Renewable Energy 242 (2025) 122293

Contents lists available at ScienceDirect

Renewable Energy

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

Pathway to energy transition and sustainable environmental development and management: Analysis of hydropower energy policy as part of climate actions

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ARTICLE INFO

Keywords:
Energy transition
Hydropower energy policy
Climate actions and goals
Environment
Sustainable development and management
10 largest hydroelectric energy generating countries

ABSTRACT

Achievement of sustainable development in both economic and environment performance involves engaging a clear cut climate actions which can be emulated by other countries in forming their climate goal policies. On this note, this study seeks to examine the environmental implication of hydropower energy policy on environment sustainable development and management of the 10 largest hydroelectric energy generating countries. By extension, the study examines the possibility of achieving hitch-free energy transition through hydropower energy sources. A study of the 10 largest hydroelectric energy producing countries is vital in framing policy based solution to environmental problems, and advice on easy way to achieve climate goal. Following the nature of this study and to derive home the objectives of the study, methods such as slope homogeneity and cross-sectional dependence (CSD) tests were applied, followed by the unit root and cointegration tests with the causality and long-run relationship. Findings from the long run relationship between the dependent variable and the independent variables are: The findings show that the N-shaped environmental Kuznets cure (EKC) hypothesis is confirmed. Also, the level of hydroelectric power generation increases in these countries, carbon dioxide (CO_2) emissions level decreases. Again, as the level of financial development increases, CO_2 level also increases. However, according to the results from causality tests, there is a one-way causal link from hydroelectric power generation to carbon emissions, and from financial development to carbon emissions. Further, a two-way causal relationship was found between economic growth and CO_2. The policy makers will pay strict attention to this development and regulate the influence of financial development to balance the sustainable development between economic growth and environment.

1. Introduction

Climate action and sustainable development, as enshrined under the 17 Sustainable Development Goals (SDGs) of the United Nations, are two essential subjects targeted at ameliorating the adverse climate condition before 2030 (UN-SDGs, 2015). Specifically, SDGs 6 to 15 are programs designed to actualize the United Nations's agenda of sustainable development. Adverse climate conditions have been a subject of discourse among many scholars across different fields. Due to its critical nature and the urgent need to offer lasting solutions to climate change, it

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https://doi.org/10.1016/j.renene.2024.122293
Received 3 November 2023; Received in revised form 17 May 2024; Accepted 24 December 2024
Available online 9 January 2025

has sparked discussions and both scientific and literary studies among scholars across different fields, including energy and environmental economists [1,2]. While some scholars base their discussion on the immediate causes and enhancers of climate change through studying the determinants of carbon emissions [1,3] and other elements of greenhouse gas emissions, others [2,4] have taken to the research of the best and most efficient ways of mitigating the climate. All the actions, whether investigating the causes or the possible ways of mitigating climate change, are put together by the United Nations under its Sustainable Development Goals (SDGs) as climate action and sustainable development targets.

Causes of climate change through the various determinants of carbon emissions such as economic growth and development proxy by gross domestic products (GDP) per capita, constant 2015, economic liberalization policies (foreign investment, international trade, and offshore financial transactions), urbanization, financial development, energy use, industrialization, etc. have been researched by some scholars [5–8]. Activities that involve industrialization and the expansion of the economy are all dependent on energy utilization [9]. Fossil fuels are widely adopted due to their availability and cost effectiveness, and they tend to emit high levels of carbon and other pollutants [10]. Economic growth and development have been deeply researched by different authors in a quest to unravel their connectivity with climate change through their impact on environmental performance. Different theories, such as the environmental Kuznets curve [11], have been employed to study the relationship between economic growth and development. Through various findings, it has been established that economic growth has a direct link to the environment, either positive or negative [12]; [null]; [13–16]; [null]. From the findings, relationships such as U-shape, inverted U-shape, and N-shape have been identified as existing between economic growth and the environment [11]. Part of the forces fostering economic growth and development is financial progress, represented by domestic credit to the private sector by banks and measured as % of GDP. Just like in the case of income expansion and the environment, scholars [17,18] have engaged in investigating the link between financial development and the environment. Mixed evidence has been obtained, with some showing environmental distress due to financial development while others suggest a positive impact on the environment. Nations are two essential subjects targeted at ameliorating the adverse climate condition before 2030 (UN-SDGs, 2015). Specifically, SDGs 6 to 15 are programs designed to actualize the United Nations's agenda of sustainable development. Adverse climate conditions have been a subject of discourse among many scholars across different fields. Due to its critical nature and the urgent need to offer lasting solutions to climate change, it has sparked discussions and both scientific and literary studies among scholars across different fields, including energy and environmental economists [1,2]. While some scholars base their discussion on the immediate causes and enhancers of climate change through studying the determinants of carbon emissions [1,3] and other elements of greenhouse gas emissions, others [2,4] have taken to the research of the best and most efficient ways of mitigating the climate. All the actions, whether investigating the causes or the possible ways of mitigating climate change, are put together by the United Nations under its Sustainable Development Goals (SDGs) as climate action and sustainable development targets.

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However, measures to mitigate climate change through decarbonization policies have been equally discussed by some other scholars [19,20]. Some of the policies are adoption and promotion of green energy [21]; [null], technology policy, financial policy, and institution quality policy [22]. Some of the mentioned policies are utilized by different countries in pursuit of sustainable environmental development through mitigation of carbon emissions impacts [null]. Green energy policies that support the transition from carbon-intensive to less-carbon-intensive through investment and development of renewable energies such as solar, hydroelectric power, geothermal, and biomass are adopted [23]. This policy has been researched by different authors [null]; [21] in line with solving the problem of climate change through reduction of carbon emissions and has been found to be very vital in achieving sustainable environmental development. Following the Paris agreement and other global agreements on the need to control climate change and target sustainable development goals, many countries have embarked on climate action through the adoption, investment, and development of green energies to achieve their national contribution towards the fight against climate change [11].

One of the green policies is the development of hydropower renewable energy sources [20], and this has been on the increase. Some of the determinants of the development of hydropower are economic growth and development and financial development [null]. Economic growth and development entails expansion in economic activities that involve investing, development, usage, and trading of renewable energies, including hydropower [24,25]. Virtually every sector of the economy is dependent on the availability and supply of energy, so as the economy expands, it has implications for the development of the energy sector, which will impact the development of renewables [26]. Financial improvement represented by domestic loans to private sectors in a given economy is one of the major determinants of economic development [null], which impacts the energy sector either directly or indirectly. Credits could be made available to the private players in an economy, which might be part of the private sector investing in the energy sector for trading in energy, and this will definitely impact the development of the sector. The government can also act to expand the energy sector through policies that include subsidies to both private and public organizations engaging in energy investment and development [27]. The availability of water, which is the source of hydroelectricity, supports its popularity and easy access, and this has made hydropower reckoned as among the oldest and most widely used renewable energy sources in most parts of the world [28]. Many countries have adopted hydropower sources of energy as an alternative to fossil fuels in the fight against environmental dilapidation and climate change. Some of these countries are listed as the largest hydropower-generating countries and are China, Canada, Brazil, the USA, Russia, India, Norway, Japan, Sweden, and Turkey, respectively (Statista 2023). A statistical representation of the world ranking of the 10 largest hydroelectric-generating countries is shown in Fig. 1 below, with China leading with about 1300 TW h. A keen look at the statistical picture portrays a mix of both advanced and

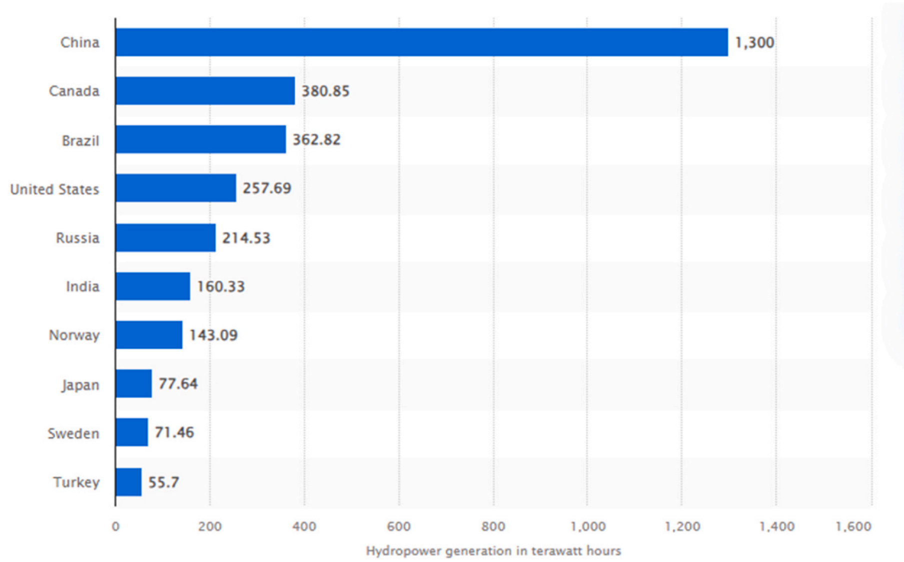

Fig. 1. Largest hydroelectric power generating countries worldwide in 2021(in terawatt hours).
Source: Statista 2023 (Published by Lucía Fernández, Aug 29, 2023).

emerging economies. This has shown that hydropower can be a boost to global energy efficiency and transition.

To this end, the present study seeks to examine the implication of energy policy centered on the development and expansion of hydropower on the sustainable environmental development and management of the top 10 largest hydropower generation countries. This study is centered on adding to climate action and sustainable development as initiated under SDG 13. According to the UN SDGs, nations are to pursue the actualization of these goals in 2030 [29,30]. Following this agenda, some of the causes of climate change through the mechanism of carbon emissions and the prospective ways of mitigating them have been outlined in the preceding paragraphs. This study, in line with climate action, seeks to examine one of the possible ways of mitigating climate change: green energy policy. For this, the study is built around the impact of hydroelectric power on the sustainable environmental development and management of the listed countries. Therefore, hydropower is considered the key independent variable to test the sustainable development of the development of the environment in the selected countries. Considering the objectives and intent of the study, other development indicators such as gross domestic product (GDP) per capita, constant 2015, and financial development are incorporated into the scientific model of this study. These indicators are also determinants of the development of renewable energy. The essence of adopting these variables is to draw a valid inference from the policy recommendation of this study. Apart from the central objective of this study, which is to examine the implication of energy policy centered on the development and expansion of hydropower on the sustainable environmental development of the top 10 largest hydropower generation countries, the objective is further broken down into five (5) specific objectives. Hence, the objectives and motivation of this study are structured as follows.

(i) to test the effectiveness of hydropower for an easy and swift energy transition.
(ii) to test the efficiency of hydroelectric energy.
(iii) to investigate the impact of hydropower on sustainable environmental development.
(iv) to investigate the link between economic growth and the environment in the selected countries.
(v) to test the impact of financial development on sustainable environmental development in the selected countries.

To advance this study, hypotheses are structured in line with the objectives and expectations of the authors as follows.

H0. Hydropower impacts positively on the sustainable environmental development of the selected countries.

H1. Hydropower does not impact positively on the sustainable environmental development of the selected countries.

H0. Hydropower is effective in the development of renewable energy and achieving the energy transition in the selected countries.

H1. Hydropower is ineffective in the development of renewable energy and achieving the energy transition in the selected countries.

H0. Hydropower impacts positively on the energy efficiency of the selected countries.

H1. Hydropower does not impact positively on the energy efficiency of the selected countries.

H0. Economic growth has a negative link with the environment through an increase in carbon emissions in the selected countries.

H1. Economic growth has a positive link with the environment through a decrease in carbon emissions in the selected countries.

H0. Financial development has a negative link with the environment through an increase in carbon emissions in the selected countries.

H1. Economic and financial development have a positive link with the environment through a decrease in carbon emissions in the selected countries.

This study is expected to contribute to the energy environment via policy-based findings. The novelty of the study is centered on adopting the 10 largest producers of hydropower, which will be used as a reference point for other countries in modeling their energy projects and policies. Following the nature of this study and to derive the objectives of the study, methodologies such as slope homogeneity and cross-sectional dependence (CSD) tests were applied, followed by unit root and cointegration tests with the causality and long-run relationship. Findings from the long-run relationship between the dependent variable and the independent variables are: As the level of hydroelectric power generation increases in these countries, the CO2 level decreases. This result shows that hydroelectric power generation is a factor that improves environmental quality. Also, as the level of financial development increases, the CO2 level also increases. As a result, the increase in bank loans to the private sector in GDP, which represents the financial development of the countries in question, has a detrimental effect on the environment. However, according to the results of causality tests, there is a unidirectional causal relationship from hydroelectric power generation to carbon emissions. Similarly, a unidirectional causal relationship was found from financial development to carbon emissions. Further, a two-way causal relationship was found between economic growth and CO_2. The findings, especially from the causality tests, have positive implications for hydropower and financial development. These findings point towards ameliorating carbon emissions with both hydropower and financial development; however, the impact of financial development as exposed by the long-run tests poses a risk to the environmental development of the selected countries. This is where the interactions between policymaking and scientific findings are very vital. Both findings point toward the domineering influence of financial development on carbon emissions, not knowing whether its impact is positive or negative. The policymakers will pay strict attention to this development and regulate the influence of financial development to balance sustainable development between economic growth and the environment.

Other sections of this study are: review of the literature; data and methodology; findings and discussions of the findings; conclusions; and policy recommendations.

2. Literature review and theoretical background

2.1. Hydroelectric production

Hydropower, one of the renewable energy sources, is a good alternative to electricity generation as a sustainable energy source. It is preferred more and more every day around the world. Compared to wind and solar, which are other renewable energy sources, the continuous availability of hydroelectric energy provides a great advantage. The electricity obtained due to intermittent wind and sunlight needs to be stored, which leads to high costs. Hydroelectric power plants, on the other hand, provide the advantage of flexibility in operations in electricity networks. Another factor that makes hydropower more competitive and attractive is the relatively low cost of electricity generation. In addition, generating electricity using naturally flowing water instead of fossil fuels and other conventional energy sources (as in conventional power plants) promotes cleanliness and less discharge into the atmosphere (such as emissions and other pollutants). Many studies have found that emissions from hydropower projects are relatively less than those from other alternative energy generation systems [31–35].

Hydropower is one of the most important renewable energy sources (IHA), which has the highest share of electricity generation among renewable energy sources (66.4 % in EU-27 in 2008) [36] and contributes approximately 16 % to global electricity generation ([37,38]; Santl and Steinman,2015).

In recent years, growing public and government awareness of sustainable hydropower development has led to an almost equal consideration of the three interconnected pillars of sustainability, namely economic development, environmental protection, and social justice. Hydropower is recognized as a very important phenomenon [39–41].

Hydropower generation is a technology that provides multifaceted social and economic benefits. In this context, hydroelectric production projects are carried out for purposes such as irrigation, tourism, control of floods, and electricity generation [42–44]. In the production of hydropower, three techniques are used: River-type (RoR) hydroelectric plant, pumped storage facility (PHP), reservoir-based hydroelectric plant. River-type hydroelectric (RoR) projects, which rely on electrical energy obtained from the current movement of the water body, have a low negative ecological and social impact. The energy obtained in PHP-type hydroelectric projects is stored. In reservoir-type hydroelectric projects, dams are built and cause negative environmental and social effects due to the accumulation of water in a certain area. A large amount of land under water can be a settlement or cultivated land. This situation causes environmental and social concerns [45,46]. The effects of reservoir-based hydroelectric facilities on the environment and social life can be listed as follows [47,48]: Sedimentation, flooding of large lands, deforestation, displacement of people living in the project area, loss of biodiversity, increase in greenhouse gas emissions, deterioration of water quality, water loss through evaporation, destruction of ecosystems, reservoir-borne earthquakes.

As a result of the establishment of hydroelectric projects, a region can be developed socially, economically, and environmentally. Renewable electricity generation creates energy production using water that is available in nature rather than consuming fossil fuels. Hydroelectric power plants are a basic tool that ensures the general development of the region where they are established. It is possible for a country to compete in the carbon trading market, obtain carbon credits, and then achieve emission reduction targets through the establishment of hydroelectric power plants.

Bilgili et al. [49] investigated the impact of hydropower on US carbon emissions from 1980 to 2019. They find hydropower impacts the carbon emissions in a disproportionate manner, hence increasing and decreasing the carbon emissions in different periods. In the case of Nepal, Aryal et al. [50] examined the capacity of its generated hydropower energy to supply both the domestic and the neighbor's end users with electricity. They find that despite the importation of its electricity, Nepal can as well extend its electricity to its neighbor during the wet season, and its hydropower energy has the capacity to reduce emissions from fossil fuels. Bega & Lin [51], in their study, show the significance of expanding hydropower projects at a massive rate with the support of China's development finance. This is expected to be beneficial to the Belt and Road Initiative (BRI) in terms of energy transition and efficiency. A study by Wang et al. [null] confirmed the effectiveness of using hydropower energy in achieving the decarbonization agenda. Their study also suggests that hydropower energy remains the best model for meeting future energy demands and systems. Haas et al. [52] conducted a study on the potentiality of pumped hydropower, and according to the study, the planning tool recommends about 1.6 and 5.0 times more pumped hydro storage compared to using average values and literature values, respectively. Toufani et al. [53] studied the energy generation and storage problem for various types of two-reservoir pumped hydro energy storage facilities, and they found that the open-loop facility is more efficient and cost-effective than the closed-loop facility. Also, Yurter et al. [54] in their study compare different categories of pumped hydro energy systems and find that open-loop facilities perform better than closed-loop and seawater facilities, dramatically lowering the need for fossil fuels in demand fulfillment. Again, in the work of Elkholy et al. [55], where they presented a new design and flexible energy management strategy for micro grids, they found that the intelligent energy management system (IEMS) achieves effective integration between the resilient microcontroller with robust performance and high responsiveness to dynamic operation scenarios.

2.2. Sustainable environmental management

The non-renewable energy sector has been helping the world economy grow rapidly for many years. The alternative idea of replacing non-renewable energy with renewable energy emerged as problems with non-renewable energy began to affect global warming. The advancement in technology and the idea of environmental sustainability are helping renewable energy become the best alternative to non-renewable energy consumption even more significantly. On the other hand, many of the developing countries are lagging behind in the renewable energy sector compared to developed economies, while at the same time, the whole world has agreed to participate in the evolution towards sanitation and low CO2 emissions. That is, the subject of empirical investigation developing in economies where energy-managed advances are working is an evaluation ranging from the use of non-renewable energy to the use of renewable energy, which resists the growth of the economy in developing countries [56,57]. In their study, Murshed et al. [58] exposed the moderating power of renewable energy through improving energy efficiency and moderating carbon productivity through the inclusion of financial development. However, economic growth exacerbates the carbon emissions problem in the selected countries. From the perspective of sustainable development, Manigandan et al. [59] in their study identified financial development and green innovation as boosters of India's sustainable development. Also, in their study on India's sustainable development, Alam et al. [60] find economic globalization and agricultural expansion exacerbating pollution, while renewable energy mitigates pollution.

Economic development also increases electricity production rapidly all over the world. Concept of sustainable energy: renewable energies, which have noticeable importance compared to non-renewable resources and are also suitable for sustainable development, have recently reached an increasing use [61]. Hydroelectricity is one of the most important energy sources as an alternative to fossil fuels to provide large-scale electricity production [62,63].

It is important to evaluate the effects of social impact assessment (SIA) and environmental impact assessment (EIA) at an early stage as a result of the planning and design of projects. Assessing these at an early stage is a very frequently used tool [64,65]. EIA is used as a scientifically based legal tool that provides quality-oriented assistance to make the right decisions aimed at sustainable development [66,67]. For countries with EIA, it is not possible to evaluate the impacts of hydroelectric projects without obtaining permission.

Many developing countries that are not yet developed have an EIA system. However, system developers can manipulate this process to a large extent due to corruption by making secret agreements with country bureaucrats [46,68].

AbdulSattar [67] investigated the reasons why the EIA fails in underdeveloped countries. As a result of this research, it was concluded that EIA is limited in many aspects. For example, it is attempted to be accomplished with limited time and cost with readily available skills. Also, while great importance is given to the content of the EIA in the first place, this interest may decrease when it comes to the implementation phase.

The International Hydropower Association (IHA), which works on the evaluation of the sustainability of hydroelectric projects around the world, was established in 2010 within the framework of the Hydroelectric Sustainability Assessment Protocol (HSAP) [69,70]. As a result, hydropower-related problems can be used to guide projects from the very beginning to the end in order to evaluate the important issues and gaps that need to be taken into account and the sustainability performance of the developed projects.

Hydropower has a multidimensional impact on the world. In line with the World Bank [71] directives, countries need to review their policies in terms of hydro energy development and revise them when necessary. Making these regulations may bring with it some difficulties. Directives in the development of hydropower are twofold. The first is direct investment. The second is to strengthen the foundation of the hydropower sector. In order for these to be achieved, technical assistance and information sharing must be sufficient and timely.

The biggest criticism of hydroelectric projects is the lack of environmental and social issues and the uncertainty of cost. Estimating dam costs is becoming increasingly difficult due to various uncertainties. It has become mandatory for countries to evaluate hydroelectric projects comprehensively in terms of quality and quantity before making any making any newly planned investments [72,73].

Every construction project to be carried out brings with it some risks. The main reason for these risks may be the fact that the programs reach the exceeding point within the scope of hydroelectric projects. In order to minimize these risks, delivering the projects to contractors who have expertise in their fields and ensuring adequate communication between customers and project consultants are among the main precautions to be taken. Apart from these, materials, equipment, etc. must be provided and delivered on time. Contractors' payments must be made on time to the extent they deserve.

Hydropower projects carry a high risk of safety failures for a number of reasons. Some of these risks are as follows: large amounts of construction work carried out in a small area; frequent weather work [74].

In addition to the benefits that developed hydroelectric projects provide to the country, they may also cause some environmental and social negativity. In order to prevent these negative effects from occurring, they should be examined and evaluated in detail before EIA studies. Correct planning should be made, and targets appropriate to this planning should be determined. Implementing EIA in the field from an operational perspective rather than examining and interpreting it only from a theoretical perspective will contribute to the sustainability of the projects. The most important steps that developed countries should take into consideration when designing projects are technical and financial constraints. When designing hydroelectric projects, the construction process should be detailed first. At this stage, it affects all program and cost elements. It should be given enough time and detail.

If the limit is exceeded while the projects are being designed, this will negatively affect the financial situation of the country. As the cost of electricity increases, the financial situation of the country will gradually worsen [null]; [75]. In order for hydroelectric projects to avoid negative consequences, the risk management process must be carried out in a transparent, effective, and comprehensive manner. All risks that may arise at the beginning of the project should be systematically evaluated. Within the scope of the program, one should be proactive at all levels, and an aggressive monitoring policy should be implemented. In developing countries, there may often be uncertainties. A more accurate approach would be to include risk examinations in the cost research and to use preliminary costs to provide sufficient financing. Hydroelectricity can provide various benefits to society if it is built in the right place and sustainability criteria are met [76]. For the execution of designed projects, previously prepared sustainability guidelines should be taken into consideration. Various procedures, safety measures, and regulations must be taken into account. In order to minimize risks and eliminate confusion, appropriate strategies should be determined first. If hydropower projects are designed to reduce all risks that may arise in line with sustainable development goals, they will provide social and economic benefits worldwide [77,78].

2.3. *The relationship between the N-shape hypothesis and sustainable environmental management*

Towards the end of the 1900s, the unlimited use of natural resources, climate change, air pollution, and increased CO_2 emissions brought environmental problems. The development of the production and consumption economies on an international scale has brought the issue of taking measures on environmental and energy issues to the agenda. In this regard, Kuznets [79] hypothesized that there is a relationship between economic growth and inequality in income distribution.

Kuznets [79] found that national income increases with economic growth, and income inequality increases in the first stage of economic development. He stated that income inequality decreases after a certain turning point in the process of economic development and that this process is shaped in an inverted-U form [79]. The inverted-U shape, called the Environmental Kuznets Curve (EKC), was adapted to the environment in the 1990s, and studies on the relationship between national income and environmental quality were conducted [80–83]. It has been concluded that environmental pollution first increases with the increase in economic growth (scale effect), decreases after a certain stage in the process of economic growth, and then returns to normal life and maintains ecological protection [84]. The so-called Environmental Kuznets Curve (EKC) hypothesis is the inverted-U-shaped relationship between national income per capita and the level of environmental pollution.

In the Environmental Kuznets EKC hypothesis, when CO_2 emission is taken as the environmental variable, it is stated that economic growth and income increase will initially increase CO_2 emission with the scale effect, and CO_2 emission will decrease at a certain level of the process as the level of development continues to increase. In addition to CO_2 emission as an environmental variable, variables such as energy consumption, openness to foreign trade, sustainable energy, and financial development have also been researched [85–87]. Fig. 1 shows the relationship between income level and CO_2 emissions on which the N-Shape EKC hypothesis is based.

Grossman [88] stated that economic growth has a scale effect, a structure effect, and a technical effect. In the early stages of economic expansion, the unlimited use of natural resources in production led to the emergence of a significant amount of harmful chemicals and ecological and climate change. As economic development increased, the structure of the market began to change, and sustainable technologies, climate, and environmental sustainability gained importance. In economic life, governments and businesses have started to spend on knowledge and innovation. This process graphically takes an inverted U shape as shown in Fig. 1 [89]. As economic growth increases, income levels will increase, but the level of environmental pollution will also increase [90]. Fig. 2 shows the N-shaped structures resulting from the possible relationships between CO_2 emissions and GNI per capita (see Fig. 3).

N-shapes also vary according to the characteristics of the country's economy. However, in the long run, the N-shaped EKC improves CO_2 emissions and GNP [81,91]. Depending on technological development, the use of more renewable energy in industrial and commercial buildings will increase efficiency. In the transition to green energy sources, the energy sector will be the catalyst of change. The use of green energy sources reduces costs ensures more energy sustainability and reduces pollution. Therefore, it is aimed to reach the zero carbon target and reduce environmental degradation with electricity generation from renewable sources [92].

Using ARDL [93], investigated the environmental implication of economic growth on France economy for the periods of 1987 and 2019, and they find economic growth increasing carbon emissions. This means that economic growth instigates environmental degeneration for France.

3. Data collection, models and empirical procedure

3.1. Data and variables

The main objective of this study is to determine the impact of hydropower on sustainable environmental management. In other words, the impact of hydroelectric power generation (HYDRO) and financial development on carbon emissions (CO) will be determined. In addition, the study will test the validity of the N-shaped EKC hypothesis to determine the role of income expansion on ecological development. In the study, the data of the world's 10 largest hydroelectric energy producing countries for 2021 are applied. The data applied in this study include hydropower, financial development and economic development. The definition of the variables and the data with their measurements are presented in Table 1 below. The nations are China, Canada, Brazil, USA, Russia, India, Norway, Japan, Sweden, and Turkey, respectively. The surveyed countries occupied the strategic position in the performance of climate change through their economic activities that are capable injecting excessive carbon on the environment. Apart from releasing excessive carbons and other greenhouse gas emissions, the selected countries are also dominating in the production of hydropower which is expected to enhance the energy-switching process in those countries. It is important to note that these countries are also among the top carbon emitting countries in the world. Hence, they are stakeholders in the management of global warming through production of both conditions (*carbon emissions and hydropower*) that are capable of escalating and ameliorating the impacts of the climate change. Findings from this study are expected to form a pathway of achieving sustainable environmental development through the control of carbon emissions which other nations with same economic and geographic features can adopt.

In justification of the selected variables, economic growth is achieved under activities such as production, distribution and transportation and consumption studies that engage energy use. In the process of using these energy sources, environments are affected through the emissions from those productive activities. The interference of environmental performance through the activities that surround economic growth is viewed in different ways by different scholars through their research [88,90,93]. Patterns such as positive or negative or positive and negative connections exist economic growth and environment have been identified by different scholars through their scholarly research [93]. These patterns have given rise to a notable hypothesis (environment Kuznets curve-EKC), which was named after Simon Kuznets. Through the EKC, different shapes (U-shape, inverted U-shape and N-shape) representing the relationship between the economic growth and environment development have been established [81, 91]. The trend that establishes these pattern always starts from the initial stage of growth to a turning point where the shape is formed. Following these scenarios of link between economic growth and environmental development, the link between the economic growth and environment can either be positive or negative which will lead to any of the above-mentioned shapes. The finding from this analysis is expected

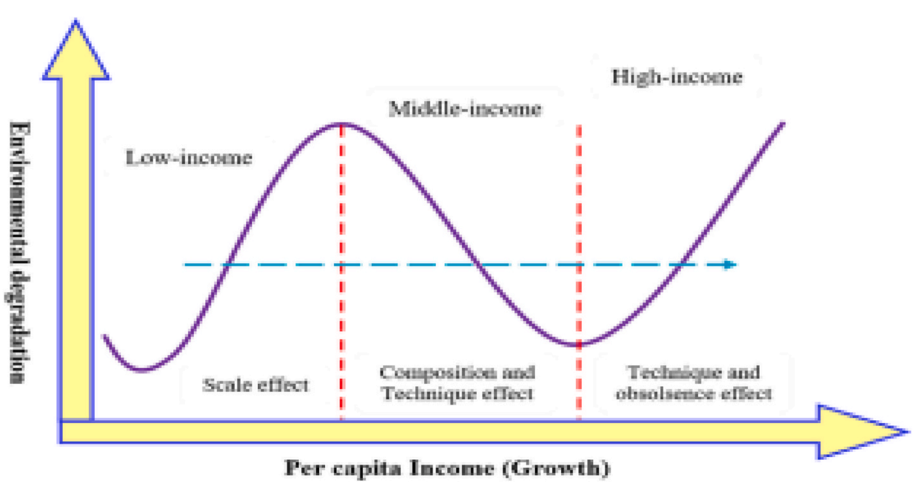

Fig. 2. N-shaped EKC hypothesis.
Source: (Zhengxia et al., 2023: 89757).

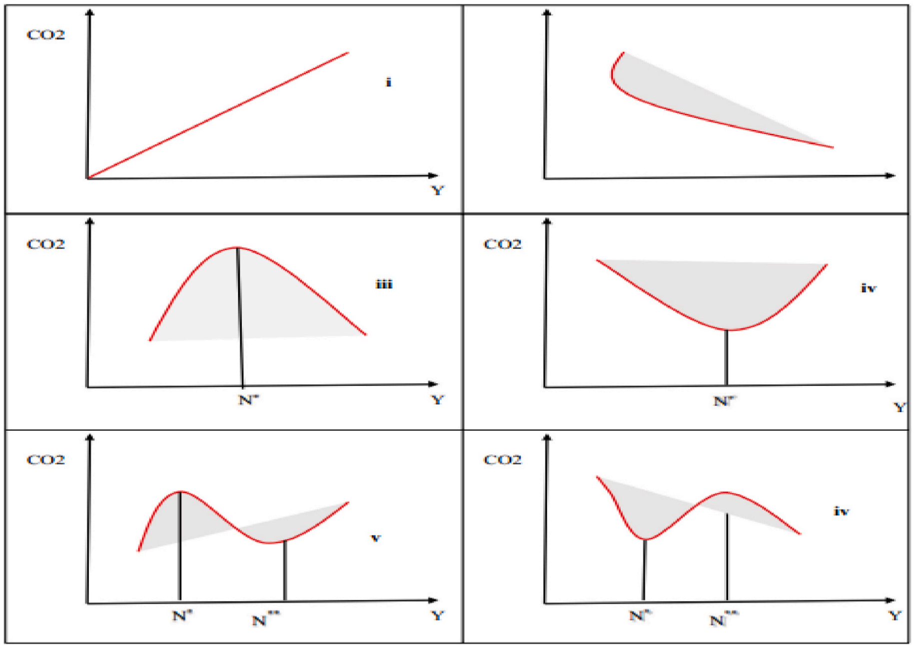

Fig. 3. Possible relationships between CO_2 emissions and GNP per capita.
Source: [90].

Table 1
Dependent and independent variables used in the study.

Variables	Descriptions	Sources
CO_2	*CO_2 emissions (metric tons*per capita*)*	*World Bank*
HYDRO	*Hydro Generation – TWh*	*Bp Statistical Review of World Energy*
FD	*Domestic credit to private sector by banks (% of GDP)*	*World Bank*
GDP	*GDP*per capita *(constant 2015 US$)*	*World Bank*

Source: Authors compilation

to reveal the kind of EKC shape that exist between economic growth and environmental development for the selected countries.

Following the objectives of this study, financial and hydropower are considered essential variables in this study. This is expected to give a view of the interplay among economic growth, financial development, and hydropower in achieving the sustainable environmental development for the selected countries. The target variable among the selected explanatory variables is hydropower. Hydropower has been identified as among green energy to achieve energy transition and security before 2030 [92]. However, considering the importance of financing the installation, development and enlargement of the sector (green energy sector), there is a need to incorporate financial development in this study. Depends on the priority and efficient use of finance by both private and public investors, financial development can either induce or mitigate carbon emissions. Many scholars [59] have studied the environmental implication of financial development and came up with mixed results. Some find financial development harmful to the environment through the inducement of carbon emissions, while others find financial development enhancing environment quality through the mitigation of carbon emissions. Hence, the impact of financial development on environmental development can be either positive or negative. Through the adopted methods, the inference between the variables are established and this will help justify the objectives of this study. The interconnections among the selected variables (*carbon emissions, economic growth, financial development and hydropower*) are exposed with the adopted methods. With this, relationship between the variables of interest are determined and justification of the findings and policies to attain sustainable environ mental development dully suggested.

3.2. Scientific method and modeling

Following the nature of this study, a scientific methodology was adopted with the following methods to derive home the objectives of the study. Firstly, slope homogeneity and cross-sectional dependence (CSD) tests were applied. Secondly, unit root and cointegration tests were performed. Thirdly, causality and long-run relationship were estimated.

In addition, the model was developed by taking the logarithm of the variables to determine the interactions between these variables. The following 3 models were developed with these variables:

$$CO_{2it} = \beta_0 + \beta_1 HYDRO_{i,t} + \beta_2 FD_{i,t} + \beta_3 GDP + \varepsilon_{i.t} \tag{1}$$

$$CO_{2it} = \beta_0 + \beta_1 HYDRO_{i,t} + \beta_2 FD_{i,t} + \beta_3 GDP + \beta_3 GDP^2 + \varepsilon_{i.t} \tag{2}$$

$$CO_{2it} = \beta_0 + \beta_1 HYDRO_{i,t} + \beta_2 FD_{i,t} + \beta_3 GDP + \beta_4 GDP^2 + \beta_5 GDP^3 + \varepsilon_{i.t} \tag{3}$$

In equation 1$t = 1, ...N$ horizontal cross-section units, 1 $t = 1, ...T$ time period, $\varepsilon_{i.t}$ error terms and parameters measuring the impact of exogenous instruments on the endogenous instrument, $\beta_{1,........\beta_5}$. The variables used in the study are presented in Table 1.

The presence of CSD is important in panel analyses. If it is not taken into account, it causes inconsistent model estimates [94]. The following tests, Breush-Pagan, Pesaran scaled LM ($\boldsymbol{CD_{LM}}$) and (LMadj) test are applied to test CDS. The lighlighted tests are expressed in formulas 4, 5, 6 and 7:

$$LM = T\sum_{i=1}^{N-1}\sum_{j=i+1}^{N}\widehat{\rho}_{ij^2} \tag{4}$$

$$\boldsymbol{CD_{LM}} = \sqrt{\frac{\mathbf{1}}{\boldsymbol{N(N-1)}}}\sum_{i=1}^{N-1}\sum_{j=i+1}^{N}\left(T\widehat{\rho}_{ij^2} - 1\right) \tag{5}$$

$$\boldsymbol{CD} = \sqrt{\frac{\mathbf{2T}}{\boldsymbol{N(N-1)}}}\left(\sum_{i=1}^{N-1}\sum_{j=i+1}^{N}\widehat{\rho}_{ij}\right) \tag{6}$$

$$LM_{adj} = \left(\frac{2}{N(-1)}\right)^{1/2} \sum_{i=1}^{N-1} \sum_{j=i+1}^{N} \widehat{\rho}_{ij^2} \frac{(T-K-1)\widehat{\rho}_{ij} - \widehat{\mu}_{Tij}}{V_{Tij}} \sim N(0,1) \tag{7}$$

After testing for horizontal cross-section dependence, the slope homogeneity is examined with the Δ tests introduced by Pesaran et al. [95]. If there is serial correlation and heteroscedasticity, a correctional test is applied. The HAC system of the homogeneity test is expressed in equations (8)–(11):

$$\Delta_{HAC} = \sqrt{N}\left(\frac{N^{-1}S_{HAC} - K}{\sqrt{2K}}\right. \tag{8}$$

$$S_{HAC} = \sum_{i=1}^{N} T(\widehat{\beta}_i - \widehat{\beta}_i)'\left(\widehat{O}_{iT} V_{iT}{}^{-1} \widehat{O}_{iT}\right)(\widehat{\beta}_i - \widehat{\beta}_i) \tag{9}$$

$$\widehat{\beta} = \left(\sum_{i=1}^{N} T\widehat{O}_{iT} V_{iT}{}^{-1} \widehat{O}_{iT}\right)^{-1} \sum_{i=1}^{N} \widehat{O}_{iT} \widehat{V}_{iT}{}^{-1} X_i' M_T y_i \tag{10}$$

$$\widehat{V}_{iT} = \widehat{r}_i(0) + \sum_{j=1}^{T-1} K\left(\frac{j}{M_{iT}}\left[\widehat{r}_i(j) + \widehat{r}_i(j)'\right]\right. \tag{11}$$

In the presence of CDS, second generation panel unit root tests are used. Accordingly, Cross Sectional Augmented IPS (CIPS) and Cross-Sectional Augmented ADF (CADF) panel unit root tests introduced by Pesaran [96] are used. Equations (12) and (13) are used for Pesaran [96] CADF unit root test:

$$\Delta y_{it} = a_i + \beta_i y_{i,t-1} + u_{it} \tag{12}$$

$$u_{it} = \gamma f_t + \varepsilon_{it} \tag{13}$$

In case there is no autocorrelation in the factor or error term, CADF regression equation (14) is used.

$$\Delta y_{it} = a_i + \beta_i y_{i,t-1} + d_0 \breve{y}_{t-1} + d_1 \Delta \breve{y}_t + \varepsilon_{it} \tag{14}$$

In the presence of endogeneity, y_{it} , ve $\breve{y}_t$ the model can be expressed as in formula 15 by allowing the 1st order of integration of and:

$$\Delta y_{i,t} = a_i + \rho_i y_{i,t-1} + c_i \breve{y}_{t-1} + \sum_{j=0}^{\rho} d_{i,j} \Delta \breve{y}_{t-j} + \sum_{j=0}^{\rho} \beta_{i,j} \Delta y_{i,t-j} + \mu_{i,t} \tag{15}$$

In order to analysis the CIPS stats in formula 16, the mean t-stats of lagged instruments are:

$$CIPS = \frac{1}{N} \sum_{i=1}^{N} CADF_i \tag{16}$$

In panel data analysis, after determining CDS, slope homogeneity and stationarity, the most appropriate cointegration test is applied. The Westerlund and Edgerton [97] cointegration test considering CDS is based on the Langrange test multiplier developed by McCoskey and Kao [98]. Equations (17) and (18) show the derivation of the panel cointegration test.

$$\gamma_{it} = a_i + x_{i,t}' \beta_{i,t} + Z_{it} \tag{17}$$

$$Z_{it} = \mu_{it} + V_{i,t} V_{i,t} = \sum_{j=1}^{t} n_{ij} \tag{18}$$

In Equation (19), Z_{it} the partial sum of the error term is denoted by $Z_{it}{}^2, \mu_{it}$ and the long-run variance of is denoted by $\widehat{\omega}_i{}^{-1}$. The LM statistic of the Westerlund and Edgerton [97] cointegration test under CDS with bootstrap critical values is as follows:

$$LM_N^+ = \frac{1}{NT^2} \sum_{i=1}^{N} \sum_{j=1}^{t} \widehat{\omega}_i{}^{-2} S_{it}{}^2 \tag{19}$$

If there is at least one of heteroscedasticity, autocorrelation and CDS in the regression model, either the standard errors should be corrected without touching the parameter estimates, or if they exist, they should be estimated with appropriate methods [99]. In this study, the robust estimator developed by Beck-Katz [100] is preferred since it is resistant to these problems and can be applied in the case of T < N, and standard errors are corrected. Equation (20) shows the panel-corrected standard error (PCSE) approach developed by Beck and Katz [100]:

$$y_{it} = x_{it}\beta + \varepsilon_{it} \tag{20}$$

Where $i = 1 \ldots m$ is the number of; $t = 1 \ldots \mathcal{T}_i$; $\mathcal{T}_i$ is the number of periods in panel i; and ε_{it} is a disturbance that may be autocorrelated along t or contemporaneously correlated across i. This model is written as a panel and shown in equation (28):

$$\begin{bmatrix} y_1 \\ y_2 \\ \vdots \\ y_m \end{bmatrix} = \begin{bmatrix} x_1 \\ x_2 \\ \vdots \\ x_m \end{bmatrix} \beta + \begin{bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \vdots \\ \varepsilon_m \end{bmatrix} \tag{21}$$

For a model with heteroskedastic disturbances and contemporaneous correlation but with no autocorrelation, the disturbance covariance matrix is assumed to be:

$$\sum [\varepsilon\varepsilon'] = \cap = \begin{bmatrix} \sigma_{11}I_{11} & \sigma_{12}I_{12}\cdots & \sigma_{1m}I_{1m} \\ \sigma_{21}I_{21} & \sigma_{22}I_{22}\cdots & \sigma_{2m}I_{2m} \\ \vdots & \vdots \ddots & \vdots \\ \sigma_{m1}I_{m1} & \sigma_{m2}I_{m2}\cdots & \sigma_{mm}I_{mm} \end{bmatrix} \tag{22}$$

where σ_{ii} is the variance of the disturbances for panel i, σ_{ij} is the covariance of the disturbances between panel i and panel j when the panels' periods are matched, and $\boldsymbol{I}$ is a $\mathcal{T}_i$ by $\mathcal{T}_i$ identity matrix with balanced panels.

Dumitrescu and Hurlin [101] causality test can be used in heterogeneous panels, N > T or T > N and horizontal cross-section dependence [101]. The linear model testing the causality relationship between X and Y is as follows.

$$y_{i,t} = a_i + \sum_{k=0}^{k} \beta_{ik} y_{i,t-k} + \sum_{k=0}^{k} \gamma_{i,k} X_{i,t-k} + \varepsilon_{i,t} \tag{23}$$

In equation (23), $X_{i,t}$ ve $y_{i,t}$ denotes the observation of stability of instruments in period t for each i. The lag length is considered to be constant for each i and the panel is assumed to be consistency.

4. Findings and discussions

Here, the quantitative analysis of the relationship between CO_2 and HYDRO, FD, GDP variables are presented.

Table 2 shows the descriptive statistics results of the variables used in the research. According to the results, the average CO_2 emission in metric tons per capita for the countries used in the research sample was determined as 7.89. GDP per capita variable average is calculated as 9.487.64.

Table 3 shows the results of the correlation relationship between the variables used in the research. According to the results, there is a

Table 2
Descriptive statistics.

Variable(s)	Obs	Mean	Std.dev	Min	Max
CO_2	280	7.89	5.45	0.689	20.47
HYDRO	280	187.22	195.44	24.14	1271.49
FD	280	0.612	0.188	0.229	0.920
GDP	280	9.487.64	7.404.53	2.248.65	8.835.65

Source: Authors computation

Table 3
Correlation matrix.

Variable(s)	CO_2	HYDRO	FD	GDP
CO_2	1.0000			
HYDRO	−0.3404	1.0000		
FD	0.6471	0.2051	1.0000	
GDP	0.5877	0.0412	0.5932	1.0000

Source: Authors computation

negative relationship between hydroelectric energy production and CO_2 emission. In other words, a one unit increase in hydroelectric energy production decreases CO_2 emission level by 34 %. In addition, a strong and positive relationship was found between financial development and CO_2 emission. In addition, there is a positive relationship between CO_2 emission and economic growth. Finally, the absence of a strong link among the independent instrument used in this research work increases the reliability of the model.

CDS test results for CO_2, FD and GDP variables are shown in Table 4. As a result of the CDS test, all variables are statistically significant. As a result, the hypothesis H_0 ″there is no horizontal cross-section dependence" is rejected and there is horizontal cross-section dependence for all series.

The results of the slope homogeneity test are shown in Table 5. As a result of the Blomquist and Westerlund (2013) test, it is understood that the $\boldsymbol{H_0}$ hypothesis expressing the presence of heteroscedasticity of in the models developed in the research is rejected. This shows that there is slope heterogeneity in the models developed in the research.

In Table 6, a stability tests is applied to test whether there is a unit root in terms of the variables used in the analyses. According to the results of the analysis, all variables are stationary at first difference and the null hypothesis H_0 ″the series are unit rooted" is rejected.

In Table 7, after the stability determination of the instruments and the presence of CDS, the second generation method, Westerlund-Edgerton LM Bootstrap (2007) test, was used to determine the long-run cointegration relationship between the variables. Bootstrap-p value should be taken into account due to the presence of CDS in the variables. It is understood that the Bootstrap-p value is greater than 0.10 in the model for the effect of HYDRO, FD and GDP independent variables on the dependent variable CO_2. In this context, there is a cointegration relationship.

Table 8 reveals the output of three Panel-Corrected Standard Error (PCSE) equations. The models developed are for the effect of HYDRO, FD and GDP on carbon emissions (CO_2) for the nations that dominate in the hydroelectric generation. In the study, the effects of independent variables are developed with single, double and triple models and their effects on R^2 are compared. In addition, the presence of the N-shaped EKC theory was tested by adding economic growth (GDP), square of economic growth (GDP^2) and cube of economic growth (GDP^3) variables to these models.

According to the results, hydroelectric power generation (HYDRO) has a negative and significant effect on carbon emissions (CO_2) in all models. In other words, as the level of hydroelectric power generation increases in these countries, CO_2 level decreases. These results show that

Table 4
Cross-sectional dependence test results.

Variable(s)	CO_2	HYDRO	FD	GDP
Breush-Pagan LM	435.45***	501.207***	403.291***	743.24***
Pesaran scaled LM	31.321***	28.156***	21.965***	38.512***
Bias-corrected scaled LM	29.291***	22.931***	19.531**	42.591***
Pesaran CD	9.745***	12.531***	17.511***	29.621***

Note: The p-values are given in parentheses. *** denotes significance at 1 % level.
Source: Authors computation

Table 5
Test of slope homogeneity.

Models	Statistics	P-Values
$\tilde{\Delta}$	13.621	0.000***
$\tilde{\Delta}$ adj	10.183	0.000***

Note: the asterisk signs *** represent significance of the results at 1 % level.
Source: Authors computation

Table 6
CADF and CIPS stationarity results.

Variable(s)	CADF t-stats		CIPS t-stats	
	Level	first difference	Level	first difference
CO_2	−0.972	−3.385***	−1.093	−5.673***
HYDRO	−1.201	−4.301***	−1.303	−4.936***
FD	−1.042	−3.504***	−1.623	−5.549***
GDP	−1.831	−5.035***	−1.034	−7.042***

Note: *, ** and *** represent sig. at 10 %, 5 % and 1 % level, respectively.
Source: Authors computation

Table 7
Westerlund-Edgerton's LM bootstrap cointegration test result.

Test	LM Statistics	Asymptotic-p Value	Boostrap-p Value
LMN^T	16.538	0.000	0.691

Note: *The number of bootstrap iterations is 1000. The test result is obtained with the constant and trend models.*
Source: Authors computation

Table 8
Findings of long-run elasticity estimates.

Variables	(Model 1)	(Model 2)	(Model 3)
	CO_2	CO_2	CO_2
HYDRO	−7.73*** (−0.06)	−6.84*** (−0.08)	−6.89*** (−0.07)
FD	12.43*** (6.81)	13.02*** (6.61)	13.35*** (7.11)
GDP	6.67*** (2.06)	3.12*** (1.28)	2.92*** (1.18)
GDP^2	–	−3.85*** (−0.325)	−3.89*** (−0.317)
GDP^3	–	–	7.10** (2.32)
Constant	−12.13*** (−9.16)	−5.50*** (−5.39)	7.10*** (2.39)
Observations	280	280	280
R-squared	0.5041	0.5467	0.5555
Number of groups	10	10	10

Note: the asteris signs *** represent significance of the results at 1 % level.
Source: Authors computation

hydroelectric power generation is a factor that improves ecological development value. The link between hydropower generation and carbon release may vary from one region or country to another. What is true in one region may not be universally applicable. The observed impact can be influenced by a variety of other factors, such as a country's energy mix, industrial activities, energy efficiency measures, and government policies. These factors can interact with hydropower generation and its impact on emissions. The geographical condition and features of the selected countries such as availability of water resources like oceans and seas contribute towards the enhancement of the hydroelectric production in the countries. Countries like China, the USA and Turkey are among the water surrounded nations, and are doing great in hydroelectric production. The analysis may be based on a specific period and may not capture long-term trends or changes in energy and environmental policies.

This finding of our study coincides with the finding that the Gökçekaya dam reduces the carbon footprint of € 408,533.57 tCO_2 per year based on fossil resources from Turkey [102]. Another finding that supports our study is that the nexus between electricity, hydropower and technical improvement reduced CO_2 in China from 1990 to 2018 [103]. A study conducted at the level of 29 provinces in China from 2013 to 2017 is similar to the findings of our study [104]. These align with the finding in this study. According to the empirical results of the analysis in the study, which aims to investigate the carbon situation in emerging economies such as India and China according to the Pollution Paradise Hypothesis (PHH), it is observed that ecological footprint of China is induced by the coal and hydro energy sources. Similarly, China's foreign direct investments also increase its carbon footprint. In addition to the results of the analysis, environmental degradation is caused by FDI [105]. All available evidence from a study examining CO_2 emissions from electricity generation sources in ASEAN countries shows that coal is among the influencers of carbon emissions [106].

The second independent variable, financial improvement (FD), causes the increase of carbon emissions. In other words, as the level of financial development increases, CO_2 level also increases. As a result, the surge in bank loans to the private sector in GDP, which represents the financial development of the countries in question, has a detrimental effect on the environment. Specifically, it means that as the level of financial development increases (measured by the increase in bank loans to the private sector as a percentage of GDP), carbon dioxide (CO_2) emissions also increase. In simpler terms, this means that in the context of the countries analyzed, greater financial development is associated with greater carbon emissions, which are considered harmful for the environment. If increased financial development is indeed associated with higher carbon emissions, policymakers and researchers may need to explore strategies to reduce the environmental impacts of economic growth and financial development. Reviewing the requirements for giving loans to the private industries to include environment consciousness practises such as adopting green practices like adopting new technologies and less carbon intensive practices in their investment and production. This may include implementing environmental regulations, promoting green finance and encouraging sustainable practices in various sectors of the economy.

Das et al. [107] in their study of Bangladesh sustainable development, they found a link among per capita CO_2 emissions and financial development. Acheampong [108] in a study conducted for 46 sub-Saharan African countries found that the financial indicators has a significant effect. D'Orazio and Dirks [109] in a study analyzing the effects of financial development, economic growth and climate-related fiscal policies on carbon emissions for G20 countries, empirical results show advert effects of fiscal policies on carbon release.

The last independent variable in the study, the effect of income expansion on ecological value, was tested with the N-shaped EKC theory. When the results are analyzed, it is understood that the first level of income (GDP) has a negative effect on environmental quality for the countries with the highest hydroelectric energy production in all models. On the other hand, the second level of income (GDP^2) contributed to the reduction of carbon emissions. However, the third level of income (GDP^3) has been found to increase carbon emissions. As a result, the N-shape hypothesis does not provide information on hydropower consumption and environmental quality.

These findings of our study are in line with the study investigating the mechanisms of the interaction between income expansion and pollutants in 27 EU member states in a panel frame [110]. A study on the effect of income disparity on emissions for the case of Indonesia supports the findings in our study [111]. The findings of the study analyzing the effect of nuclear energy consumption on GDP growth and CO2 emissions in 30 major nuclear energy consuming countries support the findings of our study [112].

After estimating the long-run elasticity coefficients, the causality relationship between CO_2, HYDRO, FD and GDP variables was determined by Dumitrescu-Hurlin test in Table 9. According to the results, there is a one-way causal link from hydroelectric power generation to carbon emissions. Similarly, a unidirectional causality relationship was found from financial development to carbon emission. Further, two way causal relationship was found between economic growth and CO_2. This situation can be associated with the increase in economic activities with the increase in financial development and the increase in commercial activities that may harm the environment. The increase in hydropower energy consumption, which is a renewable energy, can be explained by reducing the amount of carbon emissions per capita. The use of sustainable clean resources by these countries is a factor that improves environmental quality. While the impact of hydropower generation on carbon emissions can take time to materialize, carbon emissions can have an immediate impact on financial development. Bidirectional causality often indicates the presence of feedback loops in the system. Changes in one variable may affect the other, which in turn may feedback and affect the first variable. For example, economic growth can lead to higher emissions, but higher emissions can also influence economic policies and technological innovations aimed at reducing emissions, which in turn can influence economic growth.

Table 9
Dumitrescu-Hurlin panel causality test results.

	W-bar	Z-bar	P-values
CO2 $\nrightarrow$ *HYDRO*	2.841	3.913	0.000
HYDRO $\nrightarrow$ CO2	2.913	4.351	**0.000**
CO2 $\nrightarrow$ *FD*	1.071	1.012	0.171
FD $\nrightarrow$ CO2	3.531	5.651	**0.000**
CO2 $\nrightarrow$ *GDP*	2.013	4.291	**0.000**
GDP $\nrightarrow$ CO2	3.331	6.291	**0.000**

Note: The maximum lag length is taken as 1.

5. Conclusion and policy recommendation

5.1. Concluding summary

The present study is undertaken as an inquiry into a possible way to mitigate environmental issues to achieve a better sustainable environmental development and management which complements the climate action, and enabling ground for energy transition. As the world grapples with the urgent need to address climate change and transition to sustainable energy sources, hydropower plays a crucial role in achieving these goals. This study in line with climate action to mitigate the climate change through green energy policies. For this, the study is built around the impact of hydroelectric power on the sustainable environment development and management of the listed countries. Following the central objective of this study, hydropower is considered the key independent variable to test the sustainable environment development in the selected countries. Considering the objectives and the intent of the study, other development indicators such as gross domestic products (GDP) per capita, constant 2015 and financial development are incorporated in the scientific model of this study. These indicators are also determinants of the renewable energy development. The essence of adopting these variables is to draw a valid inference in the policy recommendation of this study. The objectives and motivations of this study as mentioned in the introduction section are outlined as follows: *i) can hydropower aid in easy and swift energy transition and efficiency? ii) What is the link between economic growth and environment in the selected countries? iii) What is the impact of financial development towards the sustainable environment development in the selected countries?* This study is expected to contribute to the energy -environment via policy based findings. The novelty of the study is centered on adopting the 10 largest producers of hydropower which will be used as a reference point for other countries in modeling their energy project and policies.

The study adopts the following methods for insightful analysis of the subject matter, hence: slope homogeneity and cross-sectional dependence (CSD) tests were applied, followed by the unit root and cointegration tests with the causality and long-run relationship. Findings from the long run relationship between the dependent variable and the independent variables show that: as the level of hydroelectric power generation rises in these countries, CO_2 level reduces, the increase in bank loans to the private sector in GDP, which represents the financial development of the countries in question, has a detrimental effect on the environment. Results from causality tests backs the findings from the long run test, hence, a unidirectional causality relationship is found from hydroelectric power generation to carbon emissions, and from financial development to carbon emission. Further, two way causal link was found between income expansion and CO_2. The findings especially from the causality tests have positive implications for the case of hydropower and financial development. These findings are pointing towards ameliorating the carbon emissions with both hydropower and financial development, however, the impact of financial development as exposed by the long run tests is posing risk to the environment development of the selected countries. This is where the interactions between policy making and the scientific findings is very vital. Both findings point toward the domineering influence of financial development on carbon emissions, notwithstanding, whether it's impacting positive or negative. The policy makers will pay strict attention to this development and regulate the influence of financial development to balance the sustainable development between economic growth and environment.

5.2. Policy recommendations

To guide policymakers both now and in the future, we offer recommendations for developing effective hydropower policy as part of broader climate action and sustainable environmental governance.

Incentivize Research and Development: It is important to invest in research and development to advance hydropower technologies such as advanced turbines, fish-friendly designs, and energy storage solutions. Encourage innovation in small-scale and decentralized hydropower projects to exploit the full potential of various hydropower sources, including river and tidal energy.

Environmental Impact Assessment: Conduct comprehensive environmental impact assessments before starting any hydropower project to reduce ecological damage. Promote adaptive management strategies that continuously monitor and address the environmental impacts of existing hydropower facilities.

Stakeholder Engagement and Community Benefits: Policies should be developed that ensure meaningful consultation and participation of local communities in decision-making for hydropower projects and guarantee equitable distribution of economic benefits to host communities, including revenue-sharing mechanisms and job creation.

Regulatory Framework and Licensing: Clear regulatory frameworks should be established that streamline the permitting and licensing process for hydropower projects while maintaining environmental and safety standards. Standardized guidelines for decommissioning and removal of aging hydropower infrastructure should be implemented to prevent long-term environmental damage.

Grid Integration and Flexibility: Invest in a robust grid infrastructure that can efficiently integrate variable hydropower outputs and balance supply and demand. Encourage the development of grid-scale energy storage systems to store excess hydropower during peak production for later use.

Climate Resilience and Adaptation: Assess the vulnerability of existing hydropower facilities to changing climate conditions develop adaptation strategies to ensure their long-term viability and incorporate climate resilience into the design and construction of new hydropower projects.

International Cooperation and Knowledge Sharing: Cooperate with neighboring countries on transboundary hydropower projects to maximize regional benefits and address common environmental concerns. Facilitate knowledge sharing and technology transfer to accelerate hydropower development in regions with untapped potential.

Economic Incentives and Market Mechanisms: Incentives, subsidies, and carbon pricing mechanisms should be established to encourage private sector investment in hydropower projects. Feed-in tariffs or power purchase agreements should be implemented to provide revenue certainty to hydropower producers.

Education and Public Awareness: Education programs should be developed to raise awareness about the benefits of hydropower and its role in climate change mitigation and encourage the adoption of energy-efficient practices among consumers to reduce overall energy demand.

Long-Term Planning and Monitoring: Develop long-term energy transition plans with clear targets and milestones for hydropower deployment and emissions reduction. The effectiveness of hydropower policies should be regularly monitored, evaluated, and adjusted as necessary to align them with evolving climate and environmental objectives.

By following these recommendations, policymakers can ensure that hydropower policies contribute to the broader goals of climate action, sustainable environmental development, and governance. These measures will not only reduce greenhouse gas emissions but also promote economic growth and environmental stewardship for current and future generations.

5.2.1. Innovations and future prospects in hydropower

1. Advanced Turbine Technologies

One of the key innovations in hydropower is the development of advanced turbine technologies. High-efficiency, fish-friendly turbines are being designed to maximize energy extraction while minimizing the impact on aquatic ecosystems. Innovations like adjustable-speed turbines and modular designs allow for more flexibility in adapting to varying flow conditions.

2. Pumped Storage Hydropower

Pumped storage hydropower is gaining prominence as a way to store excess energy generated during periods of low demand. This technology involves pumping water uphill to a reservoir during surplus energy production and releasing it through turbines to generate electricity during peak demand. It serves as an efficient and flexible energy storage solution, making it an essential component of a reliable grid powered by intermittent renewable sources.

3. Small-Scale Hydropower

Small-scale hydropower systems are becoming increasingly viable, especially in remote or off-grid areas. These systems can harness energy from small rivers or streams, providing sustainable power to communities that were previously reliant on fossil fuels. Miniaturized turbine designs and efficient transmission technologies make this innovation accessible to a wider range of locations.

4. Floating Hydropower

Floating hydropower platforms are being developed to harness energy from previously untapped water bodies, such as reservoirs, ponds, and even the open ocean. These platforms can be deployed quickly and can help address energy demands in densely populated coastal regions.

5.2.2. Technological developments in hydropower

1. Digitalization and Automation

Hydropower facilities are becoming more digitally integrated, enabling real-time monitoring and control. Automation systems optimize energy production by adjusting turbine settings based on weather forecasts and grid demand. Predictive maintenance algorithms help prevent downtime and reduce operational costs.

2. Environmental Monitoring

Advanced sensor technologies are being used to continuously monitor environmental parameters around hydropower facilities. This data helps operators make informed decisions to minimize the impact on aquatic life and ecosystems. For example, acoustic fish tracking systems help guide fish away from turbines.

3. Grid Integration

Technological developments in grid integration allow for better coordination between hydropower plants and other renewable energy sources. Smart grid solutions enable seamless energy transfer between different types of power generation, enhancing grid stability and reliability.

5.2.3. Potential for improved environmental management

1. Fish-Friendly Turbines

The development of fish-friendly turbines, designed to reduce fish mortality during passage through turbines, is a significant step toward improved environmental management. These turbines incorporate features like bypass channels and screens to protect aquatic life.

2. Habitat Restoration

Hydropower operators are increasingly engaged in habitat restoration efforts to mitigate the environmental impact of dams and reservoirs. This includes projects to improve fish passage, restore riparian zones, and enhance water quality downstream of hydropower facilities.

3. Adaptive Operations

Hydropower plants are implementing adaptive management strategies that consider environmental conditions and seasonal variations. These strategies involve adjusting water release schedules to mimic natural flow patterns, which can benefit downstream ecosystems.

5.2.4. Future Proposals for integration with other renewable energy sources

1. Hydropower and Solar/Wind Integration

Integrating hydropower with intermittent renewable sources like solar and wind can create a balanced and reliable energy mix. Hydropower can serve as a backup during periods of low solar or wind generation, ensuring a steady power supply.

2. Green Hydrogen Production

Hydropower can play a crucial role in green hydrogen production. Electrolysis powered by excess hydropower can produce hydrogen, which can be used as a clean energy carrier for various sectors, including transportation and industry.

3. Regional Energy Grids

Developing regional energy grids that interconnect hydropower-rich areas with regions rich in other renewable sources can optimize energy generation and distribution. This approach reduces the need for extensive energy storage solutions.

In conclusion, the innovations and future prospects in hydropower, along with technological advancements, offer promising avenues for sustainable energy generation and environmental management. However, our study has some limitations that are centered on choice of variables and the consideration of regional cum geographical importance of hydropower energy system. Other green energy products such as solar and wind energy systems are missing from this analysis. Also, there are no consideration of the geographical importance of hydropower such as availability of water resources in the selected countries. Hence, future studies on this topic can integrate other green energy products such as solar and wind energy production, and compare the efficiency of the various products to know the most efficient and effective product in curtailing the menace of carbon emissions. Also, geographical conditions should be considered in studying any energy products in future studies. By integrating hydropower with other renewable sources and implementing environmentally friendly practices, we can advance the transition to a cleaner and more sustainable energy future.

CRediT authorship contribution statement

Ayşe Meriç Yazici: Data curation, Investigation, Methodology, Software. **Edmund Ntom Udemba:** Conceptualization, Formal analysis, Supervision, Validation. **Mesut Öztirak:** Writing – original draft, Writing – review & editing. **Vildan Bayram:** Writing – original draft, Writing – review & editing. **Yu Mei:** Investigation, Supervision, Writing – review & editing.

Data availability Statement

Data will be made available by authors on request.

Authors declare that this research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

‘Declaration of Generative AI and AI-assisted technologies in the writing processes

Statement: During the preparation of this work the author(s) did not use AI and AI-assisted technologies in the writing processes.

Funding

Authors acknowledged that there was no funding for this study.

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.

Acknowledgements

Authors acknowledged that this study has not been published or submitted to any publication outlets for publication.

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