2022 but are expected to remain above historical averages. According to the U.S. EIA, coal prices in the U.S are projected to increase annually through 2050, driven by market assumptions and industrial sector demand. The EIA also highlights that transportation costs play a significant role in the final delivered price of coal, with the electric power sector being the largest consumer of coal in the U.S. The U.S. coal prices vary based on different factors and regions. In 2022, the national average sales price of coal is $122.99 which will reduce to $119.18 until 2040 and then a bit increment will be noticed to $138.46 until 2050. The price of coal can be influenced by transportation costs, with an average transportation cost of $5.33 per short tone, accounting for about 14 % of the average delivered price to the electric power sector. Moreover, the price of coal can depend on the type of transaction, with most coal for electric power generation being sold through long-term contracts supplemented by spot purchases. Spot prices can fluctuate based on short-term market conditions, while contract prices tend to be more stable. Additionally, the price of coking coal used in steel production is higher than that used for electricity generation, with an average delivered price of about $122 per short tone in 2022. In northwest Europe, the coal-to-gas switching price has been estimated at around 26.8 euros per MWh, giving gas-fired power producers a cost advantage over coal-based counterparts. The coal price is bit expensive in Europe that is $350.24 in 2022 which will increase to $496.42 until 2040 and then $748.87 until 2050.

It is concluded that global coal prices in each country have experienced significant volatility, influenced by a complex interplay of factors including coal supply and demand dynamics, geopolitical events, environmental regulations, natural disaster, policy changes and market trends. This study gathered extensive historical coal data of each country around the globe on the basis of economic indicators of coal prices, production levels, consumption rates, and trade volumes to forecast the future until 2050. This study monitored the current coal prices in each country on the basis of economic indicators and estimated the future as per the historical data, then SARIMAX model of Python® automatically contracts to adjust coal prices predictions based on the latest economic sentiment. Model results show varying assumptions about coal demand growth, supply disruptions, and regulatory changes in each country and hence the coal prices are varied country to country. Finally, a detailed assessment on how sensitive our predictions are to changes in key variables, including supply and demand dynamics, geopolitical events, environmental regulations, natural disaster, policy changes and market trends. These strategies are implemented in this study hence the results of this paper have enhanced reliability of the time series predictions for global coal prices, allowing for more informed decision-making in an ever-changing market landscape. The recent trends suggest a decline in prices from the peaks seen in 2022, with regional variations and ongoing shifts in the global energy trade landscape impacting coal prices.

3.3. Electricity from coal

The energy status in ASEAN countries reveals a complex landscape influenced by economic growth, policy choices, and energy demands. The capacity for coal energy production in ASEAN countries will be increased from 495.47 TWh in 2023 to 793.24 TWh until 2040 and to 974.82 TWh until 2050 as shown in Fig. 7**(a)**. In Africa, the energy landscape is characterized by a significant reliance on fossil fuels, particularly coal and oil, alongside a growing interest in renewable energy sources like solar, wind, geothermal, and hydro. Fossil fuels, including coal and oil, play a predominant role in Africa's energy mix, with natural gas having the largest share in installed capacity. Coal-fired power plants contribute a significant portion of the electricity sector's total carbon emissions. In Africa the energy production from coal is forecasted as shown in Fig. 7**(a)**, it depicts that energy from coal will be increased from 242.93 TWh in 2023 to 279.11 TWh until 2040 and 302.53 TWh until 2050. Fossil fuels play a significant role in Asia's energy, with the region accounting for 80 % of global coal use and 85 % of energy consumption sourced from fossil fuels. In Asian countries, the contribution of coal energy in total energy mix is forecasted. It shows that the coal contributed to 8596.30 TWh in 2023 and it will increase to 12450.21 TWh until 2040 and 14723.6 TWh until 2050 as shown in Fig. 7**(a)**. Asia heavily relies on coal for power generation, with China being the world's largest coal consumer. In Australia, coal contributed to 114.17 TWh in 2023 as shown in Fig. 7**(a)**. However, it is forecasted that, in 2034, the coal energy contribution remains at 7.29 TWh. After 2034, the coal energy will be eliminated from the total energy mix of Australia. Australia is a major producer and exporter of coal, with a significant portion of its black coal energy production being exported. Australia holds substantial coal reserves, with recoverable economic demonstrated resources amounting to millions of tons for both black and brown coal. The country ranks among the top globally for economically demonstrated black and brown coal resources.

Bangladesh generates almost all its electricity from fossil fuels, with natural gas being the primary source, accounting for 59 % of the energy mix. Bangladesh generated 11.27 TWh of energy from coal in 2023 and it will be increased to 15.15 TWh until 2040 and 23.33 TWh until 2050 as shown in Fig. 7**(b)**. The country aims to achieve a 25 % share of clean electricity by 2030 as part of its integrated energy and power master plan. Bangladesh's energy crisis, exacerbated by fossil fuel dependency, has prompted the government to consider diversifying its energy mix and investing more in renewables. The government of Bangladesh aims to source 40 % of its energy from renewables by 2041, with a long-term goal of achieving 100 % domestic renewable energy production. Bosnia and Herzegovina both primarily generates electricity from coal-fired thermal and hydro power plants, with coal being a significant source of energy. Bosnia and Herzegovina is under pressure to transition away from coal towards cleaner energy sources. Hence it noticed that small portion of coal energy is produced in Bosnia and Herzegovina till 2050. Fig. 7**(b)** depicts that 14.17 TWh of coal energy will be produced until 2040 and 13.87 TWh until 2050 which was only 11.70 TWh in 2023. Coal was once a major indigenous energy source in Belgium. In the past, coal was used for electricity generation, but there has been a notable reduction in coal consumption over the years. Fig. 7**(b)** depicts that 11.73 TWh of coal energy will be produced until 2040 and 17.25 TWh until 2050 in Belgium which was only 2.82 TWh in 2023. Belgium has been phasing out coal-fired power plants as part of its energy policy objectives.

The substantial coal resources of Czech Republic's have contributed to its reliance on fossil fuels for energy production. Coal has been a key component of the country's total energy supply and domestic energy production. Fig. 8**(a)** depicts that 29.40 TWh of coal energy will be produced until 2040 and then suddenly reduced to 23.36 TWh until 2050 which was too high 36.13 TWh in 2023 in Czech Republic. The Czech Republic is facing pressure to phase out coal due to new climate targets at the European level, making coal less competitive. While coal's phase-out is assumed to occur between 2035 and 2038, rising costs of carbon credits have already made coal power plants financially challenging. China's energy landscape is heavily influenced by coal, with the country being the world's largest consumer, producer, and importer of coal. Coal accounts for a substantial portion of China's total energy consumption, with coal-fired power plants making up around 50 % of the global operating capacity. The country's abundant coal reserves and historical economic growth have driven its reliance on coal as a cost-effective energy source, supporting its industrial development and economic competitiveness globally. Fig. 8**(a)** depicts that 7935.2 TWh of coal energy will be produced until 2040 and 9367.50 TWh until 2050 which was only 5692.31 TWh in 2023. China's consumption of coal alone produces more carbon emissions annually than the total energy-related emissions of the United States in a year. Coal power is also a major contributor to toxic air pollution and carbon emissions in Canada. Provinces like Alberta, Saskatchewan, and Nova Scotia, which heavily rely on coal for electricity generation, have some of the most polluting electricity systems in the country. The energy from coal is contributed to 31.33 TWh in 2023 and coal will be eliminated from the total energy mix of Canada from 2032 and onwards as shown in Fig. 8**(a)**.

The energy mix of Europe in 2023 is diverse, with various sources contributing to the region's energy supply. Fig. 8**(b)** depicts that 273.90 TWh of coal energy will be produced until 2040 which was only 691.07 TWh in 2023 and then coal will be phase out from Europe after 2043. The region's transition towards cleaner energy sources aligns with climate targets and aims to further diversify the energy mix while making progress towards sustainable and climate-friendly energy systems. Energy from coal is forecasted for the European Union (EU) as shown in Fig. 8**(b)**. 169.05 TWh of coal energy will be produced until 2040 which was too high 468.39 TWh in 2023 and then coal phase out in EU until 2042. The EU faced challenges in meeting its targets, including a decline in investment in renewable energy by one-third compared to the previous year. To achieve green energy goals, more ambitious policies are needed to accelerate the deployment of renewable energy sources, particularly in transport and heating sectors.

Between 2021 and 2022, G7 nations have been investing more in fossil fuels than clean energy, despite commitments to "build back better". The G7 countries are urged to transition faster towards clean energy to accelerate the phase-out of fossil fuels, which is essential for both business and climate reasons. However, coal phase out is possible after 2043, but before this the share of coal will be 225.29 TWh until 2042 which was too high 1153.62 TWh in 2023 as shown in Fig. 9**(a)**. The G7 nations have a critical role in leading the push for a global deal to gradually quit oil, coal, and gas, with a focus on developing new global targets for renewable energy. In 2022, G20 countries spent a record $1.4 trillion on fossil fuels, significantly surpassing investments in renewable energy sources. Despite commitments to triple renewable energy capacity by 2030, there is a persistent lack of strong promises to phase out fossil fuels, hindering progress in combating climate change. Fig. 9**(a)** depicts that 14090.34 TWh of coal energy will be produced until 2040 and 16688.68 TWh until 2050 which was only 9638.86 TWh in 2023 in G20 countries. The subsidies for fossil fuels in G20 nations have increased, with countries like China, the United States, Russia, the EU, and India being major subsidizers. These subsidies pose challenges to the cost-competitiveness of renewable energy, as they reduce the price of fossil fuels for end-users and create incentives for continued investment in fossil fuel production.

In high-income countries, the energy status reflects a significant reliance on fossil fuels despite efforts to transition to cleaner and renewable energy sources. Fossil fuel energy consumption remains a substantial part of the energy mix in these nations, contributing to carbon emissions and air pollution. In this regards, the contribution of coal energy in total energy mix is forecasted in high income countries as shown in Fig. 9**(b)**. It is found that coal energy will remain until 2035 with 48.56 TWh contributions then after 2035 coal will be phase out from high income countries. However, in the initial stage of 2023, it was

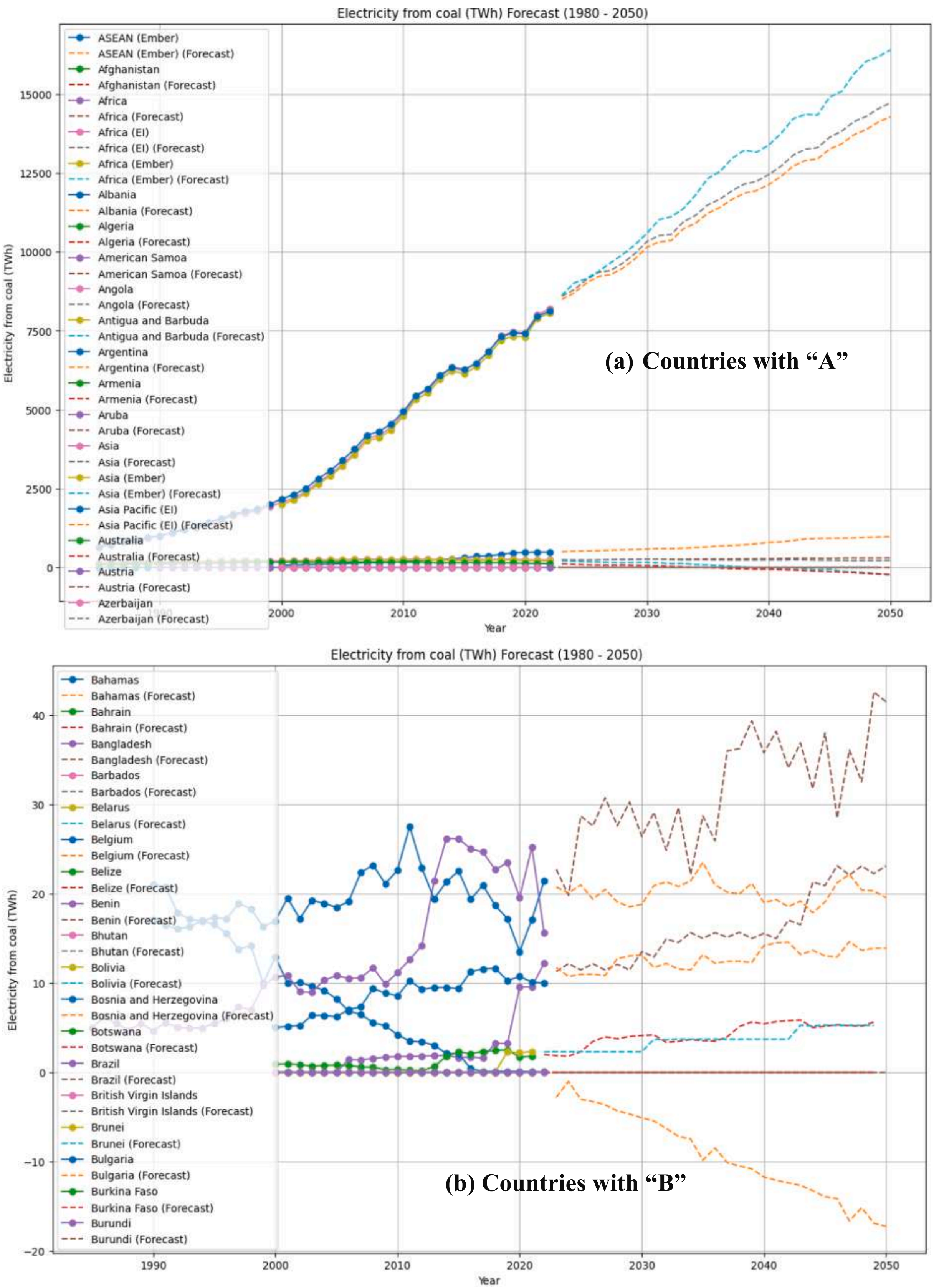
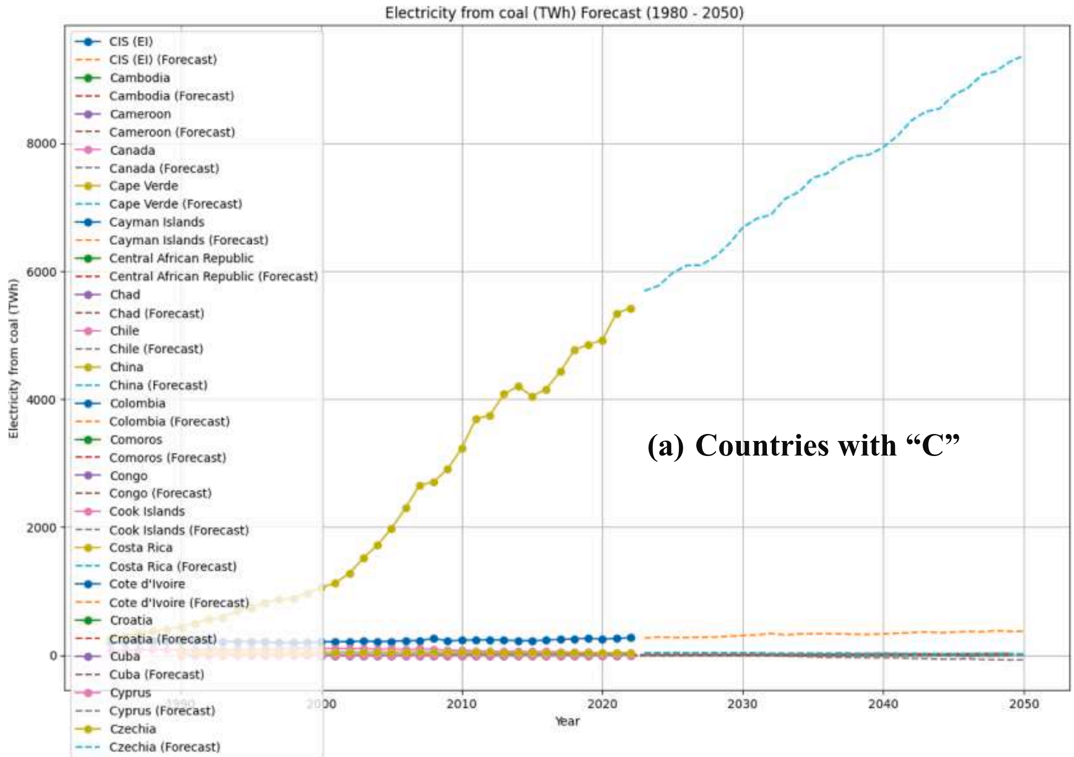


Fig. 7. (a,b): Electricity from coal for countries starting with alphabet "A" and "B".



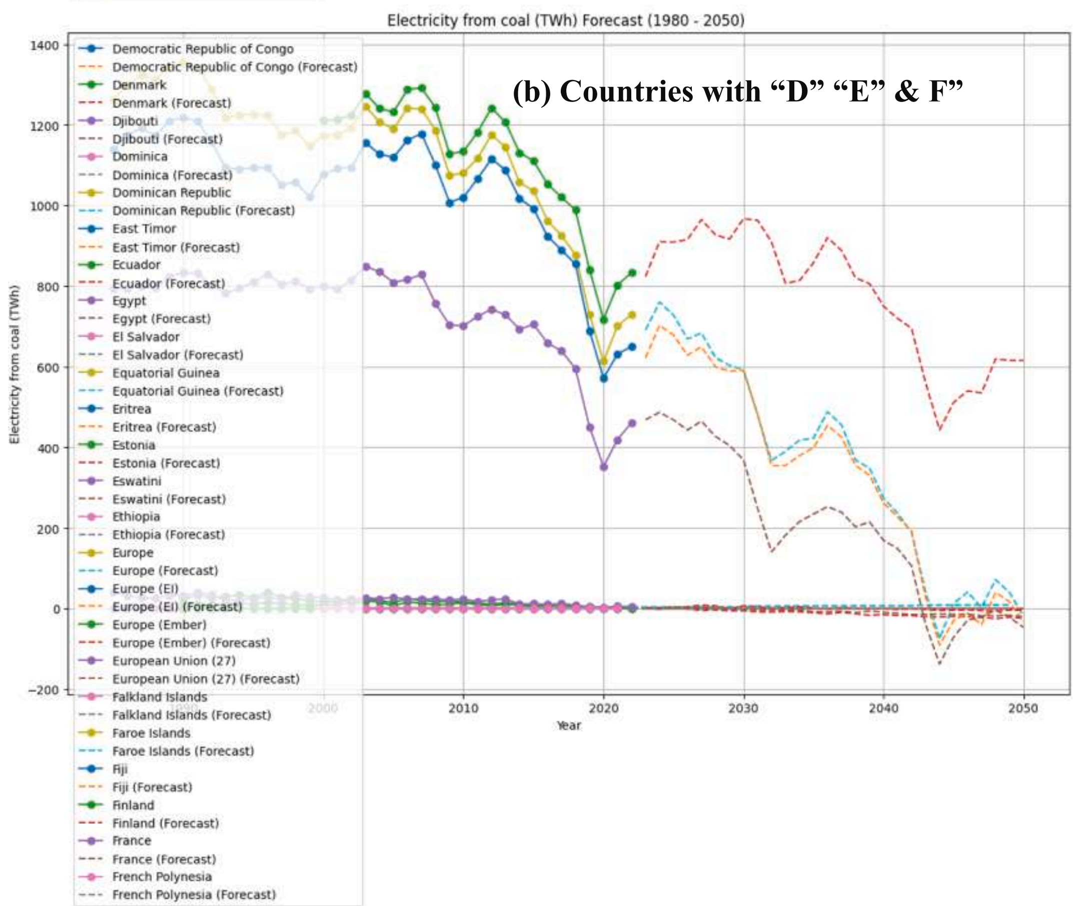


Fig. 8. (a,b): Electricity from coal for countries starting with alphabet "C" to "F".

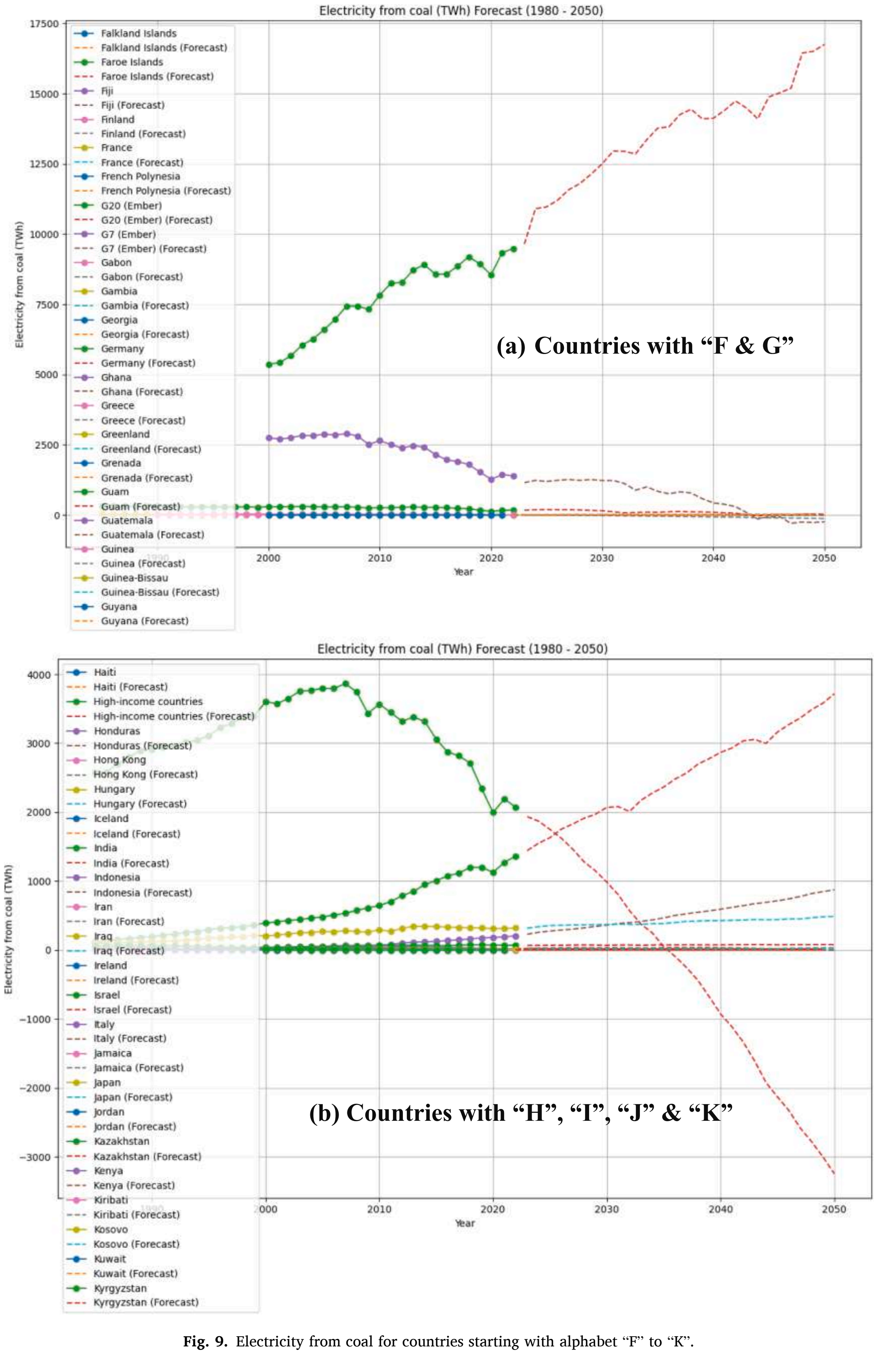


Fig. 9. Electricity from coal for countries starting with alphabet "F" to "K".

1935.64 TWh which was too high. High-income countries face challenges related to energy imports, price fluctuations, and the need to accelerate the shift towards reliable and affordable renewable energy sources. Despite efforts to transition to renewables in India, coal remains the dominant fuel source, mainly coal, making up 75 % of India's power supply. Hence energy from coal is forecasted which is continuously increasing from 1441.81 TWh in 2023 to 2867.09 TWh until 2040 and 3718.20 until 2050 as shown in Fig. 9**(b)**. India's transition away from coal is not imminent, with coal expected to remain a key energy source for the country's development in the coming years. Italy holds 19 million tons of proven coal reserves, ranking 67th globally. Hence energy from coal is forecasted which is increasing from 23.69 TWh in 2023 to 31.76 TWh until 2040 and then it will reduce to 30.29 TWh until 2050 as shown in Fig. 9**(b)**. The country's coal consumption is substantial, with imports necessary to sustain consumption levels due to limited domestic reserves. Italy has taken steps to phase out coal from its energy generation sector, with a commitment to cease electricity generation from coal nationwide by the end of 2025, except for the island of Sardinia. The decision to phase out coal reflects Italy's efforts to reduce carbon emissions and align with global sustainability goals. Japan's energy mix is characterized by a significant reliance on fossil fuels, with coal, oil, and natural gas accounting for a substantial portion of the country's energy supply. The future contribution of coal energy is forecasted which is continuously increasing from 316.74 TWh in 2023 to 426.29 TWh until 2040 and 486.98 TWh until 2050 as shown in Fig. 9 **(b)**. The country has made efforts to increase the share of renewables to reduce its dependence on imported fossil fuels and lower carbon emissions. The government has set ambitious goals to transition towards a carbon–neutral society by 2050, aiming to reduce carbon emissions and enhance energy security through a mix of nuclear, renewable, and thermal power sources.

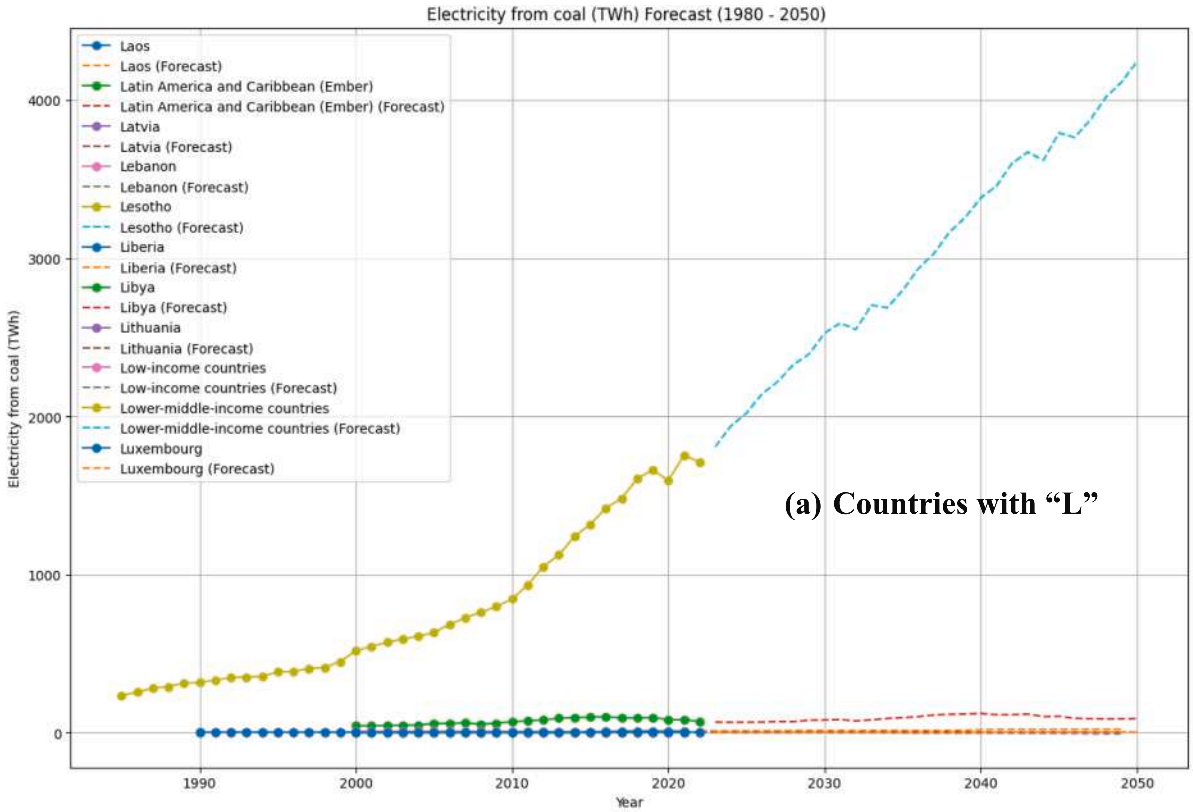
In Latin America and the Caribbean, coal plays a minor role in the energy mix, providing just 4 % of the region's electricity in 2022. The region's electricity generation is less fossil-intensive than the global average, with a lower carbon intensity of 238 gCO_2 per kWh in 2022 compared to the global average of 436 gCO2/kWh. Fig. 10**(a)** depicts that 121.69 TWh of coal energy will be produced until 2040 and then it will reduce to 88.12 TWh until 2050 which was only 66.84 TWh in 2023. Latin America and the Caribbean's ability to scale up clean power, particularly wind and solar, has been crucial in meeting growing electricity demand while reducing fossil fuel generation. In low-income countries, the impact of coal energy on poverty, the environment, and economic development is complex. While coal can provide affordable energy and support economic growth but its use raises concerns about environmental degradation, health risks, and social implications. Coal mining in these countries often involves challenges such as inadequate regulation, displacement of communities, and long-term environmental damage. However, the energy contribution from coal in low income countries will remain until 2030 with share of 0.41 TWh which will increase to only 3.30 TWh until 2050 as shown in Fig. 10**(a)**. In lower-middle-income countries, coal plays an important role in the energy mix, with electricity production from coal sources accounting for a large percentage of the total. Fig. 10**(a)** shows that coal energy will increase to 3384.93 TWh until 2040 and 4250.71 TWh until 2050 which was only 1808.73 TWh in 2023 in lower-middle-income countries. Coal can provide affordable energy and support economic growth but its negative impacts on health and environment is significant. The transition to cleaner and more sustainable energy sources is crucial for equitable and environmentally friendly energy future. Policymakers in these countries face challenges in balancing economic growth, energy access, and environmental sustainability, requiring a careful consideration of the political economy dynamics surrounding coal use and the transition to cleaner energy sources.

Malaysia has historically relied on coal resources for electricity generation, with coal contributing a substantial portion to the power mix. Fig. 10**(b)** shows that 76.06 TWh energy is produced from coal in 2023, which will increased to 108.79 TWh until 2040 and 121.22 TWh until 2050. However, recent developments indicate a transition away from coal towards renewable energy sources. Coal energy in Mexico contributed around 6.44 % to the energy profile in 2019. In 2023 coal contributes to 20.76 TWh which further increased to 25.11 TWh until 2040 and then suddenly drop to 23.42 TWh until 2050 as shown in Fig. 10**(b)**. President of Mexico has shown enthusiasm for coal, aiming to reactivate coal-fired plants to support the local economy and mining industry, despite concerns about the environmental impact and climate change implications of coal usage.

Coal energy in New Zealand contributes to about 7 % of the country's total energy supply, with coal being used for various purposes such as steel manufacturing, electricity generation, and industrial processes. New Zealand's coal reserves are mainly located in regions like Waikato, Taranaki, West Coast, Otago, and Southland, covering a wide range of coal ranks, although lignite dominates the inventory. The coal energy contributes to only 0.25 TWh in 2023 which then become zero in 2024 as shown in Fig. 11**(a)**. The country's coal market is complex, with a declining trend in coal usage for electricity generation but continued demand from industries and smaller users like hotels, schools, and hospitals. Coal energy in Non-OECD countries has been a focal point of energy policy discussions, with significant financial commitments made towards coal projects. Hence the contribution of coal in total energy mix will be increased from 8491.66 TWh in 2023 to 12650.33 TWh until 2040 and 15,256 TWh until 2050 in Non-OECD countries as shown in Fig. 11**(a)**. Moreover, there has been a noticeable shift away from new coal projects in Non-OECD countries, with a substantial decline in the coal power plant pipeline. In OECD countries, coal phase out is possible until 2036 but until 2035 coal will contributes to 99.20 TWh. In 2023 the contribution of coal is much greater around 2053.89 TWh in OECD as shown in Fig. 11**(a)**. Coal energy in North America remains a significant part of the energy landscape, with coal being extensively used for power generation and heavy industry due to its availability and low cost. The phase out of coal is possible in North America in 2032 but until 2031 it will contributes to 115.61 TWh but at initial stage of 2023 it contributes to 745.33 TWh as shown in Fig. 11**(a)**. The coal supply in North America includes both domestic production and imports, with different types or ranks of coal being utilized for various purposes such as steel making and electricity generation.

Pakistan produced 33.29 million tons of coal every year, with a notable portion being thermal coal used for electricity generation. The energy forecasted from coal contributes to 15.90 TWh in 2023 which will increase to 42.25 TWh until 2040 and 79.31 TWh until 2050 as shown in Fig. 11**(b)**. The Philippines also utilizes coal for energy production, with the country's coal consumption reaching 22.37 billion cubic feet in recent years. The energy forecasted from coal in Philippines contributes to 53.73 TWh in 2023 which will increase to 80.12 TWh until 2040 and 102.06 TWh until 2050 as shown in Fig. 11**(b)**. Russia is a major player in the global coal market, producing 435.3 million tons of coal every year after 2021. The country's vast coal reserves and production capacity, position it as one of the leading coal producers globally, supporting both domestic consumption and exports. The energy forecasted from coal contributes to 187.13 TWh in 2023 which will increase to 204.81 TWh until 2040 and 224.30 TWh until 2050 as shown in Fig. 11**(b)**. Romania has a history of coal production, with the country producing 17.7 million tons of coal in each year after 2021. Coal mining in Romania supports various industries and contributes to the country's energy needs, although there have been efforts to transition towards cleaner energy sources in line with global trends. Hence, the share of coal energy will become decreasing from 12.40 TWh in 2023 to 7.29 TWh until 2040 and 3.73 TWh until 2050 as shown in Fig. 11**(b)**.

Coal is a vital energy source for South Korea, with coal being the second-largest energy source after oil, accounting for 44.1 % of the country's electricity generation. Fig. 12**(a)** shows that coal contribution in total energy mix will be increased from 203.93 TWh in 2023 to 280.33 TWh until 2040 and 330.27 TWh until 2050. On the other hand, in South



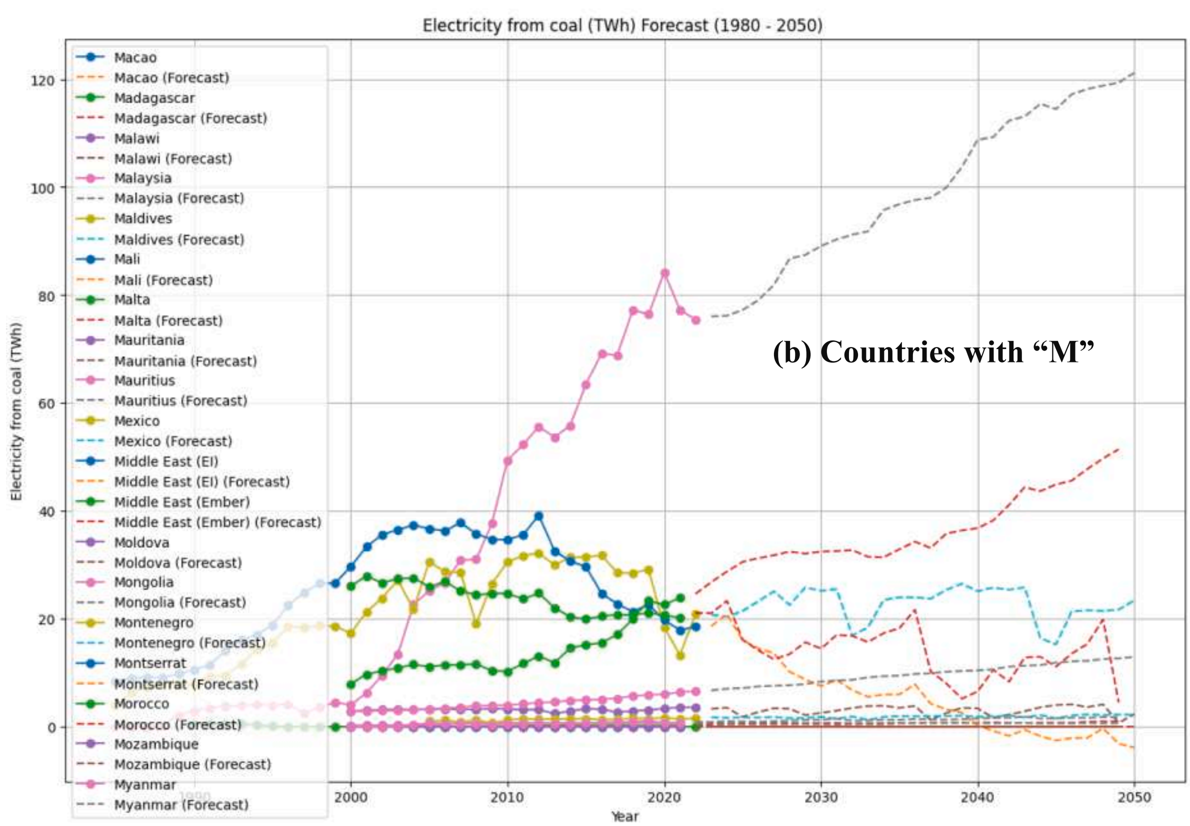


Fig. 10. (a,b): Electricity from coal for countries starting with alphabet "L" and "M".

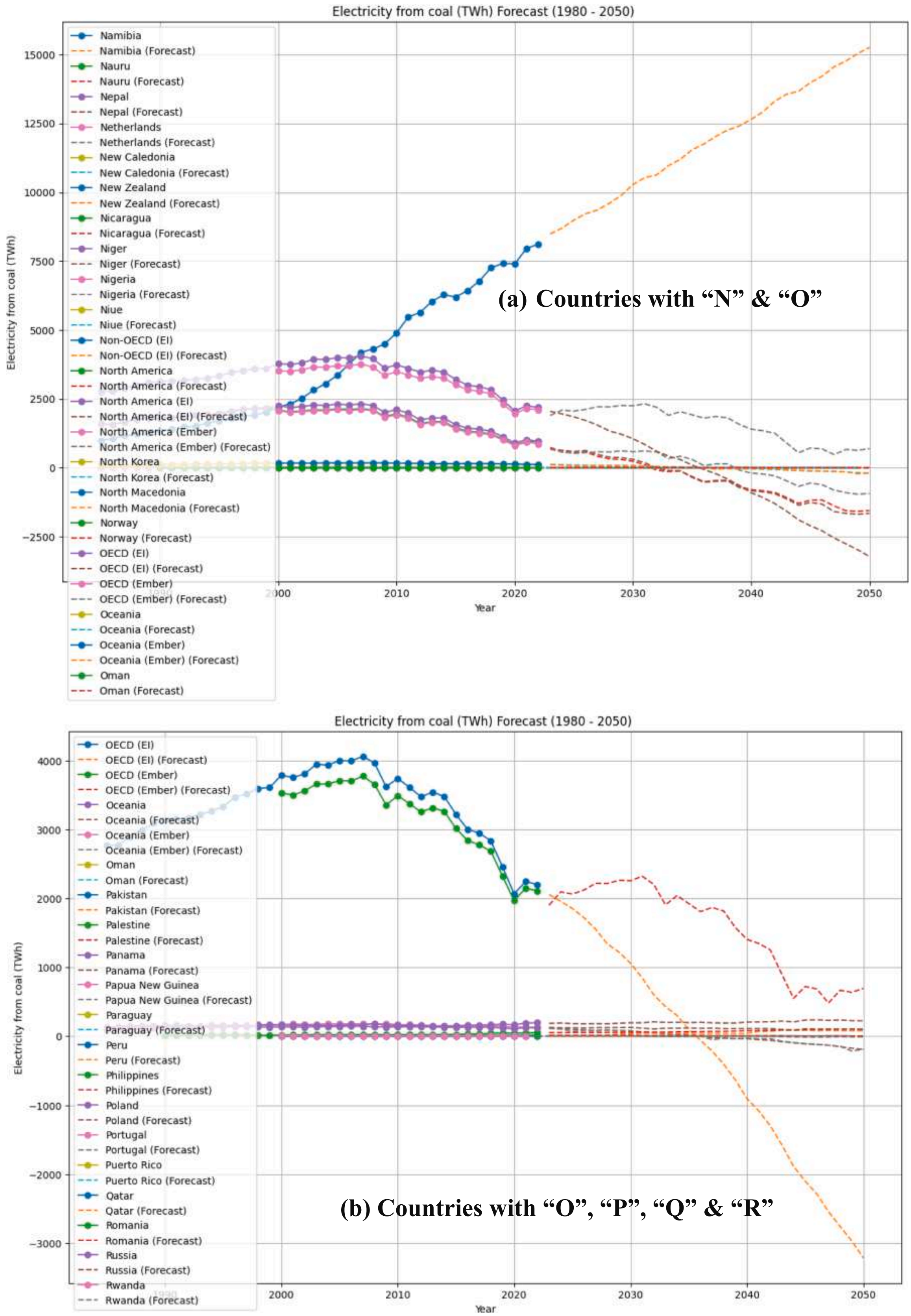


Fig. 11. (a,b): Electricity from coal for countries starting with alphabet "N" to "R".

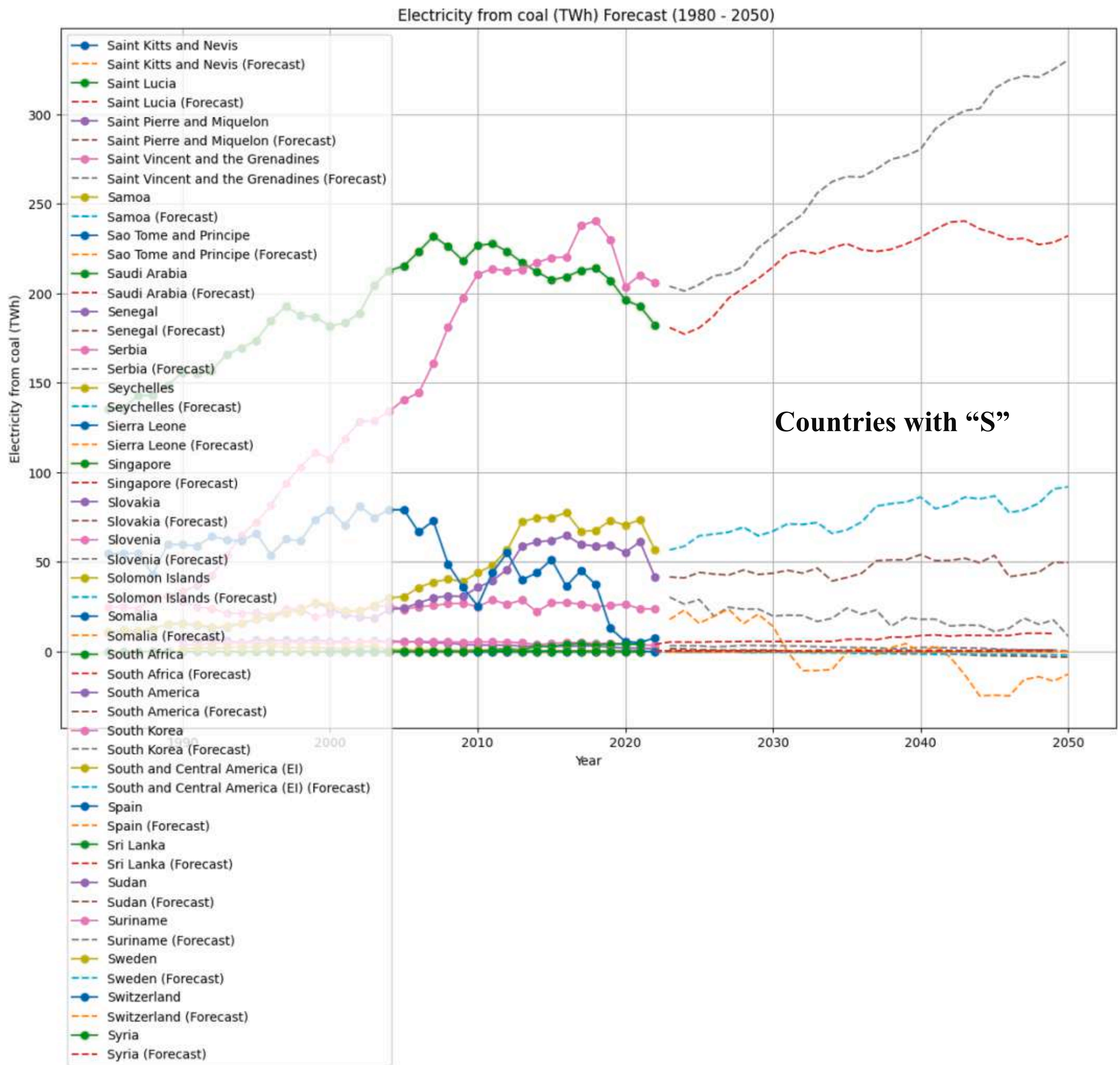


Fig. 12. Electricity from coal for countries starting with alphabet "S".

America, the use of coal for energy varies across countries. Fig. 12**(a)** shows that coal contribution in total energy mix will be increased from 41.53 TWh in 2023 to 54.03 TWh until 2040 and then suddenly drops to 49.64 TWh until 2050. However, the overall contribution of coal in the energy mix of South America is relatively lower compared to other regions like Asia and Europe. Coal stands out as the primary energy source in South Africa, responsible for a substantial portion of electricity production and overall energy supply. Fig. 12**(a)** shows that coal contribution is continuously increasing from 180.80 TWh in 2023 to 231.12 TWh until 2040 then it will remain flat until 2050 with some more or less energy contribution. In South and Central America, the energy mix is diverse, however, the contribution of coal in 2023 is 56.65 TWh which will increase to 86.18 TWh until 2040 and 91.88 TWh until 2050 as shown in Fig. 12**(b)**. The region is leading the global energy movement, with a strong focus on renewable energy sources like hydropower, solar, and wind.

Coal power has fluctuated in Thailand around 20 % over the last decade, with about 6 GW of coal power capacity in operation as of 2021. The country aims to reduce its dependence on coal by promoting renewable energies like wind and solar, which currently contributes to only 4 % to its electricity generation. Fig. 13**(a)** represent that coal energy will be increased from 38.60 TWh in 2023 to 55.92 TWh until 2040 and 64.40 TWh until 2050. The Turkey's coal-fired power stations, totaling 54 with a capacity of 21 GW, played a crucial role in generating about a third of Turkey's electricity. Despite European efforts to decarbonize, Turkey has doubled down on coal, evident from its substantial expenditure of $3.7 billion on imported coal for electricity generation in 2023. Turkey's coal reserves, which consist mainly of subbituminous and lignite, were estimated to be around 13 billion tons as of 2023, indicating a substantial domestic resource base for coal-fired electricity generation. It is forecasted that energy from coal in Turkey will increase from 117.04 TWh in 2023 to 173.12 TWh until 2040 and

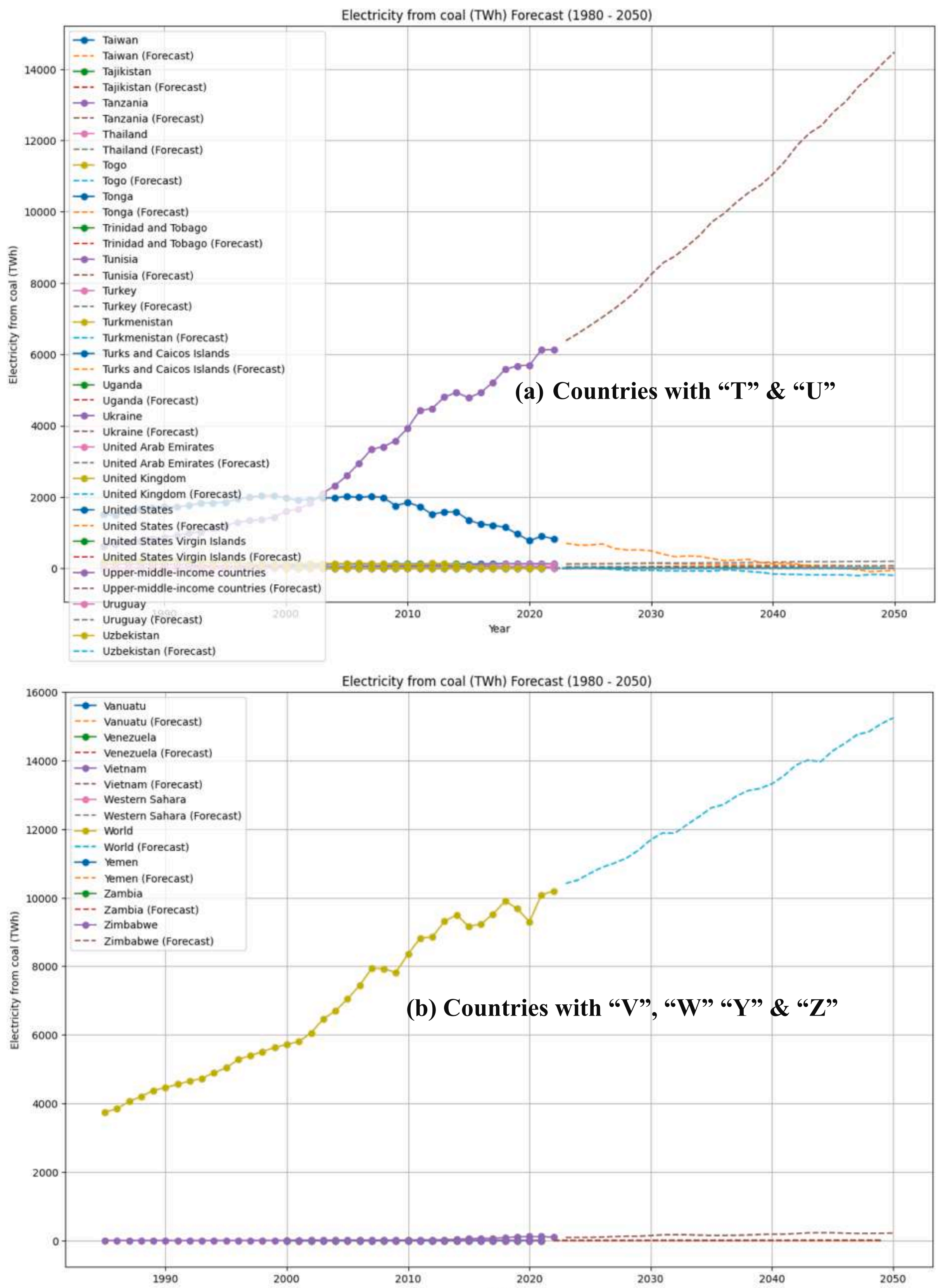


Fig. 13. (a,b): Electricity from coal for countries starting with alphabet “T” to “Z”.

198.99 TWh until 2050 as shown in Fig. 13**(a)**. The United States' continues to rely on coal for electricity generation, there are ongoing discussions and efforts to repurpose, retrofit, or retire coal plants to address emissions and work towards net-zero goals. Hence, coal energy production will decrease from 694.69 TWh in 2023 to 54.80 TWh until 2040 and then to 37.49 TWh until 2042. After 2042 coal will be phase out from the U.S as shown in Fig. 13**(a)**.

In 2023, Vietnam faced a critical juncture in its energy transition, particularly concerning coal. In Vietnam coal thermal power accounting for nearly half of the total power output in 2023. Therefore, the coal energy share is continuously increasing from 88.58 TWh in 2023 to 184.49 TWh until 2040 and 219.04 TWh until 2050 as shown in Fig. 13 **(b)**. However, the challenges of financing a rapid coal phase-out and ensuring effective governance to facilitate this transition remain significant hurdles for Vietnam. The world demand for coal energy is expected to remain high, with global coal use reaching higher record levels in 2023. Despite declining consumption in the United States and Europe, demand growth in China, India, and other Asian countries is outpacing these reductions. IEA forecasts that global coal use will surpass 8.5 billion metric tons in 2023. It is forecasted that coal will always increase globally with major contribution of 13316.57 TWh until 2040 and 15243.36 TWh until 2050 which was bit low around 10415.49 TWh in 2023 as shown in Fig. 13**(b)**. The IEA also highlights that coal consumption may be decline until 2026, if expansion of renewable energy capacity playing a role in lowering coal usage. However, to meet the goals set by the Paris Agreement, a faster reduction in the use of unabated coal is necessary.

3.4. Carbon emissions from coal and coal phase-out targets

Africa's per capita emissions are the lowest among all continents, with an average of 1 tone of CO_2 emitted annually per individual, highlighting the continent's minimal contribution to global carbon emissions compared to other regions. African carbon emissions from coal will be increased from 4307 billion metric tons in 2023 to 4740 billion metric tons until 2040 and 4954 billion metric tons until 2050 as shown in Fig. 14**(a)**. On the other hand the Asia-Pacific region, particularly China and India, heavily relies on coal for energy, contributing significantly to global carbon emissions. Fig. 14**(a)** shows that carbon emissions in Asia will be increased from 124,721 billion metric tons in 2023 to 160,540 billion metric tons until 2040 and 180,795 billion metric tons until 2050. Bangladesh's carbon emissions from coal are relatively low compared to other Asian countries. Carbon emissions are increasing from 146 million metric tons in 2023 to 261 million metric tons until 2040 and 344 million metric tons until 2050 as shown in Fig. 14**(b)**. In Brazil, coal is a significant contributor to energy generation capacity after hydropower. Brazil's carbon emissions will be increased from 704 million metric tons in 2023 to 905 million metric tons until 2040 and 1026 million metric tons until 2050 as shown in Fig. 14**(b)**.

Chile's energy sector accounts for three-quarters of total emissions, with coal being a significant contributor to electricity generation alongside diesel. Chile country has committed to carbon neutrality by 2050 and plans to shut down all coal-fired power plants by 2040. Therefore, the forecasted carbon emissions from coal will be slightly increased from 266 billion metric tons in 2023 to 336 billion metric tons until 2040 and then it will increase to 358 billion metric tons until 2050 as shown in Fig. 15**(a)**. China, as the largest emitter of carbon emissions globally, heavily relies on coal for energy generation, with coal accounting for 79 % of total carbon emissions from fuel combustion in 2021. Furthermore, in 2023, carbon emissions remain at 88,501 billion metric tons which will be increased to 103,924 billion metric tons until 2040 and 117,138 billion metric tons until 2050 as shown in Fig. 15**(a)**. Egypt's carbon emissions from coal are a significant concern, with the country ranking 27th globally in terms of energy-related carbon emissions. The forecasted carbon emissions from coal will contributes to global warming upto 20,157 million metric tons until 2050 which was only 6900 million metric tons in 2023 as shown in Fig. 15**(b)**. European carbon emissions from coal have significantly decreased in recent years and in future it will also decrease to 878 billion metric tons until 2040 and 505 billion metric tons until 2050 but initially in 2023 it was too high around 1308 billion metric tons as shown in Fig. 15**(b)**.

France and Germany have distinct approaches to coal emissions. France, with its significant reliance on nuclear power, emits far less carbon emissions around 3160 million metric tons in 2023 which will further reduces to 2275 million metric tons until 2040 and 1032 million metric tons until 2050 from coal as shown in Fig. 16**(a)**. Germany produces greater carbon emissions from coal around 24,961 million metric tons in 2023 which will increase to 19,851 million metric tons until 2040 and finally, it will reduce to 13,640 million metric tons until 2050 as shown in Fig. 16**(a)**. Japan and India have contrasting approaches to coal emissions as shown in Fig. 16**(b)** because both countries plans to add more coal based power plants in future. The coal emissions will increase from 432 billion metric tons in 2023 to 500 billion metric tons until 2040 and 527 billion metric tons until 2050 in Japan and In India, the emissions from coal will increase to much higher level around 3473 billion metric tons until 2040 and 4564 billion metric tons until 2050 which was only 1931 billion metric tons in 2023.

In low income countries the carbon emissions will slightly increase to 65 billion metric tons until 2040 from 58 billion metric tons in 2023 which then in 2050 it becomes constant to 64 billion metric tons as shown in Fig. 17**(a)**. In Malaysia, coal emissions will increase until 2040 around 17,350 million metric tons which was only 8824 million metric tons in 2023. After 2040, carbon emissions will start decreasing to 2101 million metric tons until 2050 as shown in Fig. 17**(b)**. The country Netherland has been taking steps to reduce its reliance on coal and transition towards cleaner energy sources. Hence their forecasted carbon emissions are 23,270 million metric tons in 2023, and then slight increment will be noticed until 2040 to 33,326 million metric tons which will then reduce to 21,651 million metric tons until 2050 as shown in Fig. 18**(a)**. The forecasted carbon emissions from coal for Pakistan, Philippines, Poland and Russia are shown in Fig. 18**(b)**. Pakistan will contribute to more around 7906 million metric tons until 2040 and 12,579 million metric tons 2050 which was only 6261 million metric tons in 2023. Philippines will also contribute to more around 17,745 million metric tons until 2040, 24,913 million metric tons until 2050 which was only 7869 million metric tons in 2023. In Poland and Russia, slight decrement will be noticed after 2023. Poland produced carbon emissions from coal around 18,453 million metric tons in 2023 than it will reduce to 17,598 million metric tons until 2040 and 14,143 million metric tons until 2050. Russia produced carbon emissions from coal around 38,991 million metric tons in 2023 than it will reduce to 35,898 million metric tons until 2040 and 31,243 million metric tons until 2050. Fig. 19 represented that South Africa and South Korea have significant coal emissions, with South Korea being one of the top coal polluters among G20 member states, along with Australia. South Africa will produce 38,279 million metric tons until 2040 which will remains flat until 2050 and was only 36,951 million metric tons in 2023. South Korean coal will produce 42,144 million metric tons of carbon emissions until 2040 and 46,600 million metric tons until 2050 which was only 33,712 million metric tons in 2023.

Future carbon emissions from coal are also forecasted for Taiwan, Thailand, and upper middle income countries as shown in Fig. 20**(a)**. Taiwan will contribute to more around 2392 billion metric tons until 2040 and 2704 billion metric tons until 2050 which was only 1653 billion metric tons in 2023. Thailand has bit lower values then Taiwan, but it will contributes to global warming until 2050. 993 billion metric tons and 1165 billion metric tons of carbon emissions will be produced until 2040 and 2050 which was only to 723 billion metric tons in 2023. In upper middle income countries, coal exploitation for electricity generation is much greater than any continent of the world. Upper middle income countries will produce carbon emissions of capacity

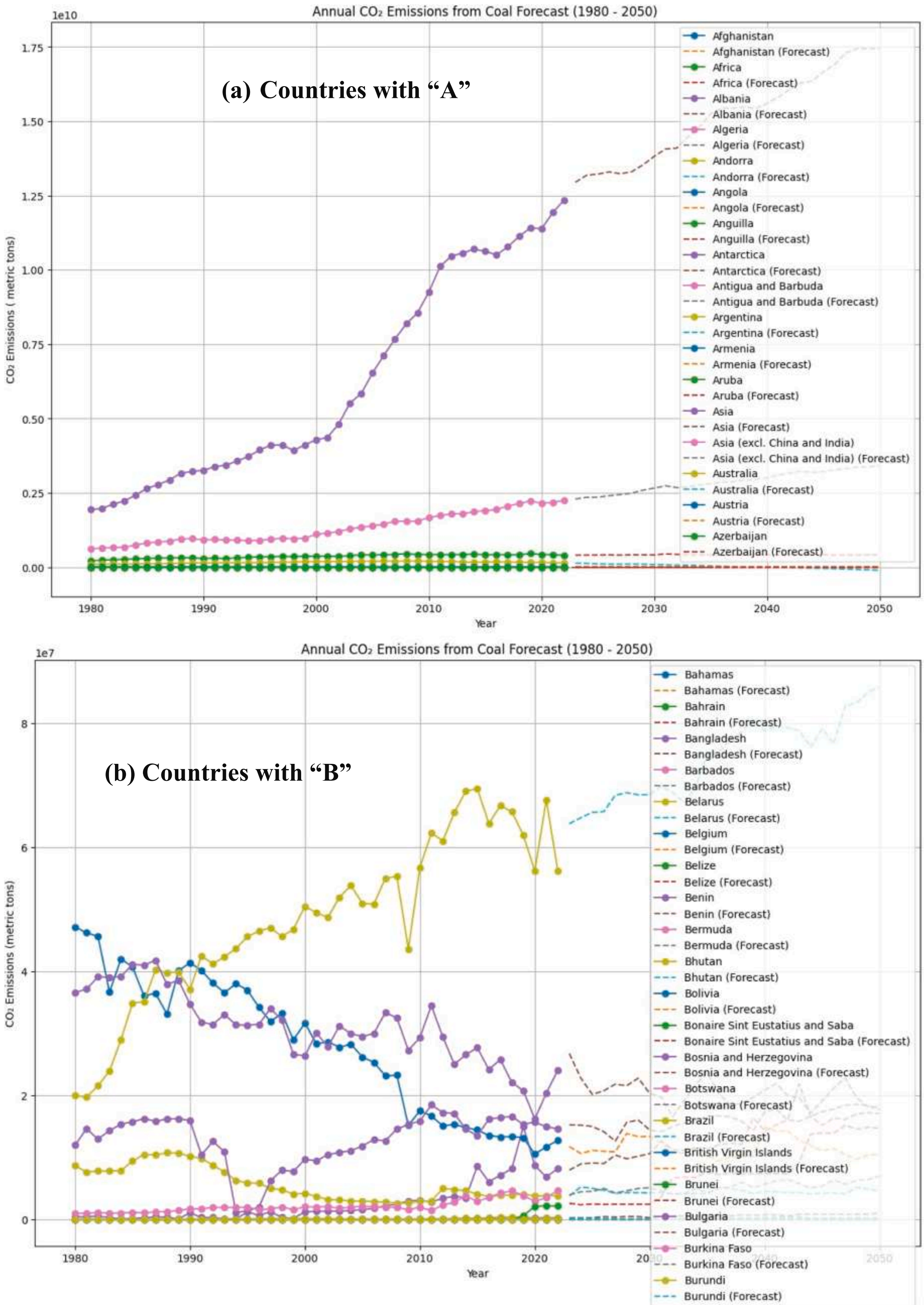


Fig. 14. (a,b): Carbon emissions from coal for countries starting with alphabet "A" and "B".

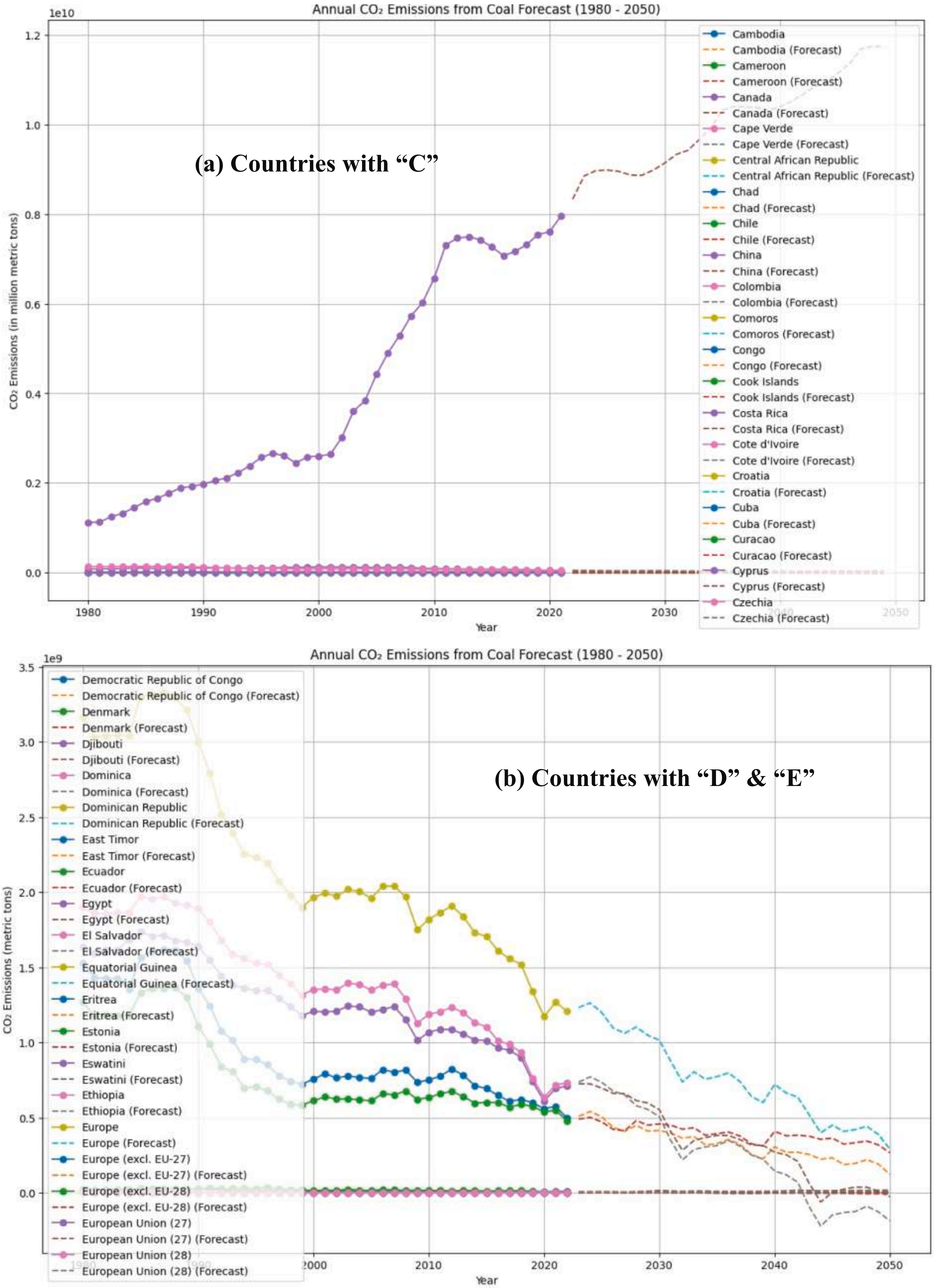


Fig. 15. (a,b): Carbon emissions from coal for countries starting with alphabet "C" to "E".

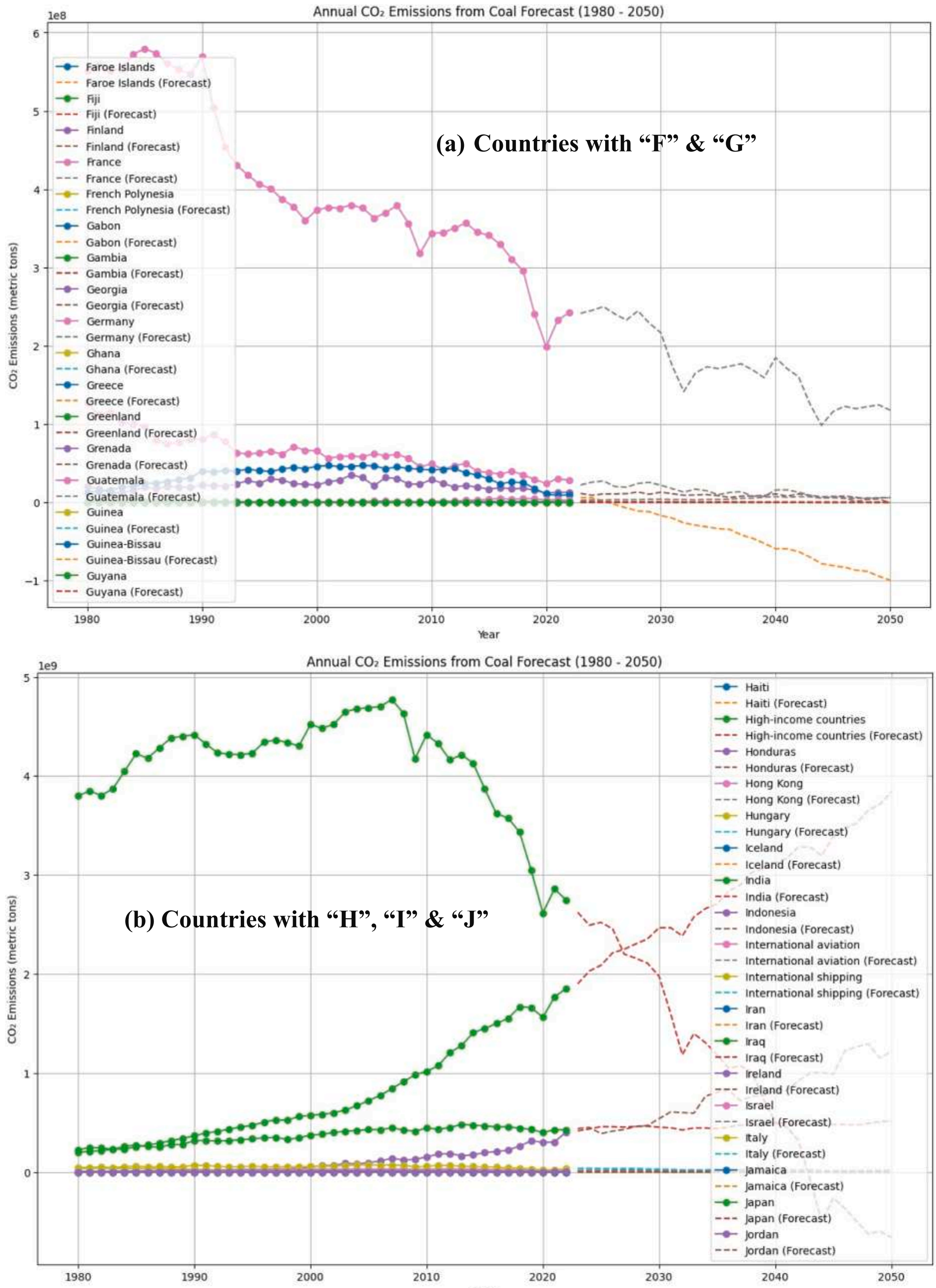


Fig. 16. (a,b): Carbon emissions from coal for countries starting with alphabet "F" to "J".

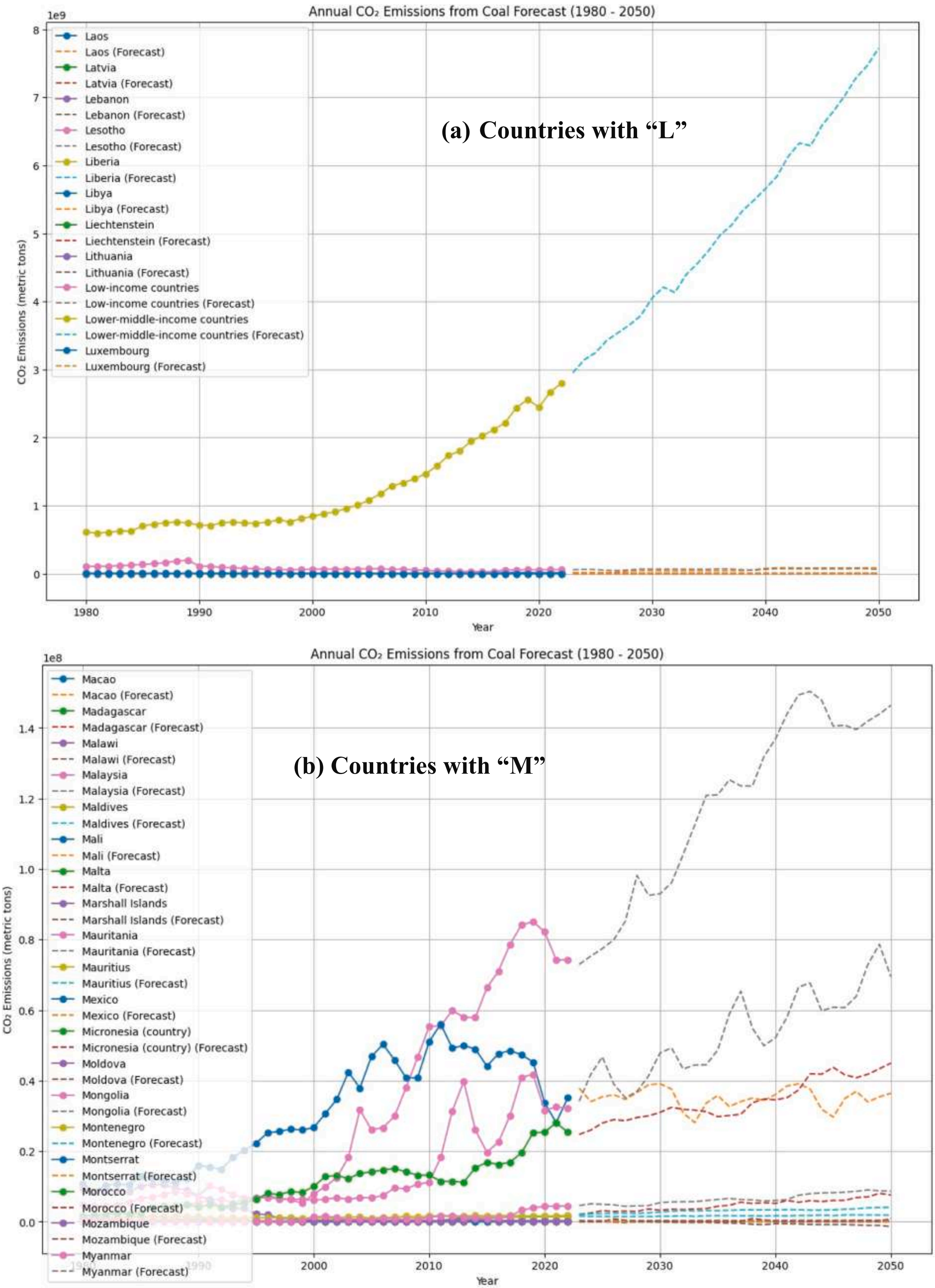


Fig. 17. (a,b): Carbon emissions from coal for countries starting with alphabet "L" and "M".

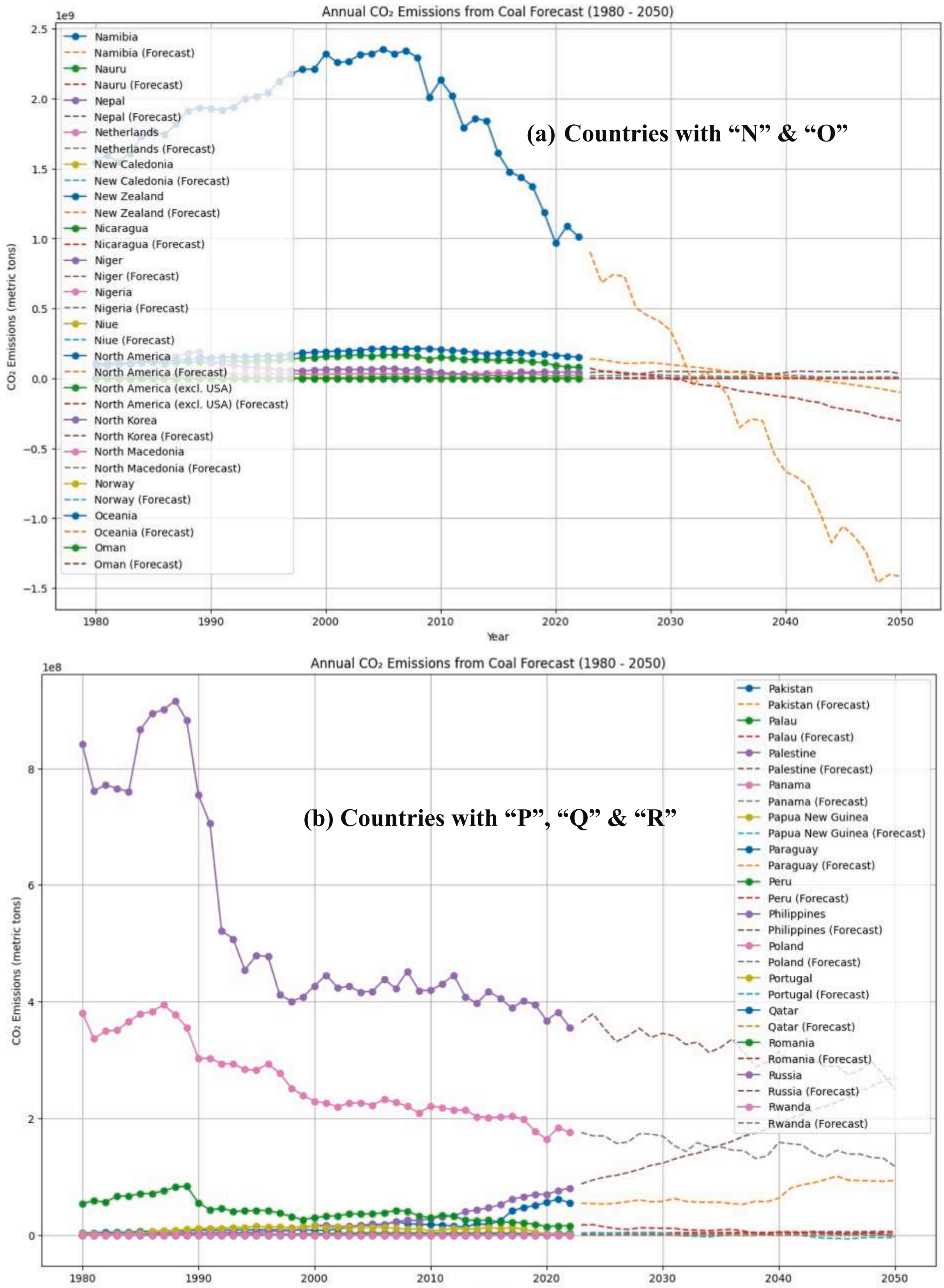


Fig. 18. (a,b): Carbon emissions from coal for countries starting with alphabet "N" to "R".

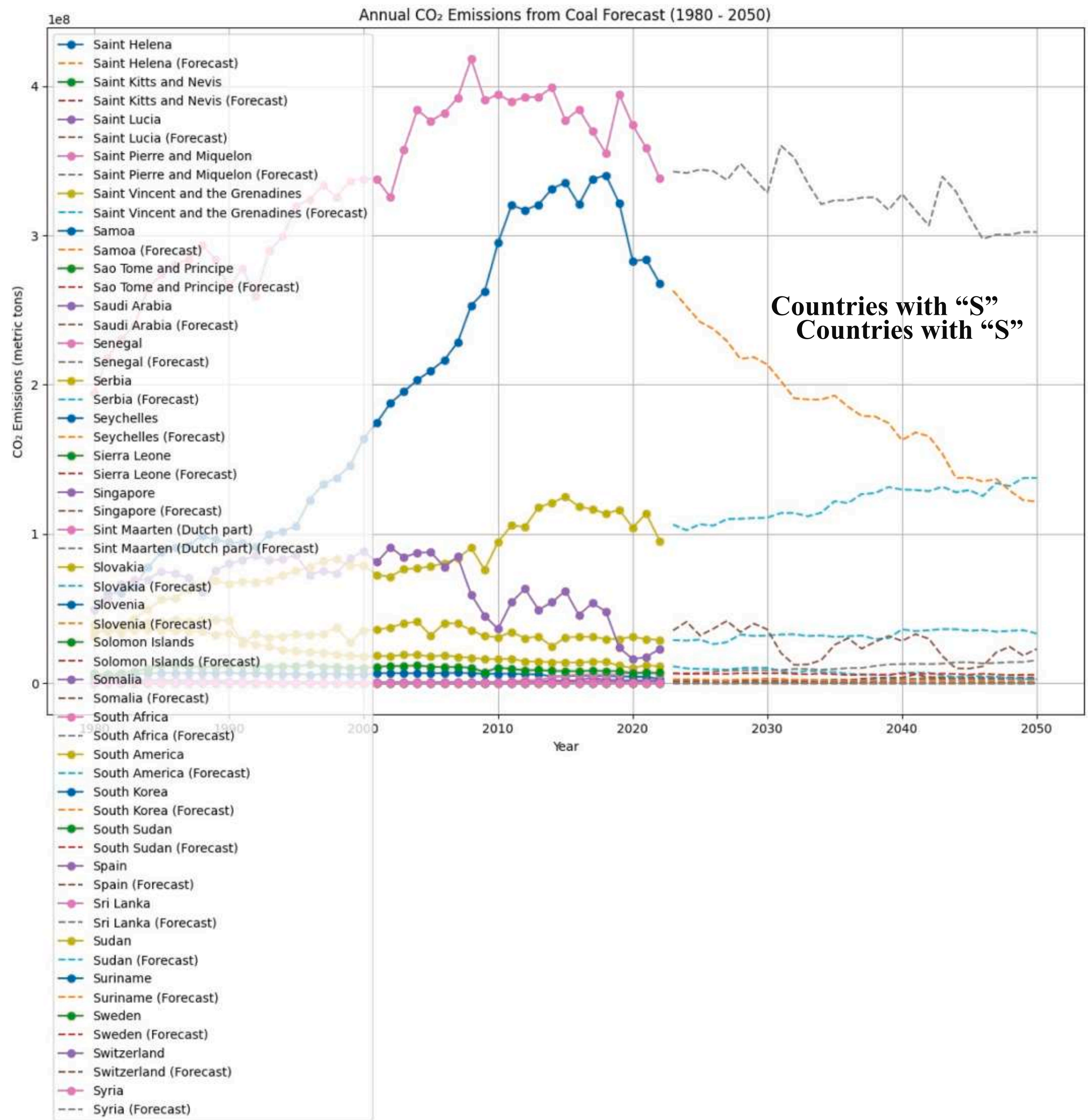
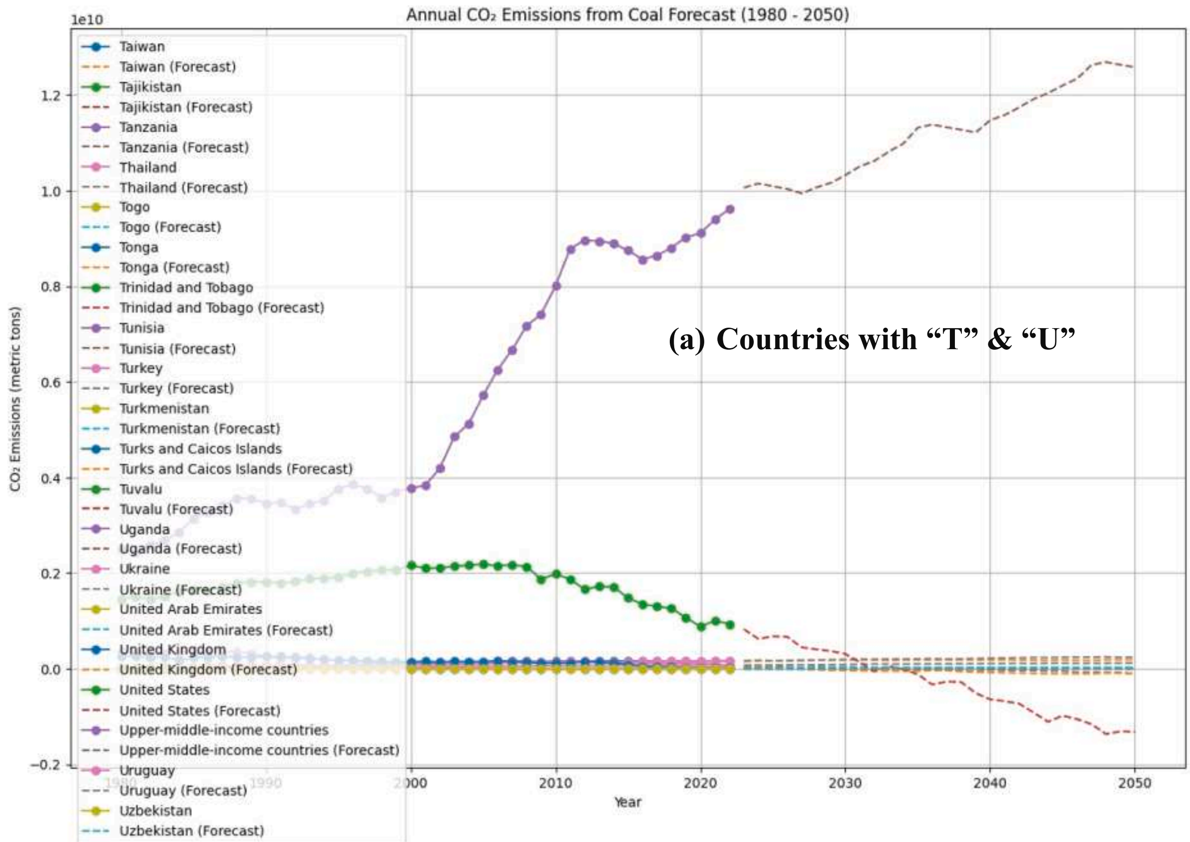


Fig. 19. Carbon emissions from coal for countries starting with alphabet "S".

118,346 billion metric tons until 2040 and 130,472 billion metric tons until 2050 which was only 97,307 billion metric tons in 2023. Fig. 20**(b)** represent that Vietnam will contribute to 2535 billion metric tons until 2040 and 3444 billion metric tons until 2050 which was only 1955 billion metric tons in 2023. Global coal emissions have been a significant contributor to the increase in global carbon emissions. In 2023, coal demand in emerging market and developing economies was a major driver of global emissions growth, with coal accounting for around 70 % of the increase in global emissions from energy combustion. This rise in coal emissions has been a concerning trend, with coal contributing the most to the increase in global carbon emissions in the post-pandemic era. The carbon emissions will produce from coal around 188,535 billion metric tons until 2040 and 215,077 billion metric tons until 2050 which was only 157,768 billion metric tons in 2023.

The global coal production trends suggest that despite the growth in coal output, there should be discussions and actions on coal phase-outs. The concept of coal phase-out refers to the gradual reduction and eventual elimination of coal production and usage due to environmental concerns, climate change mitigation efforts, and the transition to cleaner energy sources. While coal remains a significant energy source globally, the push for reducing carbon emissions and transitioning to cleaner alternatives has led to discussions and policies aimed at phasing out coal. Fig. 21**(a,b,c)** represented the coal free countries until 2021 while the future coal phase-out targets are shown in Fig. 22**(a,b,c).**



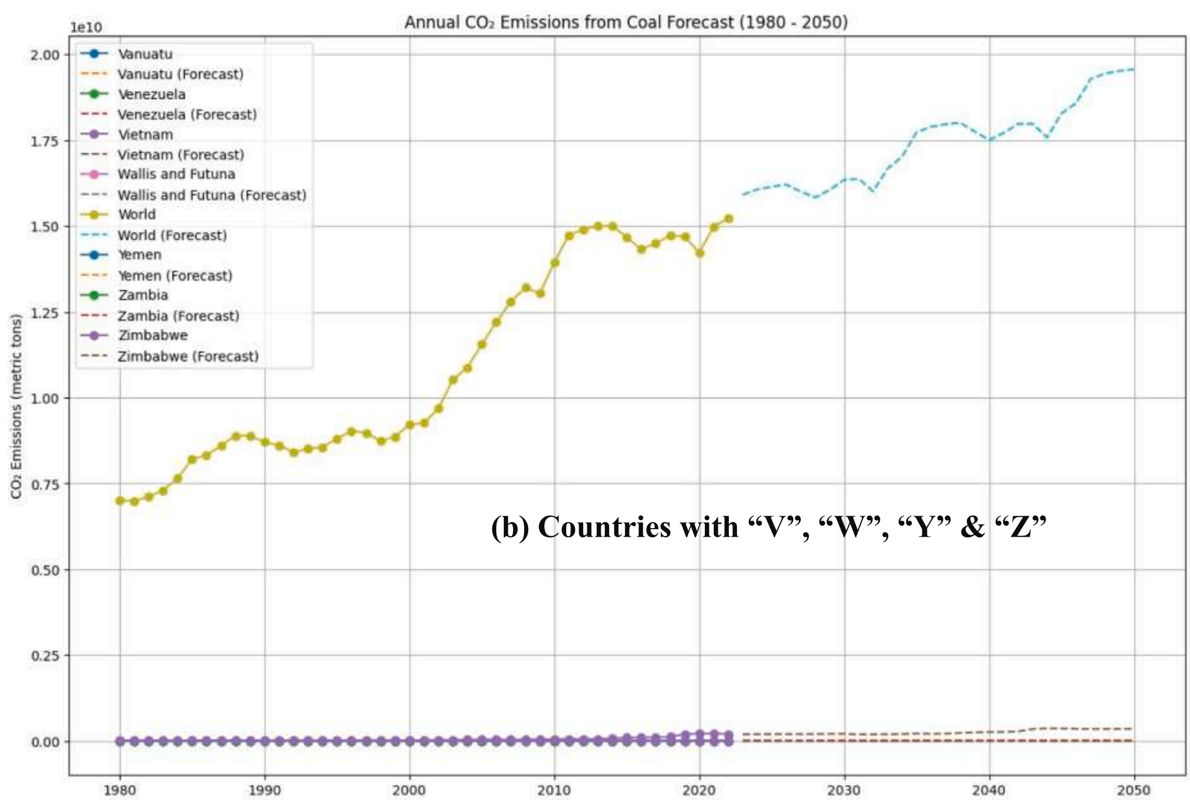


Fig. 20. (a,b): Carbon emissions from coal for countries starting with alphabet "T" to "Z".

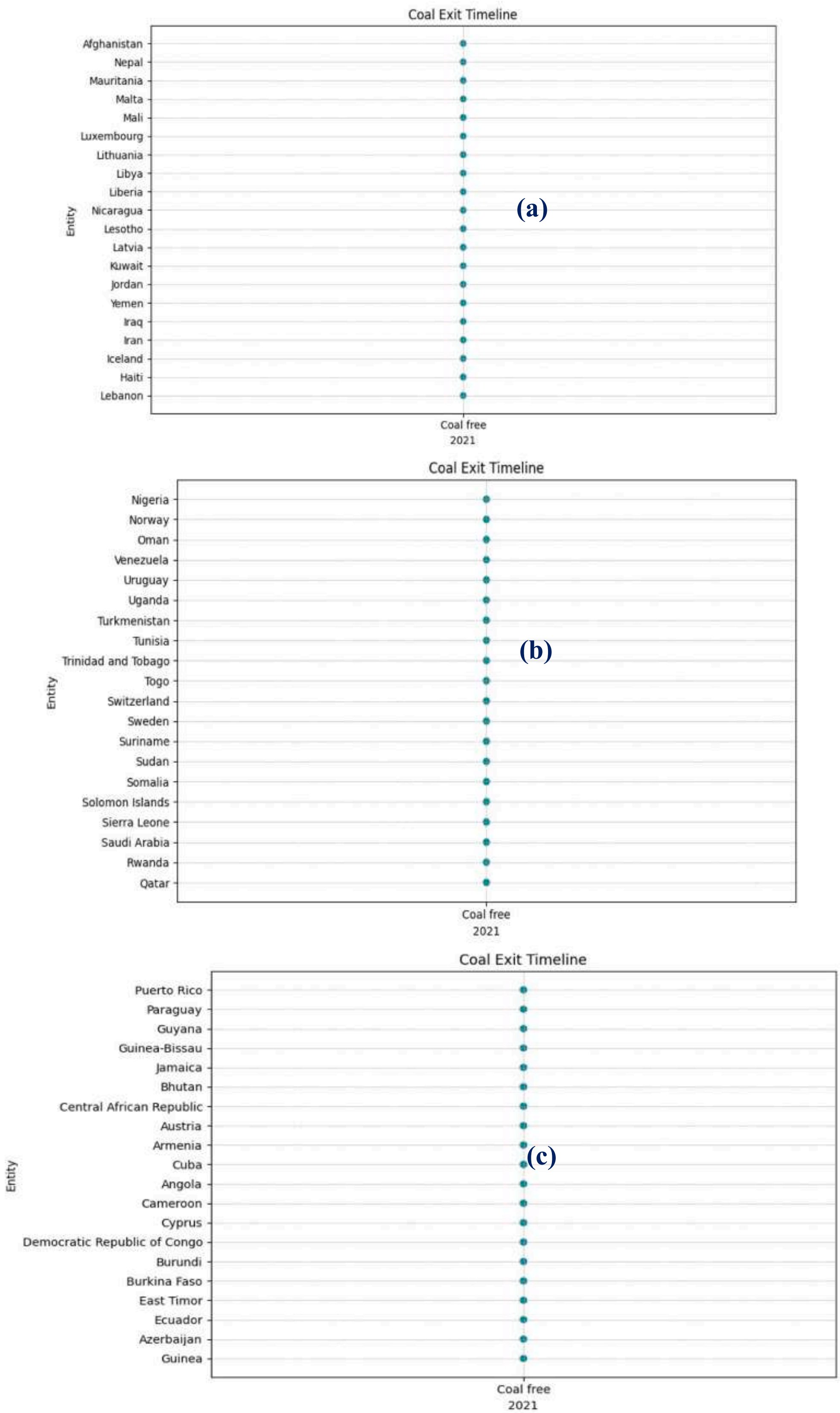


Fig. 21. (a,b,c): Coal free countries until 2021.

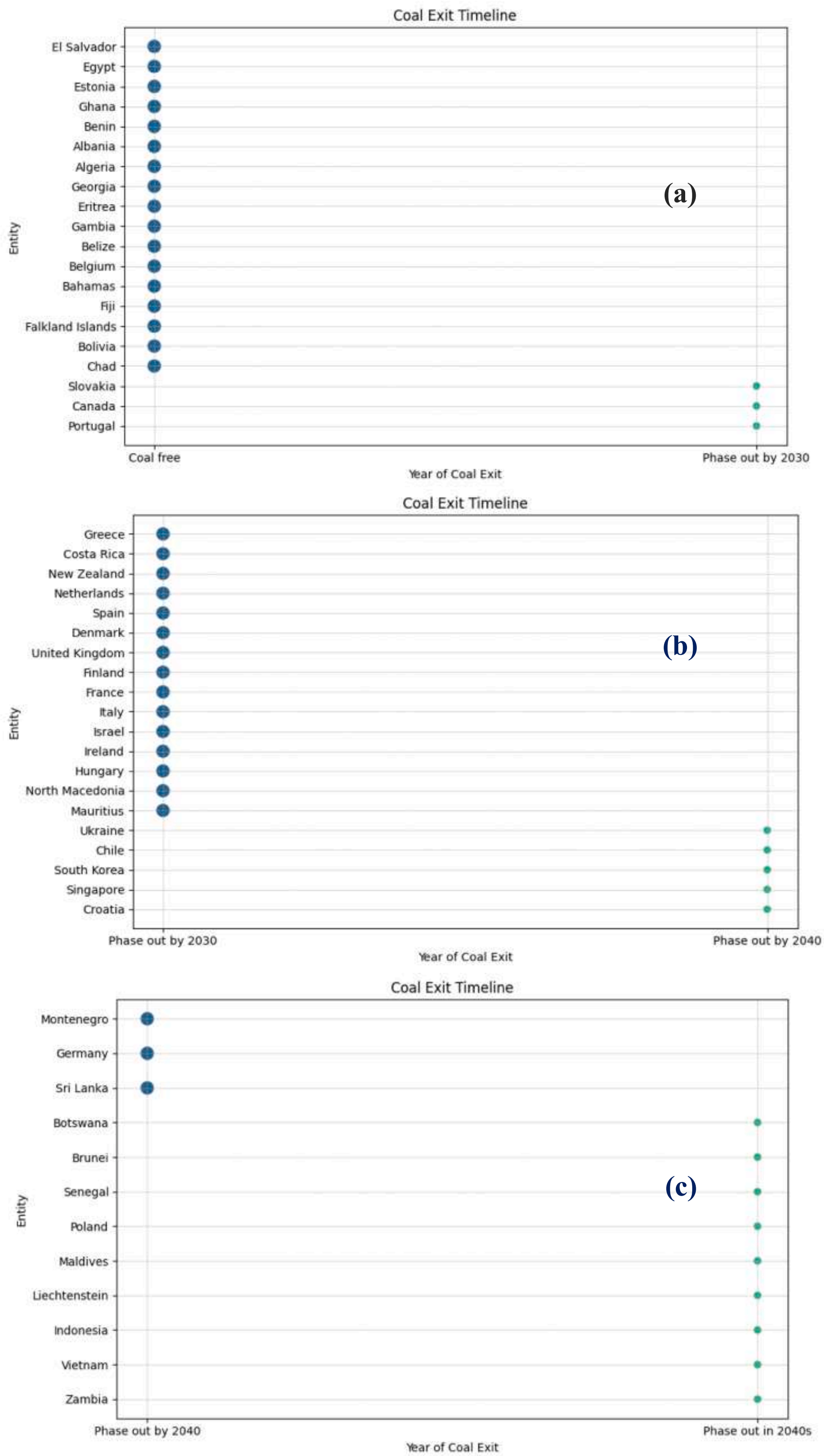


Fig. 22. (a,b,c): Future targets of coal phase out until 2030 and 2040.

To phase out coal from global energy mix for reducing the global mean temperature to 1.5 ^{0}C is need of the time. This task is very difficult to perform in low income countries due to their high dependence and also crucial for maintaining the economy of the nation. However, IPCC suggested the path to phase out coal about 70 % by 2030 and 100 % by 2040 for limiting global mean temperature to 1.5 ^{0}C, hence our study achieved the IPCC target and achieved the clean coal transition suitably. Table 1 summarizes the global studies on achieving the clean coal transition and comparison is presented with the proposed study as per IPCC requirement.

4. Conclusion, policy Recommendations, study limitations and future research directions

This research forecasted the future of coal reserves, coal prices, electricity from coal, carbon emissions and coal phase-out targets globally using the SARIMAX Python® model for the study period 2023 to 2050 by using the input data from the year 1980 to 2022. It is found that, the global coal reserve capacity is 1.07 trillion tons with an average coal prices vary with region to region, ranging from US $130 per tone to US $206 per tone until 2050. The global production of electricity from coal will also increase from 10415.49 TWh in 2023 to 13316.57 TWh until 2040 and 15243.36 TWh until 2050 which ultimately enhances the production of carbon emissions, increases from 157,768 billion metric tons in 2023 to 188,535 billion metric tons until 2040 and 215,077 billion metric tons until 2050. The recent data on coal production, electricity generation, emissions, and the impact on the environment indicate several key conclusions:

- Coal production has faced challenges in recent years due to decreasing global demand, competition from natural gas, and disruptions in the supply chain. Despite a temporary rise in demand in 2021, coal production struggled to return to pre-pandemic levels due to labor shortages, logistical issues, and slow investment in new mines.
- The electricity sector has witnessed a shift away from coal-fired generation towards natural gas and zero-carbon sources. Between 2023 and 2050, a significant decline in coal-fired generation capacity while natural gas-fired capacity increased, and zero-carbon generation also grew, reaching a 60 % share of the total generation mix after 2040.
- Coal related emissions decreased by 7 % in 2022, primarily due to a decline in coal-fired power generation resulting from retiring coal-fired capacity. This reduction in coal emissions is part of a longer-term trend, with coal emissions having fallen by 57 % from their peak in 2005. Despite this decline, overall energy-related carbon emissions increased slightly between 2023 and 2050 in some countries, driven by other sectors like transportation and residential/commercial sectors.

The following are the policy implications for transitioning to clean coal technologies:

- The greater use of coal for power generation enhances the production of carbon emissions which leads to acidic rain and air pollution. The transition towards renewable energy sources is vital for long-term sustainability, but clean coal efficient technologies like CFBC-CCS, IGCC-CCS, SCPC-CCS and USCPC-CCS may play a transitional role in regions heavily reliant on coal until and unless the coal will phase out. The integration of clean coal efficient technologies for power generation will be crucial for meeting IPCC 1.5 0C climate targets and reducing the environmental impact of coal usage globally.
- The global coal reserve capacity is 1.07 trillion tons with an average coal prices vary with region to region, ranging from US $130 per tone to US $206 per tone until 2050. The global production of electricity from coal will also increase from 10415.49 TWh in 2023 to 13316.57 TWh until 2040 and 15243.36 TWh until 2050. Such huge clean energy generation would help to stabilize the global economies.
- United States have highest coal reserves globally with estimated capacity of 250.2 billion tonnes, followed by Russaia 176.8 billion tonnes, Australia 159.6 billion tonnes, China 138.8 billion tonnes and India 101.3 billion tonnes. Coal prices are high in Australia with $140/ton followed by Europe $122/ton, South Africa $116/ton and China $120/ton. In 2023, coal accounted for approximately 35.5 % of global electricity generation, maintaining its position as the largest single source of power despite being the most carbon-intensive fossil fuel. This share has remained relatively stable, with coal supplying just over a third of global electricity. While 21.1 GW of coal capacity was retired globally in 2023, this was offset by the commissioning of 69.5 GW, resulting in a net gain. Notably, retirements have slowed significantly, with 2023 seeing the least amount of coal capacity retired in over a decade. China as the largest consumer of coal, China's emissions are expected to decline due to increased hydropower generation and a significant expansion of wind and solar energy. Following a substantial decline in 2023, coal demand is projected to decrease in European Union by 19 % in 2024, primarily driven by the continued expansion of renewable energy sources.
- This study undertakes and presented the country wise examination of coal phase out and it is found that in many countries 70 % of coal will phase out by 2030 and 100 % by 2040 for meeting the IPCC 1.5 0C targets. However, the coal energy can be exploited until 2050 and beyond due to greater global indigenous coal reserves.
- The implementation of this study stabilizes economy, eliminates poverty, and reduces CO2 emissions and health related problems.

The study limitations are listed below:

- Specific advancements in USCPC-CCS coal-fired boilers are being explored, including dust handling systems and optimization techniques using artificial intelligence to enhance efficiency and reduce emissions.
- Artificial intelligence can optimize the combustion process in real-time by adjusting critical parameters such as the air–fuel ratio and fuel injection timing. This dynamic adjustment helps to maximize energy output while minimizing emissions, leading to improved overall combustion efficiency.
- Advanced artificial intelligence techniques, such as reinforcement learning, are being developed to create sophisticated control strategies for thermal power generating units.
- Artificial intelligence predicts maintenance needs in coal combustion systems primarily through the analysis of operational data collected from various sensors and equipment.

The future research directions are listed below:

- Develop some flexible laws and regulations for financial incentives to promote clean coal technology adoption.
- Develop artificial intelligence based system that can drive down costs by improving the performance of clean coal technologies.
- Develop solution for each country to eliminate the use of coal while affecting the economy and energy security of the nation.
- Future coal use will likely involve a hybrid approach, integrating coal with renewable energy sources. This includes exploring co-firing with biomass or ammonia to lower carbon emissions while maintaining energy reliability.

CRediT authorship contribution statement

Muhammad Amir Raza: Visualization, Validation, Methodology, Funding acquisition. **Abdul Karim:** Writing – review & editing, Writing

Table 1
Comparative analysis of clean coal transition studies as per IPCC requirement.

Study	Study Purpose	Method	Novelty		
			Study comparison with IPCC targets	*Economic parameters consideration	Assessment performed on all global countries
(Minx et al., 2024)	Some scenarios are focused on rapid coal phase out and some suggested very slow coal phase out at regional level.	Clustering techniques	Not achieved IPCC target of 70 % coal phase out by 2030 and 100 % coal phase out by 2050.	Not taken	No
(Achakulwisut et al., 2023)	Alleviation of fossil fuels from energy system of few countries.	Scenario analysis	Not achieved IPCC target of 70 % coal phase out by 2030 and 100 % coal phase out by 2050.	Not taken	No
(Muttitt et al., 2023)	Analyzed the coal power decline from China, India, and South Africa.	Integrated assessment model	Not achieved IPCC target of 70 % coal phase out by 2030 and 100 % coal phase out by 2050.	Not taken	No
(Raza et al., 2022)	Analysis performed on coal energy and their role in total energy mix.	Quantitative analysis	Not achieved IPCC target of 70 % coal phase out by 2030 and 100 % coal phase out by 2050.	Not taken	No
(Vinichenko et al., 2023)	Suggested the pathway to eliminate the coal from national energy system.	Empirical scenario analysis	Not achieved IPCC target of 70 % coal phase out by 2030 and 100 % coal phase out by 2050.	Not taken	No
(Mishra et al., 2015)	The role of CCS is discussed for limiting carbon emissions.	System dynamic revolution	Not achieved IPCC target of 70 % coal phase out by 2030 and 100 % coal phase out by 2050.	Not taken	No
(Wang et al., 2017)	This study promoted the use of renewables in global energy system and not considered coal.	Bibliometric analysis	Not achieved IPCC target of 70 % coal phase out by 2030 and 100 % coal phase out by 2050.	Not taken	No
(Patzek and Croft, 2010)	This study forecasted the peak of coal use in 2011 and further suggested the declination.	Multi-cycle Hubert analysis	Not achieved IPCC target of 70 % coal phase out by 2030 and 100 % coal phase out by 2050.	Not taken	No
(Raza et al., 2022)	This study promoted the use of renewables and fossil fuels.	LEAP	Not achieved IPCC target of 70 % coal phase out by 2030 and 100 % coal phase out by 2050.	Not taken	No
(Schiemann et al., 2022)	This study emphasizing the use of combustion technologies, bio-based fuels and carbon capture to decrease the carbon emissions.	Numerical method	Not achieved IPCC target of 70 % coal phase out by 2030 and 100 % coal phase out by 2050.	Not taken	No
(Ng et al., 2012)	CO_2 reuse and poly generation promoted at global scale.	ASPEN Plus	Not achieved IPCC target of 70 % coal phase out by 2030 and 100 % coal phase out by 2050.	Not taken	No
(Smoliński and Bąk, 2022)	This paper is focused on the use of clean coal technologies for emissions reduction.	Mathematical method	Not achieved IPCC target of 70 % coal phase out by 2030 and 100 % coal phase out by 2050.	Not taken	No
(Raza et al., 2022)	Focused on the use of fossil fuels for power generation.	MATLAB and LEAP	Not achieved IPCC target of 70 % coal phase out by 2030 and 100 % coal phase out by 2050.	Not taken	No
(Brown and Spiegel, 2019)	Emphasis to phase out coal from the regional or national energy mix.	Integrated assessment model	Not achieved IPCC target of 70 % coal phase out by 2030 and 100 % coal phase out by 2050.	Not taken	No
(Ordonez et al., 2024)	Focused on the regional partnership for coal phase out in high coal dependent countries.	Model based assessment	Not achieved IPCC target of 70 % coal phase out by 2030 and 100 % coal phase out by 2050.	Not taken	No
Our Proposed Work	Our proposed study considered all the individual countries around the globe and assessed their progress in terms of coal reserves, coal prices, electricity from coal, carbon emissions and coal phase out. Alongside, all the economic parameters are considered in the modelling of the study. Our suggested pathway helps the global energy system to achieve the IPCC climate change target on time.	SARIMAX Python® model	IPCC Targets achieved: 70 % coal phase out by 2030 and 100 % coal phase out by 2050.	All *economic parameters are considered during study modelling	Yes

* This study monitored the economic indicators in each country for tracking coal reserves, coal prices, electricity from coal, carbon emissions and coal phase out using the SARIMAX model of Python® by taking the historical data of economic indicators including “coal supply and demand dynamics, geopolitical events, environmental regulations, trade volumes, natural disaster, low carbon policy changes and market trend” that automatically contracts to adjust coal prices predictions

based on the latest economic sentiment. The economic strategies are implemented in this study hence the proposed method have greater reliability of the time series predictions for global coal that allows for more informed decision-making in an ever-changing market landscape.

– original draft, Visualization, Validation. **M.M. Aman:** Supervision, Project administration, Formal analysis. **Mahmoud Ahmad Al-Khasawneh:** Supervision, Project administration, Formal analysis. **Muhammad Faheem:** Visualization, Validation, Methodology, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgement

The authors are highly thankful to the international organizations that are responsible for power sector planning and energy management for sustainable energy transition globally. The authors would like to express their gratitude to the University of Vaasa, Finland.

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