Renewable and Sustainable Energy Reviews 159 (2022) 112225

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

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

Impact of innovation in marine energy generation, distribution, or transmission-related technologies on carbon dioxide emissions in the United States

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ARTICLE INFO

Keywords:
Innovation
Marine energy generation
CO_2 emissions
Renewable energy consumption
Monetary policy
United States

ABSTRACT

This study contributes to the energy economics literature by inspecting the association between innovation in marine energy generation, distribution, or transmission-related technologies and carbon dioxide emissions, with the gross domestic product per capita, expansionary monetary policy, trade openness, international collaboration in green technology development, and renewable energy consumption in the United States from 1990Q1 to 2018Q4. First, results from the canonical co-integration regression estimator, dynamic ordinary least squares estimator, and fully modified ordinary least squares estimator indicated that innovation in marine energy generation, distribution, or transmission-related technologies helps reduce carbon dioxide emissions. Second, the findings indicated that renewable energy consumption and international collaboration in green technology development were negatively associated with carbon dioxide emissions. Third, trade openness, expansionary monetary policy, and gross domestic product per capita were positively associated with carbon dioxide emissions. Fourth, the Granger causality test confirmed two-way causality between international collaboration in green technology development and carbon dioxide emissions. Fifth, the findings also showed that there exists a one-way causality between innovation in marine energy generation, distribution, or transmission-related technologies and carbon dioxide emissions, gross domestic product per capita and carbon dioxide emissions, expansionary monetary policy and carbon dioxide emissions, and trade openness and carbon dioxide emissions.

1. Introduction

There is an increasing global consensus on the notion that environmental pollution and global climate are the main threats adversely affecting economies, natural resources (forest, soil, and water), air quality, ozone layer, biodiversity, and human health [1]. Rising greenhouse gases (GHGs) and temperature have added to the increased deoxygenation of ocean water [2]. Ocean waters, acting as massive sinks for the emitted CO_2, have become more acidic. Over the last few decades, the pH of surface waters has decreased at a rate of 0.02 units per decade [2,3]. Experts support that an upsurge in energy consumption increases contributes to aggregate production and consumption. At the same time, researchers have identified high energy demands as the primary determinant of the increasing carbon dioxide emissions (CO_{2e}) [4]. Economic growth and development are dependent on energy use, even though it adversely affects environmental quality and global climate by intensifying CO_{2e}. The nexus involving energy use, economic growth, and CO_{2e} has attracted significant academic attention in recent years [5,6] because governments and policymakers have been facing the challenging task of balancing economic and environmental concerns simultaneously [6].

Academicians have been searching for new ways to counter the harmful effects of increasing CO_{2e} and global climate change. Globalization has pushed many economies towards industrial innovation and advancement. Many enterprises use modern technology to address climate change issues through product, process, and organizational innovations. Technological innovation assists in reducing CO_{2e} and energy consumption while simultaneously improving productivity [4]. It enhances the use of natural resources in developed and developing economies by facilitating the development of new renewable energy technologies for biomass, geothermal, hydro, wind, solar, and marine

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https://doi.org/10.1016/j.rser.2022.112225
Received 25 May 2021; Received in revised form 28 January 2022; Accepted 2 February 2022
Available online 11 February 2022
1364-0321/

Abbreviation and nomenclature

IMEGDT	Innovation in marine energy generation, distribution, or transmission-related technologies
CO_{2e}	Carbon dioxide emissions
GDPPC	Gross domestic product per capita
EMP	Expansionary monetary policy
TO	Trade openness
ICGTD	International collaboration in green technology development
REC	Renewable energy consumption
CCRE	Canonical co-integration regression estimator
DOLSE	Dynamic ordinary least squares estimator
FMOLSE	Fully modified ordinary least squares estimator
OECD	Organization for Economic Cooperation and Development
K	Capital goods
Z	Innovation activities
GI	General innovation
Y	Final output
R&D	Research and development
QMSA	Quadratic match sum approach
IMP	Import of goods
EXP	Exports of goods
μ_t	Error terms
m	Lag operators
BY	Break years
BT	Bound test
VRE	Variable renewable energy
PV	Photovoltaics
MW	Megawatt
OTEC	Ocean thermal energy conversion
FEMP	The Federal Energy Management Program
DOE	Department of Energy
DOI	Department of the Interior
DOD	Department of Defense
OTECH	Ocean thermal energy conversion system technology

energy [7–9]. Ocean or marine energy has enormous renewable energy capacity, as it can fulfill more than twice the world's existing electricity demand. New marine energy technologies or innovations in marine energy generation, distribution, or transmission-related technologies (IMEGDTT) have the potential to reduce CO_{2e} emissions from electricity generation and contribute to a long-term and sustainable energy future [10]. In addition to IMEGDTT, international collaboration in green technology development (ICGTD) may also play an important role in reducing CO_{2e}. ICGTD enables different economies to jointly develop new green technologies that improve environmental quality and mitigate the process of resource depletion. Dodgson [11] argued that international cooperation could help businesses become more efficient by improving R&D and innovation performance or offering quick responses to rising pollution problems.

As per the International Energy Agency (IEA), maritime energy capacity will exceed 300 Gigawatts (GW) by 2050 due to multiple factors (e.g., investments worth USD35 billion), resulting in 680,000 employment opportunities and annual CO2 emissions savings of 500 million tons [12]. In line with the predicted growth of marine energy, the National Hydropower Association (NHA) announced new industry deployment targets of 50MW by 2025, 500MW by 2030, and 1GW by 2035 [13]. The Marine Energy Council (MEC) of the NHA collaborates with government partners, academia, and private sector companies to promote the commercialization of marine energy technologies. The MEC aims to increase awareness of the industry's significant potential to create well-paying jobs while ensuring a reliable, affordable, and environmentally friendly energy future [14]. Other countries have also shown enormous potential for installing marine energy technologies for electricity generation. According to the National Energy Board of Canada, South Korea leads in tidal energy with a total installed capacity of 511MW, followed by France (246 MW), the United Kingdom (139MW), Canada (40MW), Belgium (20MW), China (12MW), and Sweden (nearly 11MW) [15].

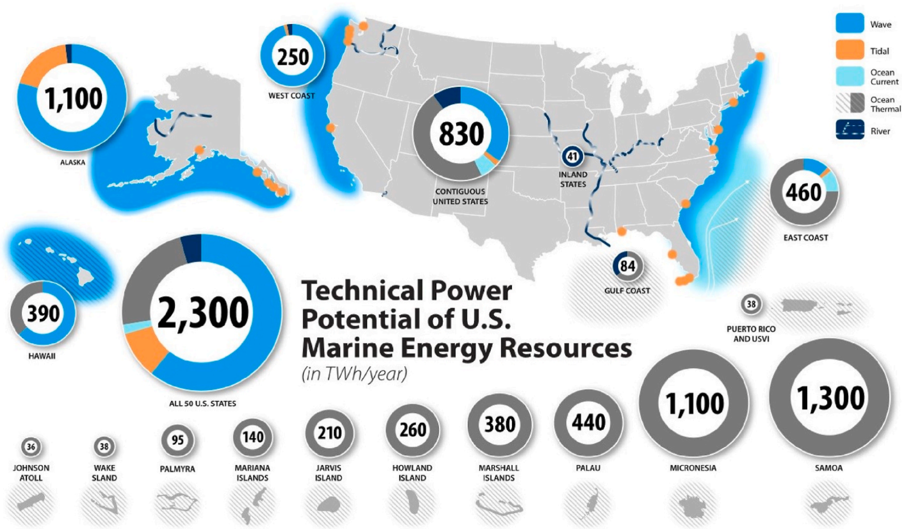
In the United States, the combined technical potential for ocean energy in the 50 states is 2300 TWh/yr, i.e., approximately fifty-seven percent of the electricity generated in those states in 2019. The Pacific and Caribbean territories of the United States and its autonomous states contribute an extra 4100 TWh/yr of ocean thermal energy. In short, ocean energy will remain relevant as an essential energy source for a sustainable future of the United States and the world. Even if a fraction of the technical resource potential is realized, maritime energy technologies can play significantly contribute to the future energy demands in the United States [16]. For instance, utilizing just ten percent of the available maritime energy resources would equal 5.7% of current electricity generation, i.e., enough to power 22 million households (see Fig. 1).

Marine energy resources are dispersed throughout the United States, providing distinct advantages for various states and areas. Each year, massive amounts of wave energy reach the United States' shores, particularly in the Pacific coastal areas, including Hawaii, Alaska, Washington, Oregon, and California. Tidal power, possibly the most reliable renewable energy resource, can significantly contribute to electricity generation in Alaska, Washington State, and other Atlantic states. Ocean current energy, mostly contained in the Gulf Stream, can provide stable and dependable power to houses in Florida, Georgia, South Carolina, and North Carolina. Ocean thermal energy presents another significant opportunity for portions of the United States Pacific territories, Hawaii, the Gulf Coast states, and the Atlantic coast [16].

Makai Ocean Engineering's ocean thermal energy conversion (OTEC) power plant in the United States is the world's largest operational plant of its sort, generating 100 kW of electricity annually, enough to power 120 households in Hawaii [17]. This plant, located at the Natural Energy Laboratory of Hawaii Authority (NELHA) in Kailua-Kona, was linked to the United States grid in August 2015. It can supply baseload power, which means it can generate electricity continuously 24 h a day throughout the year [18].

Considerable progress has been made in the field of marine energy technology. These technologies will be crucial in assisting the United States in meeting its 100% renewable energy targets and related climate change targets by 2035. Because marine energy is reliable and predictable, the short-term distribution and generation market opportunities include the development of water-based hybrid power systems, recharging of energy storage systems, aeration pumping systems, irrigation, underwater data centers, vessel charging stations, electric vehicle, clean water systems, port electrification, and "green" hydrogen production. Marine energy technology will also contribute to the development of off-grid "Blue Economy" business potential such as oceanographic research industries, electricity for the offshore aquaculture and energy, autonomous sensors, and remote underwater car charging. The US Navy is investigating the use of marine energy devices to power at-sea persistent surveillance, and communications, and maritime security systems [14].

With marine energy becoming a next-generation renewable source, several countries have initiated research and development programs to introduce new and improved marine energy generation technologies. For example, the most developed nations, including the G7, have created

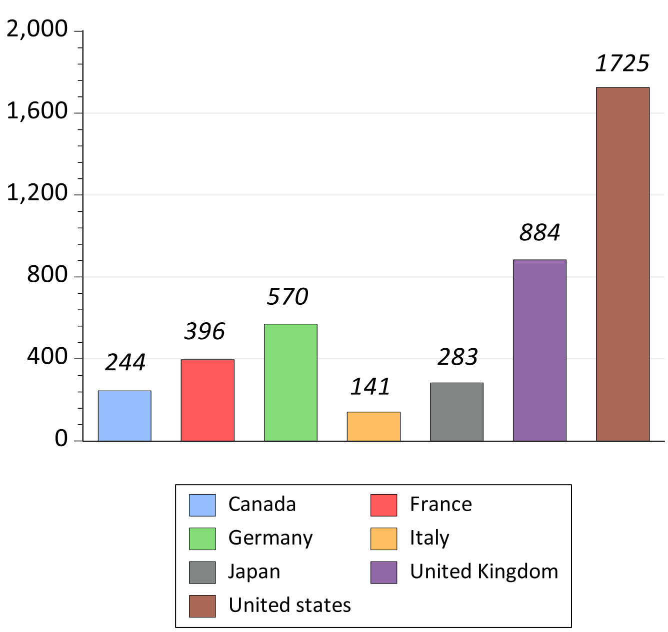


Source: [16]

Fig. 1. Marine energy generation's potential in the United States.
Source [16].

new marine energy technologies that increase energy production and reduce reliance on non-renewable energy sources. These nations have adopted these technologies due to the numerous benefits of marine energy [19]. As per Fig. 2, the United States developed more marine energy-related technologies than other G7 states between 1990 and 2018, indicating that marine energy has become a technology of choice in the United States [12].

The process of marine energy generation and technology adoption in other countries is either slow or neglected for the following reasons. First, the development of marine energy generation-related technologies requires substantial financial resources. The high project costs continue to be a serious concern, further intensified by a lack of funding due to financial crises [20]. Second, oceans serve as fisheries and shipping routes, while coasts are attractive and prime destinations for tourists. Waterways are vital for economies worldwide, and all countries have regulatory and legal restrictions and challenges. Entrepreneurs are often hesitant to invest their time, energy, and resources on projects that may become entangled in regulation and litigation. They consider such issues before venturing into the new territory of marine energy production. Third, the lack of governmental support makes it more challenging to promote renewable energy generation in other countries. Politicians are generally interested in projects that result in thousands of jobs, yet marine energy technology manufacturers cannot give such assurances. Fourth, marine energy is a new energy paradigm; thus, very few politicians comprehend its potential. Such unawareness makes it more difficult to mobilize citizens who can influence elected officials to promote marine energy development. Lastly, the public is unaware of the possibilities for marine energy devices, making it difficult to tap into a deep vein of public support to attract investors and entrepreneurs [21].



Data source: [19]

Fig. 2. Total number of marine energy generation-related technologies in G7 countries during 1990–2018.
Data source [19].

Congruent with the above, many research institutes, enterprises, governments, and universities in the United States have recognized that environmental pollution and the long-term alteration of global weather patterns are threats to humans and wildlife. Fig. 3 reflects the emphasis of the United States on IMEGDTT and ICGTD. As seen below, the IMEGDTT developed at an average rate of 16.22% between 1998 and 2016 (maximum expansion = 54%, 2007; minimum expansion = 3%, 2008). In Fig. 4, the graph shows that the ICGTD upsurged at an average rate of 3.26% between 1990 and 2018 (maximum increase = 18.2%, 1996; minimum increase = 4.5%, 2014). Considering the IMEGDTT and ICGTD developments from 1998 to 2002, 2007–2008, and 2010–2013, it seems that these technological innovations will play a significant role in shaping the environmental and technical future of the United States and the world at large. Despite that, no published work has explored the relationships between IMEGDTT, ICGTD, and CO_{2e}. This study is an initial attempt to address this knowledge gap and open possibilities for future research.

This study contributes to the extant works in several ways. Firstly, the paper offers the first empirical framework on the connections between IMEGDTT and CO_{2e}. Secondly, this study presents the first macroeconomic model that analyzes the links between IMEGDTT, ICGTD, and CO_{2e}. Thirdly, unlike the previous studies that used the STIRPAT

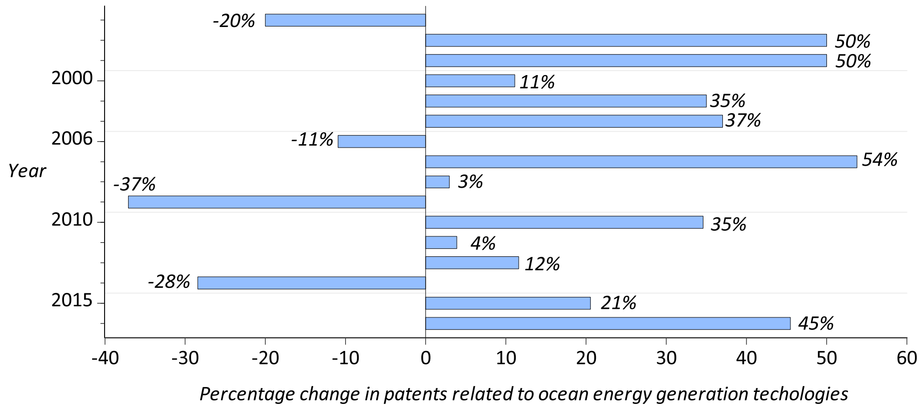


Fig. 3. Development in IMEGDTT (patents %) in the US during 1998–2016.

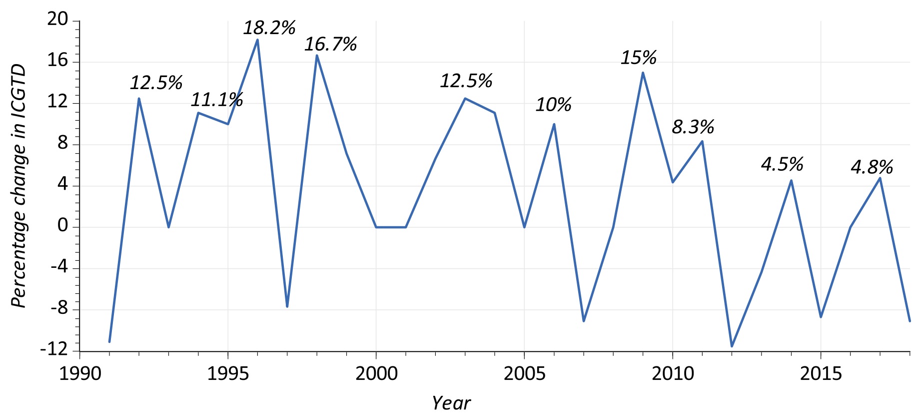


Fig. 4. Growth in ICGTD in the USA between 1990 and 2018.

model [22–25] and the environmental Kuznets curve hypothesis [26–30] to study the nexus among variables, the paper offers a novel theoretical and empirical model to explain the IMEGDTT- ICGTD-CO_{2e} nexus.

The remainder of this paper is organized as follows. Section 2 presents an overview of marine energy generation and technology progress in the United States. Section 3 discusses literature related to the nexus between innovation and CO_{2e}. Section 4 describes model specifications, data sources, and estimation techniques. Section 5 includes the results and discussion. Section 6 presents the conclusions and policy implications.

2. Literature review

Climate change is caused by emissions, such as sulfur and carbon, which interact with the atmosphere to form climate influencing aerosols [31]. CO_{2e} is not released into the environment due to industrial production or household consumption. Emissions are generated through energy-use, which includes the consumption of non-renewable resources. Researchers have evaluated these emissions in relation to a number of factors, including traditional and renewable energy sources such as geothermal, wind, and solar energy [31–35]. Several factors contribute to CO_{2e}, and include: public transportation [36], negative shocks to innovative activities [37], natural resources [38], expansionary commercial policy [39], underground economies [40], financial development [41,42], military expenses [43], inflow of remittances [44, 45], gross fixed capital formation [46], aggregate domestic consumption expenditures [47], government expenditures [48], expansionary fiscal policy [49], energy prices (Umar et al., 2021), fossil fuel consumption [51], fiscal decentralization [52], industrialization [53], globalization [54], urbanization [55], international tourism [56], electricity consumption [57], trade openness (TO) [58], gross domestic product [59], public-private co-investment in non-renewable energy [60], deforestation [61], transportation services [62], population growth [63], energy demand [64], and institutional quality [65].

Besides these, various other factors can help in mitigating CO_{2e}. These include are: green innovation [66], regulating interest rates [67] and uncertainty about economic policies (Jiang et al., 2019), high-technology exports [69], renewable energy consumption [38], information and communication technology [70], positive shocks in innovation [37], consumption of natural gas, liquefied petroleum gas, hydropower [71], contractionary commercial policy [39], governmental expenditure on education [56], contractionary fiscal policies [49], green taxation [72], contractionary monetary policies [73], higher education [74], economic complexity [75], public and private health expenditure [76], reducing income inequalities [77], waste energy usage [78], LPG consumption [79], regulating business environments [80], and good governance [80].

One of the most effective strategies for reducing CO_{2e} has been introducing and improving green technologies through green innovation. The term “green innovation” was first introduced by Ref. [81], defined as new products and processes that enable the efficient supply of products and goods from businesses to consumers and decrease negative environmental impacts [82,83]. However [84], argued that green innovation refers to any form of innovation contributing to the development of key goods that help minimize environmental damage and improve the use of natural resources. Green innovation improves environmental sustainability by establishing new green ideas, behaviors, processes, and products [85]. This form of innovation has gained momentum nowadays because it facilitates the appropriate use of natural resources to enhance human well-being [84]. Recognizing the role of green innovation in reducing CO_{2e}, several authors have examined innovative activities and their effects on environmental pollution. For instance Ref. [86], studied the nexus between technological innovation and CO_{2e} using the quantile autoregressive distributive lag technique. The results validated that technological innovation plays a vital role in reducing CO_{2e} in China. Furthermore, the authors argued that innovation also improves economic growth and saves energy by implementing sustainable business practices and energy efficiency in emerging countries. In another study [87], corroborated negative associations between innovation and CO_{2e}, encouraging economies to invest in research and development activities that combat global weather patterns by decreasing CO_{2e}. Likewise [88], reported that improving energy innovation had promoted cleaner environments in seventeen OECD economies by reducing their CO_{2e} [89]. found that energy innovations helped decrease CO_{2e}. Another study [90] found that positive shocks to innovation had decreased CO_{2e}, but negative shocks to innovation had increased CO_{2e} in OECD economies. Another study by Cheng, Ren, Wang, and Yan [91] suggested that the introduction and implementation of environmental patents had curbed CO_{2e} in BRICS countries. These findings resonate with the earlier works supporting that R&D activities reduce CO_{2e} in OECD states (e.g. Refs. [37,88,89,92]). Besides, other studies have also asserted that innovation is an important factor that mitigates CO_{2e} in the United States [93], BRICS [94], China [8, 95–105], G-7 states [106,107], Japan [108,109], Africa [110], 71 selected economies [111,112], G-20 economies [4], developed countries [113,114], selected petroleum companies [115], OECD states [66, 116–119], European economies [120], Malaysia [121], 27 EU states [122] and N-11 states [123]. Table 1 presents a summary of the selected studies that have investigated the nexus between innovation and CO_{2e}.

Table 1
Summary of the selected studies on the nexus between innovation and CO_2e.

Authors	Country	Year	Method	Relationship between innovation/green innovation and CO_2e
[86]	China	1995 to 2017	QARDL	Negative
[107]	G-7 Countries	1990–2017	CS-ARDL	Negative
[91]	BRIICS Countries	2000–2013	POLS; PQRM	Positive
[124]	Saudi Arabia	1970–2014	ARDL	No effect
[8]	China	1997–2008	DPD	Negative
[125]	China	1971–2018	Wavelet Coherence Method	Negative
[109]	Japan	2001–2010	FE	Negative
[126]	Italy	1990–2010	FE	No effect
[66]	OECD Countries	1990–2015	OLS、ARDL、VECM	Negative
[103]	China	2000–2010	Dynamic Panel Model	Negative
[104]	China	1984–2018	BARDL	Negative
[106]	G-7 Countries	1870–2014	NPPDM	Negative
[96]	China	1997–2015	STIRPAT	Negative
[100]	China	1990–2017	GLS, FMOLS, DOLS, CCR	Negative
[122]	EU-27 Countries	1992–2014	GMM	Negative
[110]	African Countries	1990–2016	FE and GMM	Negative
[117]	OECD Countries	1999–2014	STIRPART	Negative
[92]	China	2005–2018	FMOLS; DOLS; CCR	Negative
[115]	Petroleum Companies	2005–2016	ARDL	Negative
[4]	G-20 Countries	1991–2017	CCE and AUG	Negative
[89]	OECD Countries	1994–2010	FE	Negative
[101]	China	2000–2015	SPEM	Negative
[111]	71 Countries	1992–2012	PTM	Negative
[87]	Emerging Market Economies	1990–2018	FE	Negative
[88]	OECD Countries	1990–2012	FE	Negative
[99]	China	2000–2014	FE and FGLS	Negative
[120]	Europe, North America, and Japan	Since 1800	EKD	Negative
[105]	China	2001–2017	SPEM	Negative
[102]	China	1997–2014	SEM	Negative
[113]	EU Countries	1990–2013	OLS	Negative
[127]	United States	1990Q1-2018Q4	FMOLS	Negative
[121]	Malaysia	1971–2013	VECM	Negative
[51]	OECD Countries	1993–2014	GMM	Positive
[128]	96 Countries	1996–2018	SEM	Negative
[116]	OECD Countries	1990–2014	STIRPAT	Negative
[129]	BRICS Countries	1980–2016	CCEMG	Negative
[92]	OECD Countries	1996–2015	PQRM	Negative
[123]	N-11 Countries	1990–2017	CCEMG	Negative
[118]	OECD Countries	1981–2014	SVCPDM	Negative
[93]	United States	1990Q1-2016Q4	FMOLS	Negative
[94]	BRICS	1990Q1-2016Q4	AMG	Negative
[97]	China	1990–2018	ARDL	Negative
[114]	Developing nations	1990–2016	FMOLS	Negative

3. Model specification, data sources, and estimation techniques

3.1. Model specification

Following [130,131], values representing the relationship between a single input and final output can be obtained using the following equation:

$$Y_t = A_t K_t^{\theta} \tag{1}$$

where K_t represents the aggregate stock of capital, A_t denotes the marginal productivity of capital, and Y_t represents the aggregate final productivity.

The primary objective of every firm is to increase profits and lower production costs [132]. They can achieve this goal through innovative activities [133,134]. Extant literature offers the following innovation goals: i) achieving sustainable development goals; ii) lowering production costs; iii) introducing niche products or technology; iv) improving working conditions; v) improving production processes for existing products; vi) lowering energy consumption; vii) replacing products being phased out; viii) lowering raw material consumption; ix) maintaining or increasing market share; x) enhancing existing technology to reduce imported tools; xi) developing new domestic markets; xii) improving product quality; xiii) exploiting new international markets. Hence, following [37], innovation (Z) activities can be included in Equation (1):

$$Y_t = A_t K_t^{\theta} Z_t^{\delta} \tag{2}$$

The amount of money spent on innovative activities is also a good indicator of a country's creative experimental, applied, and basic research efforts. Innovative activities improve an economy's productivity and have positive spillover effects on the overall economy, including increased aggregate demand and economic growth [135].

Total innovation can be classified into general innovation and green innovation (GI) [136]. GI refers to creating and implementing novel

Note: ARDL = Autoregressive Distributive Lag, CCEMG = common correlated effect mean group, OLS= Ordinary Least Square, FE=Fixed Effect, STIRPAT= Stochastic Impacts by Regression on Population, Affluence, and Technology, NPPDM= Non-parametric Panel Data Model, SVCPDM= Short-run Time-varying Coefficient Panel Data Models, QARDL = Quantile Autoregressive Distributive Lag, GMM = Generalized Methods of Moment, CCR = canonical cointegrating regression, AUG = Augmented Mean Group, GLS = Generalized Least Square, SEM= Simultaneous Equation Models, FMOLS=Fully Modified Ordinary Least Square, EKD = Extended Kaya Decomposition, SPEM= Spatial Econometrics Model, VECM= Vector Error Correction Models, DOLS = dynamic ordinary least squares, PRQM=Panel quantile regression model, PQRM =Panel Quantile Regression Method, POLS=Panel OLS Methods, VECM= Vector Error Correction Models, PTM= Panel Threshold Model, BARDL= Bootstrapping Autoregressive Distributed Lag Modeling, SPEM= Spatial Econometrics Model and DPD = Dynamic Panel Data.

green and sustainable technologies that increase energy efficiency and productivity and reduce CO_{2e} [137]. In most cases, firms initiate GI due to strict environmental regulations. For instance, Borsatto and Bazani [138] argued that environmental regulations positively affect GI and contribute to decreases in CO_{2e}. Thus, Z can be substituted by GI using the following equation:

$$Y_t = A_t K_t^{\theta} \mathrm{GI}_t^{\delta} \tag{3}$$

In addition to GI, some firms are also involved in international collaboration in green technology development (ICGTD) to co-develop green technology. Generally, ICGTD involves sharing green knowledge, costs, and efforts, to promote and accelerate technical green developments and the co-invention of environmentally friendly technologies [139]. It is an efficient approach that slows the process of biodiversity loss and pollution [140]. International cooperation can help economies become more efficient by improving green R&D performance and enhancing sustainable development [11]. Hence, ICGTD can be applied through the following mathematical expression:

$$Y_t = A_t K_t^{\theta} \mathrm{GI}_t^{\delta} \mathrm{ICGTD}_t^{\gamma} \tag{4}$$

The burning of fossil fuels and industrial activity are the primary sources of CO_2 from human activities [141]. [142] argued that industrial sectors are the main sources of CO_2 emissions. Following [39], the nexus between industrial production (Y_t) and CO_{2e} can be represented in the following equation:

$$CO_{2et} = f(Y_t) \tag{5}$$

where $f(Y_t) = A_t K_t^{\theta} \mathrm{GI}_t^{\delta} \mathrm{ICGTD}_t^{\gamma}$. After inserting Equation (4) into Equation (5), the following equation is obtained:

$$CO_{2et} = A_t K_t^{\theta} \mathrm{GI}_t^{\delta} \mathrm{ICGTD}_t^{\gamma} \tag{6}$$

In general, GI can be classified into the following categories: production or processing of goods, wastewater treatment, ocean renewable energy generation, information and communication technologies (ICT), adaptation technologies, energy efficiency in communication networks, processing of minerals, energy generation from fuels of non-fossil origin, energy efficiency in buildings, combustion technologies with mitigation potential, integration of renewable energy sources in the building, and efficient electrical power generation, transportation, and disposal of perfluorocarbons [143]. It can be assumed that enterprises involved in the above industries engage in innovations related to marine energy generation, distribution, or transmission-related technologies (IMEGDTT). Hence, GI can be replaced by IMEGTT, obtaining the following equation:

$$CO_{2et} = A_t K_t^{\theta} \mathrm{IMEGDTT}_t^{\delta} \mathrm{ICGTD}_t^{\gamma} \tag{7}$$

Marine energy refers to energy extracted from oceanic sources using various methods. There are four primary ways to generate electricity from oceans using marine currents. Underwater turbines, conceptually similar to wind turbines, can be used to draw energy from oceans. The second source of marine energy is wind-generated waves. The energy contained in these waves can be harnessed using a variety of installations placed near the shore, anchored to the seabed, floating, or in deep water. Heat, indirectly through the Sun, is the third source. The oceans of the world, particularly those in tropical regions, are giant solar collectors accumulating heat energy during the day. The fourth energy source is released when surface water from a river enters the ocean and combines with salt water [144].

Like other emerging technologies, marine energy devices inhibit a high potential to contribute to green and sustainable technological progress. Device-specific R&D, technological enhancements, and innovation in marine energy converters are crucial for achieving these advances. With combinations of tidal and wave projects, the increasing numbers of offshore wind turbine installations could lead to shared infrastructure developments [145,146].

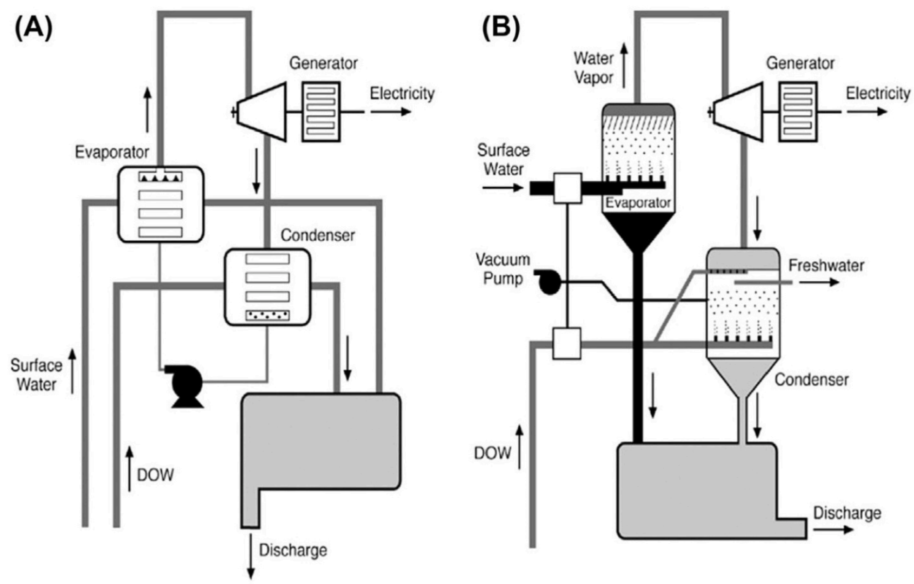
There is a range of fields where innovative solutions and technological advancements in the marine energy industry can solve technical and environmental problems. These benefits include, but are not limited to lower-costs, technology-specific installations, oil and mineral methodologies, improved biofouling and corrosion-resistant materials and/or coatings, cost-effective and durable moorings/foundations, robust and affordable watertight seals and bearings, robust dynamic umbilical cables, and cost-effective electrical wet-mate connectors [147].

Climate change mitigation and CO_{2e} are among the main drivers of the increased demand for IMEGDTT. The willingness to reduce the environmental impact of fossil fuels, especially CO_{2e}, and lessen dependence on energy imports has been the main driver for promoting IMEGDTT in most industrialized economies. IMEGDTT holds the potential to improve access to modern energy services that are reliable, accessible, and clean. It is especially well-suited to remote rural communities, and in many cases, it is the lowest cost option to obtain electricity. Compared to fossil fuels, most new technologies related to ocean energy generation emit less CO_{2e} into the environment, making them valuable tools for combating climate change [146]. For example, ocean thermal energy conversion system technology (OTECH), which generates electricity by combining cold deep ocean water (DOW) with warm surface water, is frequently employed. Open-cycle OTEC and small pilot-scale closed-cycle plants (see Fig. 5) were successfully conceived, constructed, and tested during the subsequent decades. A single OTEC plant can be used to generate freshwater and electricity. DOW-enhanced open ocean mariculture can significantly boost global fish catch and facilitate the movement of CO_{2e} from air to water. As a result, the integrated development of DOW as a natural resource lies at the heart of a blue revolution that can address four of the world's most pressing issues: CO_{2e} (global warming), food security, freshwater, and energy [148].

Besides, the hybrid cycle (see Fig. 6) combines the benefits of both open- and closed-cycle systems, integrating the ability to produce drinking water with significant amounts of power. This cycle involves the entry of warm salt water (from the water's surface) into a vacuum chamber, where it is flash-evaporated. Following that, this steam is routed to a heat exchanger, where it acts as a warm fluid that heats the working fluid in a close loop. The ammonia is used to power a turbine connected to an energy generator, which supplies electricity to households. Both OTECH and hybrid systems represent clean, renewable energy types that do not entail the combustion of fossil fuels, the emission of significant volumes of greenhouse gases, or the release of hazardous air pollutants. OTEC and hybrid systems may also assist in reducing current dependency on fossil fuels (e.g., oil) and marine pollution caused by oil tanker spills [148]. Thus, electricity or energy generation via marine technologies is environmentally friendly and contributes to CO_{2e} abatement. Based on the above arguments, it is expected that $\delta < 0$.

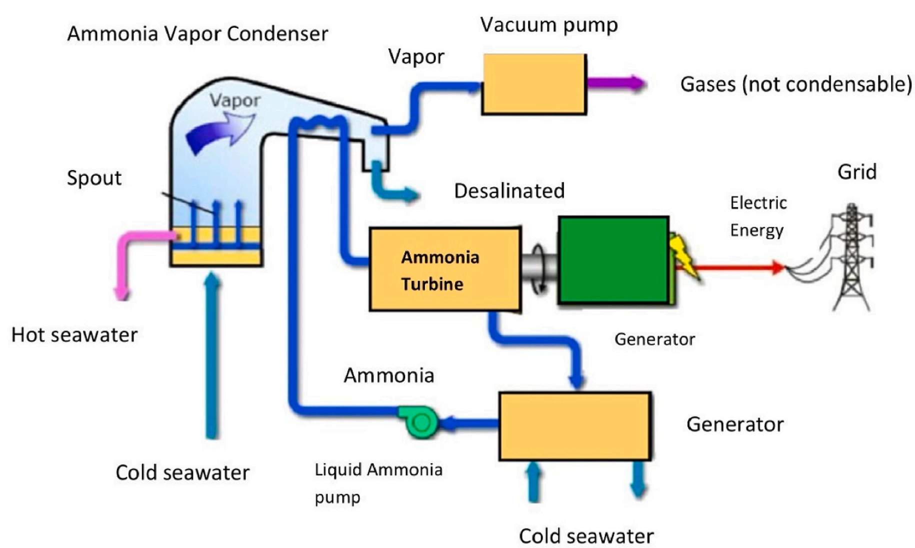
Next, following previous studies of [49,73,149–153], this study integrates gross domestic product per capita (GDPPC), TO, and expansionary monetary policy (EMP) in the following equation:

$$CO_{2et} = A_t K_t^{\theta} \mathrm{IMEGDTT}_t^{\delta} \mathrm{ICGTD}_t^{\gamma} GDPPC_t^{\varrho} TO_t^{\xi} EMP_t^{\Gamma} \tag{8}$$



Source: [148]

Fig. 5. OTECH systems (A represents a small pilot-scale closed-cycle plant; B indicates the DOW technology system).
Source [148].



Source: [148]

Fig. 6. Hybrid marine energy generation, distribution, or transmission system.
Source [148].

where K represents the total capital resources used in production activities. Capital resources can also be divided into two categories: energy and non-energy capital resources [49]. suggested that only energy capital resources lead to CO_{2e}. Following the studies of [37,47], K_t can be replaced by REC_t:

$$CO_{2et} = A_t REC_t^{\theta} IMEGDTT_t^{\delta} ICGTD_t^{\gamma} GDPPC_t^{\varrho} TO_t^{\xi} EMP_t^{\Gamma} \tag{9}$$

Following the studies of [49,129,154,155], it is expected that $\theta < 0$, $\varrho > 0$, $\xi > 0$ and $\Gamma > 0$. In addition, the introduction and development of ecological technologies via ICGTD not only reduces the consumption of non-renewable energy but also assists in shrinking businesses' carbon footprint, reducing CO_{2e}, and reducing waste. Therefore, it is expected that $\gamma < 0$.

Using the logarithm of Equation (9), a linear model is obtained:

$$\begin{aligned} logCO_{2et} = {} & \alpha_0 + \theta logREC_t + \delta logIMEGDTT_t + \gamma logICGTD_t + \varrho logGDPPC_t \\ & + \xi logTO_t + \Gamma logEMP_t \end{aligned} \tag{10}$$

The following final model in obtained after adding error terms to Equation (10):

$$\begin{aligned} logCO_{2et} = {} & \alpha_0 + \theta logREC_t + \delta logIMEGDTT_t + \gamma logICGTD_t + \varrho logGDPPC_t \\ & + \xi logTO_t + \Gamma logEMP_t + \mu_t \end{aligned} \tag{11}$$

3.2. Data description

This study used data from a series that included: imports of goods (constant USD), GDP per capita (constant USD), renewable energy consumption (thousands toe), exports of goods (constant USD), GDP (constant USD), international collaboration in green technology development (percent within country-co-inventions), innovation in marine energy generation, and distribution. The World Bank and OECD databases were used to compile the data. The data on renewable energy consumption, international collaboration in green technology development, innovation in marine energy generation, distribution, or transmission-related technologies, and carbon dioxide emissions were accumulated from the OECD database. At the same time, imports of goods, gross domestic product per capita, exports of goods, and gross domestic product were collected from the World Bank. This study used a quadratic match sum approach (QMSA) to transform annual data into the quarter frequency to increase the frequency of data [39]. This technique corrects intermittent or irregular fluctuations and reduces point-to-point variations [141]. All variables were converted into logarithms. Table 2 presents a description of all variables.

Table 2
Summary and description of the variables and data.

Variables	Notation	Description	Source of data	Estimation method
Imports of goods	IMP	Constant US$	[156]	QMSA
Gross domestic product per capita	GDPPC	Constant US$	[156]	QMSA
Renewable energy consumption	REC	Thousands toe	[157]	QMSA
Exports of goods	EXP	Constant US$	[156]	QMSA
Trade openness	TO	Sum of EXP and IMP divided by GDP	–	QMSA
Gross domestic product	GDP	Constant US$	[156]	QMSA
Interest rates	IR	Percentage per annum	[158]	QMSA
International collaboration in green technology development	ICGTD	Patents on environment-related technologies (percent within country-co-inventions)	[19]	QMSA
Innovation in marine energy generation, distribution, or transmission-related technologies	IMEGDTT	Number of green patents related to energy generation, distribution, or transmission-related technologies	[19]	QMSA
Carbon dioxide emissions	CO_{2e}	Million tones	[143]	QMSA

3.3. Estimation techniques

3.3.1. Unit root tests

Several financial and economic time series (i.e., exchange rates, trade openness, real GDP, asset prices, etc.) show nonstationary or trending behavior in their means. Determining the most suitable form of the trend in the data is an essential econometric task. Time-trend regression and first differencing are two typical trend removal techniques. For $I(0)$ time series, time-trend regressions are suitable, and for $I(1)$ time series, first differencing is appropriate. Unit root tests can be applied to determine if the trending data should be $I(1)$.

Moreover, finance and economic theory often assume the presence of a long-run equilibrium nexus among nonstationary time-series variables. Co-integration techniques may be used to model these long-run relationships if these variables are $I(1)$. Therefore, the unit root is employed to determine the order of integration [159]. This study uses [160,161] unit root tests with a breakpoint. The critical difference between PP and Augmented Dickey-Fuller (ADF) tests is how they sort out heteroscedasticity and serial correlation in the errors. In particular, the PP tests avoid any serial correlation in the regression. In contrast, the ADF tests use a parametric autoregression to estimate the ARMA structure of the errors in the test regression [162].

Standard unit root tests, such as PP fail to detect the presence of structural breaks in the time series, resulting in biased and inconsistent results. Structural breaks have a significant impact on the properties of the data, and thus, they provide useful knowledge on how they behave. The study of structural breaks in the periodic development of variables offers valuable details about the function and evolution of the variables and ties real-world events to econometric analysis. Therefore, it is important to employ this method. Furthermore, structural breaks in unit root tests lead to incorrect inferences about the order of integration [163]. Therefore, this study also employs the [161] unit root test with a breakpoint.

3.3.2. Co-integration tests

The co-integration associations among IMEGDTT, TO, EMP, GDPPC, ICGTD, REC, and ICGTD can be checked using the bound co-integration test. The bounds test for co-integration has several advantages. First, this approach applies to small sample size. Second, the bounds test can be used to inspect the co-integration nexus irrespective of the order of integration series (i.e., I (0) or I (1) or a mixture of both). Third, unlike other traditional co-integration methods, the bounds test allows for various optimal lags for the variables. Finally, other traditional co-integration techniques use system equations to compute the co-integration nexus; conversely, the bounds test applies a single reduced-form equation to compute both co-integration associations [164,165]. The bounds test for co-integration is based on the computation of the following econometric equation:

$$\begin{aligned}\Delta logCO_2e_t = \beta_0 + \sum_{i=1}^{m}\chi_1 logCO_2e_{t-i} + \sum_{i=1}^{m}\chi_2 \mathrm{logICCMTCI}_{t-i} \\ + \sum_{i=1}^{m}\chi_3 log\mathrm{ICGTD}_{t-i} + \sum_{i=1}^{m}\chi_4 \mathrm{logTO}_{t-i} + \sum_{i=1}^{m}\chi_5 \mathrm{logREC}_{t-i} \\ + \sum_{i=1}^{m}\chi_6 \mathrm{logGDPPC}_{t-i} + \sum_{i=1}^{m}\chi_7 \mathrm{logEMP}_{t-i} + \sum \chi_8 BY + \psi_1 logCO_2e_{t-i} \\ + \psi_2 \mathrm{logIMEGDTT}_{t-i} + \psi_3 \mathrm{logICGTD}_{t-i} + \psi_4 logTO_{t-i} \\ + \psi_5 logREC_{t-i} + \psi_6 logGDPPC_{t-i} + \vartheta_7 logEMP_{t-i} + \vartheta_8 BY + \mu_t\end{aligned} \quad (12)$$

where μ_t denotes error terms, m indicates lag operators, β_0 is intercepts, Δ is the first difference operator, and BY represents the break years. After the computation of Equation (10), the following hypothesis is tested using the F-statistic:

$$H_0: \ \psi_2 = \psi_3 = \psi_4 = \psi_5 = \psi_6 = \psi_7 = \psi_8 = 0$$

$$H_1: \ \psi_2 \neq \psi_3 \neq \psi_4 \neq \psi_5 \neq \psi_6 \neq \psi_7 \neq \psi_8 \neq 0$$

3.3.3. Estimation of long-run coefficients

After confirmation of co-integration, the next step is to estimate long-run coefficients by employing the fully modified ordinary least squares (FMOLS), canonical co-integration regression (CCR), and dynamic ordinary least squares (DOLS). The FMOLS estimator was introduced to compute long-run coefficients by modifying the conventional OLS. It sorts out the problems of serial correlation and endogeneity that usually occur when employing the conventional OLS technique [39,166,167]. Previous research has shown that FMOLS is superior to other econometric techniques for estimating co-integration associations. For instance Refs. [168,169], validated the merits of FMOLS in computing the co-integration nexus among variables and correcting endogeneity and serial correlations. In addition, the FMOLS allows for the possible existence of an association among error terms, constant terms, and the difference among regressors [170].

Compared to FMOLS, DOLS is a parametric technique that corrects autocorrelation. Moreover, the DOLS is also applicable to a small data series and allows for the combination of different variables in the analysis, and has several advantages in estimating cointegrated vectors. Furthermore, the DOLS can be used to estimate cointegrated vectors for small datasets and accounts for the combination of various variables in this study. It also has a variety of advantages when estimating cointegrated vectors. The DOLS is also used to test for consistency between expectations and estimators [170]. In addition to DOLS and FMOLS, the CCR employs a stationary conversion method to overcome the long-run interaction between stochastic regressor errors and the co-integration equation [171].

4. Results and discussion

The descriptive statistics (i.e., maximum, minimum, median, mean, standard deviation, etc.) of the data series are shown in Table 3. The median value of the level of GDP (constant US$), RIR (percentage), REC (thousands toe), IMP (constant US$), EXP (constant US$), GDPPC (constant US$), ICGTD (green co-inventions), CO_{2e} (million tons) TO (percentage), and IMEGDTT (green patents related to ocean renewable energy generation) are 1.22×10^{13}, 0.50, 106066.7, 1.80×10^{12}, 1.18×10^{12}, 41712.80, 79, 5355.71, 0.25, and 28, respectively. The minimum levels of GDP (constant US$), RIR (percentage), REC (thousands toe), IMP (constant US$), EXP (constant US$), GDPPC (constant US$), ICGTD (green co-inventions), CO_{2e} (million tons) TO (percentage), and IMEGDTT (green patents related to ocean renewable energy generation) during 1990–2018 were 5.96×10^{12}, −0.91, 89223.75, 6.24×10^{11}, 5.52×10^{11}, 23888.60, 70, 4900.40, 0.20, and 1, respectively. Furthermore, the US's highest level of GDP (constant US$), RIR (percentage), REC (thousands of toes), IMP (constant US$), EXP (constant US$), GDPPC (constant US$), ICGTD (green co-inventions), CO_{2e} (million tons) TO (percentage), and IMEGDTT (green patents related to ocean renewable energy generation) during 1990–2018 were 2.06×10^{13}, 0.91, 172385.1, 3.14×10^{12}, 2.53×10^{12}, 62996.47, 93, 5861.10, 0.31, and 135, respectively.

Table 4 shows the PP unit root test statistic in the absence of a structural break. The computed values of the PP unit root test are less than the critical values at the level; hence, the null hypothesis of unit root can be accepted for all variables, including CO_{2e}, ICGTD, GDPPC, IMEGDTT, TO, REC, and EMP. This concept implies that at this level, all the variables are nonstationary. However, CO_{2e}, ICGTD, GDPPC, IMEGDTT, TO, REC, and EMP become stationary after taking the first difference. In other words, the estimated values of the PP unit root test are more significant than the critical values at the difference; thus, the alternative hypothesis of stationarity is accepted at the 1% level of significance. As noted earlier, the findings of classical unit root tests may be inconsistent and spurious in the presence of structural breaks in the data series. Therefore, the Perron unit root test with a breakpoint was employed to test for random walk and stationarity in the presence of structural breaks.

Table 4
Phillips–Perron (PP) test Unit Root Test.

Variables	Intercept	Trend and intercept	Decision
At level			
CO_{2e}	−1.585	−1.467	–
ICGTD	−1.491	−1.096	–
GDPPC	−0.858	−1.419	
IMEGDTT	−1.862	−2.929	–
TO	−1.502	−1.426	–
REC	1.029	−0.769	–
EMP	−0.472	−1.909	
At first difference			
CO_{2e}	−4.861***	−4.758***	I (1)
ICGTD	−6.419***	−9.651***	I (1)
GDPPC	−4.137**	−4.179**	I (1)
IMEGDTT	−5.938***	−5.816***	I (1)
TO	−5.227***	−5.174***	I (1)
REC	−4.905***	−4.909***	I (1)
EMP	−3.687**	−3.672***	I (1)

Note: *** depicts 1% levels of significance.

The findings of the Perron unit root test with a breakpoint are presented in Table 5. The results validated that CO_{2e}, ICGTD, GDPPC, IMEGDTT, TO, REC, and EMP have a unit root at the level. The structural breaks are detected in CO_{2e} (2008Q1), ICGTD (2001Q1), GDPPC (1991Q4), IMEGDTT (2003Q2), TO (2003Q1), REC (2009Q1), and EMP (2007Q1). After taking the first difference, all variables are stationary, indicating that CO_{2e}, ICGTD, GDPPC, IMEGDTT, TO, REC, and EMP are integrated at $I(1)$. The same integrating order of CO_{2e}, ICGTD, GDPPC, IMEGDTT, TO, REC, and EMP supports testing the presence of co-integration among variables. For this purpose, a bound test for co-integration in the presence of a structural break was applied.

The results of the co-integration tests are presented in Table 6. The Akaike information criterion (AIC) was used to determine the lag order

Table 5
Perron unit root test with a breakpoint.

Variables	t-statistic	Break year	Decision
At level			
CO_{2e}	−3.786	2008Q1	
ICGTD	−2.501	2001Q1	
GDPPC	−2.809	1991Q4	
IMEGDTT	−3.644	2003Q2	
TO	−3.473	2003Q1	
REC	−1.481	2009Q1	
EMP	−3.438	2007Q1	
At first difference			
CO_{2e}	−5.429***	1993Q1	I (1)
ICGTD	−6.891***	1992Q1	I (1)
GDPPC	−4.866**	2009Q1	I (1)
IMEGDTT	−7.211***	1992Q1	I (1)
TO	−6.012***	1993Q1	I (1)
REC	−5.266***	2001Q1	I (1)
EMP	−7.456***	2009Q1	I (1)

Note: Critical values: 1%: 5.34 5%: 4.80. *** depict 1% levels of significance.

Table 3
Descriptive statistics.

Statistics	GDP	RIR	REC	IMP	EXP	GDPPC	ICGTD	CO_2e	TO	IMEGDTT
Mean	1.24×10^{13}	0.26	117501.9	1.81×10^{12}	1.42×10^{12}	41647.81	80	5384.48	0.25	40
Medium	1.22×10^{13}	0.50	106066.7	1.80×10^{12}	1.18×10^{12}	41712.80	79	5355.71	0.25	28
Max.	2.06×10^{13}	0.91	172385.1	3.14×10^{12}	2.53×10^{12}	62996.47	93	5861.10	0.31	135
Min.	5.96×10^{12}	−0.91	89223.75	6.24×10^{11}	5.52×10^{11}	23888.60	70	4900.40	0.20	1
Std. Dev.	4.40×10^{12}	0.56	23445.49	8.39×10^{12}	6.47×10^{11}	11753.51	6.17	300.63	0.03	38.32
Skewness	0.155314	−0.74	0.937833	0.01	0.331425	0.07	0.38	0.09	0.11	0.637
Kurtosis	1.839571	2.14	2.565321	1.52	1.632718	1.81	2.35	1.70	1.82	2.203

Table 6
Co-integration tests with structural breaks.

Variables	Optimal lag length	Break years	Bound F-statistic
BT cointegration	AIC [2, 1, 1, 0, 0, 0, 2, 0]	1991Q4, 2001Q1, 2003Q1, 2003Q2, 2007Q1, 2008Q1, 2009Q1	4.972[a]***
Engle-Granger Co-integration Test	z-statistic	Break years	Decision
CO_{2e} → ICGTD	−5.571***	2008Q1, 2001Q1	Co-integration
CO_{2e} → GDPPC	−1.643*	2008Q1, 1991Q4	Co-integration
CO_{2e} → IMEGDTT	−4.861***	2008Q1, 2003Q2	Co-integration
CO_{2e} → TO	−4.193***	2008Q1, 2003Q1	Co-integration
CO_{2e} → REC	−4.597***	2008Q1, 2009Q1	Co-integration
CO_{2e} → EMP	−7.871***	2008Q1, 2007Q1	Co-integration
Augmented Engle-Granger Co-integration Test	t-statistic	Break years	Decision
CO_{2e} → ICGTD	−1.680**	2008Q1, 2001Q1	Co-integration
CO_{2e} → GDPPC	−1.917**	2008Q1, 1991Q4	Co-integration
CO_{2e} → IMEGDTT	−1.816**	2008Q1, 2003Q2	Co-integration
CO_{2e} → TO	−1.551*	2008Q1, 2003Q1	Co-integration
CO_{2e} → REC	−2.491**	2008Q1, 2009Q1	Co-integration
CO_{2e} → EMP	−2.231**	2008Q1, 2007Q1	Co-integration

Note: a*** represents Pesaran et al. (2001) critical value significance at 1% level. ** and *** depict the 5% and 1% levels of significance, respectively.

of the CO_{2e}, ICGTD, GDPPC, IMEGDTT, TO, REC, and EMP, because of its advantage over the Schwartz Bayesian criterion (SBC). The BC test confirmed the long-term nexus among CO_{2e}, ICGTD, GDPPC, IMEGDTT, TO, REC, and EMP in the presence of structural breaks. After validating the co-integration linkage among variables, the next step was to apply DOLS, CCR, and FMOLS to estimate the long-run coefficients. The robustness of the findings was confirmed by using Engle-Granger and augmented Engle-Granger co-integration tests in the presence of structural breaks. The results of the FMOLS, CCR, and DOLS are listed in Table 7.

The first implications of the findings are that a 1% increase in IMEGDTT led to a decrease in CO_{2e} by 0.012%. This result implies that IMEGDTT can reduce CO_{2e} from electricity generation and lead to a more efficient and environmentally friendly energy future. IMEGDTT contributes to CO_{2e} mitigation in the sense that the generation of marine energy using advanced technology increases the overall percentage of renewable energy consumption and decreases reliance on fossil fuels. Although both IMEGDTT and ocean energy generations are very expensive, the United States holds a dominant position in developing new and enhanced marine energy generation-related technologies [19]. Between 1990 and 2018, the average increase in IMEGDTT (successfully developing new maritime energy generation-related technologies) activities was sixty-one percent in the United States [19]. This progress demonstrates the United States' commitment to promoting a green economy and achieving sustainable development goals, including affordable clean energy and climate action.

Table 7
Long-run estimates.

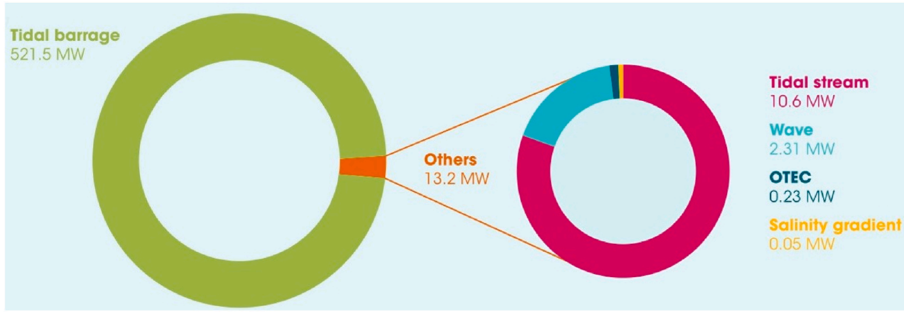
Variables	FMOLS	DOLS	CCR
ICGTD	−0.274***	−0.266**	−0.271***
	(-3.342)	(-2.428)	(-3.038)
GDPPC	0.277***	0.269***	0.274***
	(8.655)	(8.153)	(8.307)
IMEGDTT	−0.012***	−0.012**	−0.012***
	(-2.992)	(-2.064)	(-3.038)
TO	0.109**	0.133**	0.112**
	(2.129)	(2.231)	(2.264)
REC	−0.235***	−0.239***	−0.237***
	(-5.329)	(-4.385)	(-5.212)
EMP	0.025***	0.024***	0.024***
	(4.798)	(4.354)	(4.729)
C	4.280***	4.332***	4.303***
	(16.192)	(15.136)	(14.763)

Note: ** and *** depict the 5% and 1% levels of significance, respectively.

Ocean energy is regarded as an important renewable energy source. There is a growing perception that there is an infinite supply of energy awaiting utilization. Such technology has higher predictability than other variable renewable energy (VRE) sources, giving it a technological advantage over wind electricity and solar photovoltaics (PV). Marine energy generation-related technologies can generate electricity 24 h a day, seven days a week, and conserve more energy than other renewable energy sources, e.g., solar and wind [172]. In contrast, solar and wind energy are very unreliable sources of energy. Solar energy is fundamentally accessible only during daylight hours. Thus the grid operator's day-ahead plan must contain generators capable of rapidly adjusting their power output to adjust for solar generation's increase and decrease [173].

Ocean energy serves as a supplement to other renewable energy sources by providing stable power in the Hawaii state, boosting the adoption of VREs, including wind and solar energy. Currently, ocean energy generates 100 kW of regular electricity annually in the Hawaii state [18]. As a result, ocean energy is an ideal candidate for inclusion in hybrid renewable electricity generation systems. Ocean energy technology, particularly when combined with offshore wind energy, will continue to provide electricity over longer distances because waves last much longer, even if wind speeds are reduced. The applicability and affordability of ocean resources for both onshore and offshore deployments are set apart. IMEGDTT has the potential to improve the efficiency and sustainability of ocean energy technologies. It can provide electricity for several end-use sectors due to its modularity and scalability, such as desalination, cooling, ports, and tourism. Moreover, the benefits of IMEGDTT and ocean resources go beyond technological and socio-economic advantages. Because ocean energy is a renewable energy source, it helps reduce CO_{2e} from traditional CO2-intensive electricity generation sources and can help with CO_2 and climate-change mitigation [174].

Ocean energy technologies, especially wave and tidal energy, have made modest progress in the last decade. With the integration of technology (horizontal-axis turbines) and the development of many large-scale multi-turbine tidal farms, tidal energy is one step closer to commercialization. Wave energy is still in its infancy and is currently undergoing scale testing for demonstration purposes. There are a variety of new wave energy technologies being explored. Tidal energy is one, which aims for large-scale arrays. Wave energy converters are another, with two parallel pathways: one aimed at purpose-built smaller-scale devices for specific offshore applications, and the other aimed at deploying large-scale devices above 1 MW (MW). The salinity gradient and Ocean thermal energy conversion (OTEC) technologies are still in the early stages of growth, with only a few demonstration projects in place and many hurdles to overcome before achieving commercial scale. The total installed capacity of all marine energy technologies is currently 534.7 MW, with tidal barrage (or tidal range) technology accounting for the vast majority of this, as shown in Fig. 7. A tidal barrage is often excluded from current energy debates of ocean energy due to its lack of maturity and growth over the last decade. On the other hand, other



Source: IRENA (2020)

Fig. 7. Ocean energy deployment.
Source: [174].

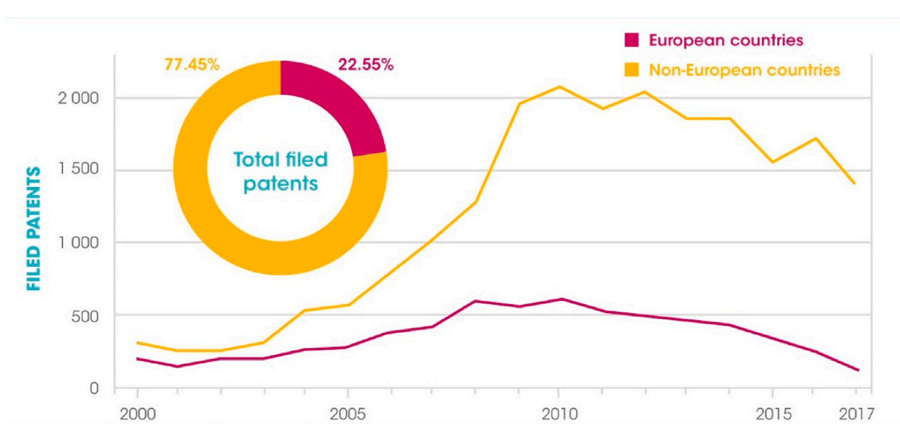
ocean energy technologies are receiving more attention due to dynamic project development. Fig. 7 provides an overview of the installed power capacity, excluding tidal barrages. Significant growth in deployment and installed capacity is anticipated in the coming years. A growing number of investors, universities, research institutes, and businesses allocate capital to advancing novel ocean technologies [174].

European countries such as Sweden, the United Kingdom (UK), Spain, Portugal, Italy, Ireland, France, and Finland, along with the United States, Canada, and Australia, have been at the forefront of the industry, with the most projects evaluated, installed, and designed in these regions. Europe intends to maintain its leadership in sustainable energy and optimize its benefits to the region. Thus, the focus is now shifting away from the western areas, with growing interest seen in various other places, most notably China, Japan, and the Republic of Korea. More experienced Western countries rapidly export climate change mitigation technology and develop projects outside their borders, with a specific interest in SIDS [174]. Furthermore, IMEGDTT is increasingly taking place outside Europe, as shown in Fig. 8.

The Federal Energy Management Program (FEMP) of the Department of Energy (DOE) assists the federal government in applying appropriate and economical energy management. They also develop policies to improve the nation's environmental stewardship and the nexus between notational security and the accessibility of natural resources for energy consumption. The FEMP aims to minimize the federal government's expenses and negative environmental impacts by encouraging energy conservation at federal facilities. The ultimate objectives are to reduce the federal government's use of fossil fuels, ensure national security, and mitigate environmental risks. The Energy Policy Act of 2005 has assisted in moving towards energy efficiency and renewable energy goals [174]. Ocean energy is an important source of renewable energy.

Oceans occupy seventy percent of the earth's surface and accumulate vast amounts of renewable energy in tidal, thermal, marine currents, and wave reserves. Even though marine energy is still in its infancy, experts are looking for ways to capture it and transform it into power. The Energy Policy Act of 2005 gives the Department of the Interior (DOI) the authority to lease land to promote energy generation, transmission, or distribution of marine energy off the Outer Continental Shelf. This leasing agency controls renewable energy plans that can use prevailing gas and oil reserves in federal waters [175].

The Levelized cost of energy (LCOE) is a cost-benefit analysis statistic for marine energy technology that includes performance and cost estimations. The Levelized cost of electricity (LCOE) is a measure of the revenue per megawatt-hour (MWh) of grid-connected electricity production required for an electricity-generating venture to "break-even" in terms of project capital and operating expenses and to provide investors with a minimum rate of return over the project's life [176]. The IEA's Technology Collaboration Program for Ocean Energy Systems analyzed the Levelized cost of energy (LCOE) for wave, tidal, and ocean thermal energy conversion technologies. The analysis drew on the industry's current state-of-the-art knowledge regarding the costs of deploying and operating each technology in its current state, as well as the cost reductions anticipated along the path to product commercialization [177]. While evaluating each technology's price and operational factors, the pre-commercial wave and tidal array, second pre-commercial wave and tidal array, and commercial-scale targets were all considered. The projected LCOE for the first commercial-scale plant was



Source: IRENA (2020)

Fig. 8. Number of ocean energy patents filed (2000–2017).
Source: [174].

USD130-280USD/MWh for tidal energy and USD120-470/MWh for wave energy. Long-term costs are predicted to fall from the initial commercial project level. Substantial cost savings in the LCOE are expected from the present installation phase to commercialization, including a 61% cost reduction for tidal energy and a fifty percent to seventy-five percent cost reduction for wave energy [177].

In comparison to other renewable energy technologies, marine energy generation-related technologies have a high potential to generate sustainable energy, supply stable electricity, and aid in CO_{2e} mitigation for the following reasons. First, while solar energy-related devices may generate electricity during overcast and rainy days, their efficiency decreases. Additionally, solar panels rely on sunshine to collect solar energy adequately. As a result, a few overcast, rainy days can significantly impact the energy system. Due to cloud cover and limited daytime hours, solar energy is intermittent and non-dispatchable without an energy storage device [178].

Conversely, marine energy-related technologies addressed these issues by ensuring constant and reliable electricity generation [179]. Second, waves are practically never stationary and are primarily in motion. Marine energy generation-related technologies further make wave energy a more reliable energy source than wind energy, as the wind does not blow continuously [179]. Third, another advantage of marine energy generation-related technologies over other renewable energy technologies is that it delivers freshwater to the populations [180]. Fourth, marine energy generation technologies, especially the OTECH, have a lower maintenance cost than solar energy generation technology [181]. Lastly, although solar panels generate clean, renewable energy, the manufacturing process can harm the environment. Solar panel manufacturing on a large scale may result in the combustion of fossil fuels and the generation of plastic trash. Even though solar generates green and sustainable energy, its production may escalate fossil fuel consumption [182]. Maritime energy generation does not cause similar issues.

Fig. 9 depicts the Federal site locations and indicates the types of marine energy technology appropriate. Dark blue highlights signify civilian facilities, while light blue highlights indicate Department of Defense (DOD) facilities and green highlights signify military bases [175]. Because of considerable progress in the production and implementation of new technologies related to ocean energy generation, reliance on fossil fuels and CO_{2e} have been reduced. As notable in Fig. 10, an increase in IMEGDTT by 25.7% (1991Q3), 42.1% (2001Q1), 51.7% (2001Q2), 54.8% (2001Q3), 51.4% (2001Q4), 43.5% (2006Q1), 39.2 (2006Q4), 38.3% (2008Q1), 27.7% (2009Q1), 8.2% (2009Q4), 4% (2014Q4) 17.4% (2016Q1), 25% (2016Q2) and 27.4% (2016Q3) led to a decrease in CO_{2e} by 0.5%, 1.2%, 2%, 2.3%, 2.2%, 1.4%, 1%, 1.5%, 8.1%, 5.5%, 0.3%, 2.3%, 2.1%, and 1.8%, respectively.

The second implication of the current findings is that implementing an EMP leads to an increase in CO_{2e}. This result implied that lowering interest rates through the monetary policy in the United States had enhanced CO_{2e}. A possible explanation is that the great recession (2009–10) in the U.S. severely affected economic activities, such as industrial production, domestic aggregate demand, aggregate income, energy consumption, and aggregate supplies. In this scenario, the central bank of the U.S. implemented an EMP to increase domestic supply and demand, industrial production, investments, and exports. For instance, a more recent case of an EMP was implemented in the United States during the Great Recession in the late 2000s. As house prices fell and the economy slowed, the Federal Reserve reduced its discount rate from 5.25% in June 2007 to 0% by the end of 2008. The decrease in real interest rate increased aggregate demand, industrial production, and fossil fuel consumption and drove up the total level of CO_{2e}. Fig. 11 depicts the unparalleled association between RIR (%↓) and CO_{2e} (%↑). This result validates previous studies conducted in Asian economies [73] and BRICS countries [49].

Third, the results suggested that a 1% increase in GDPPC led to an increase in CO_{2e} by 0.274% (CCR), 0.269% (DOLS), and 0.277% (FMOLS). This finding suggests that an increase in GDPPC induces aggregate demand, industrial activity, and the use of fossil fuels, increasing CO_{2e}. Fig. 12 depicts the parallel association between GDPPC (%↑) and CO_{2e} (%↑). This result is consistent with the previous studies carried out for emerging economies [183], NAFTA and BRIC [184], developed economies [185], global economies [186], India [187], Southern Africa [188], SEE nations [189], OECD [37], Pakistan [190, 191], G-7 nations [192], China [193], BRICS [49], South Asia [194] and U.S [195].

Fourth, the findings proposed that the REC in the production process led to a decrease in CO_{2e}. Fig. 13 depicts the unparalleled association between REC (%↑) and CO_{2e} (%↓). This result validated the previous studies conducted for Pakistan [196], Malaysia [197], Latin America [198], 17 OECD states [199], U.S. [200], BRICS [201], developing countries [202], Pakistan [203], India [204], emerging countries [205], China [206], Saudi Arab [207], Kyoto Annex countries [208], European

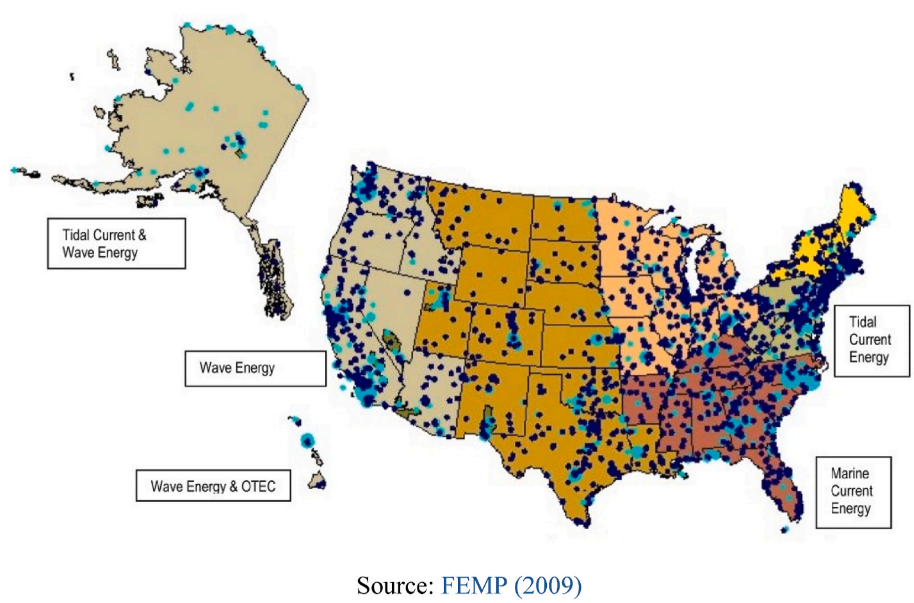


Fig. 9. Related marine energy technologies in the United States.
Source: [175].

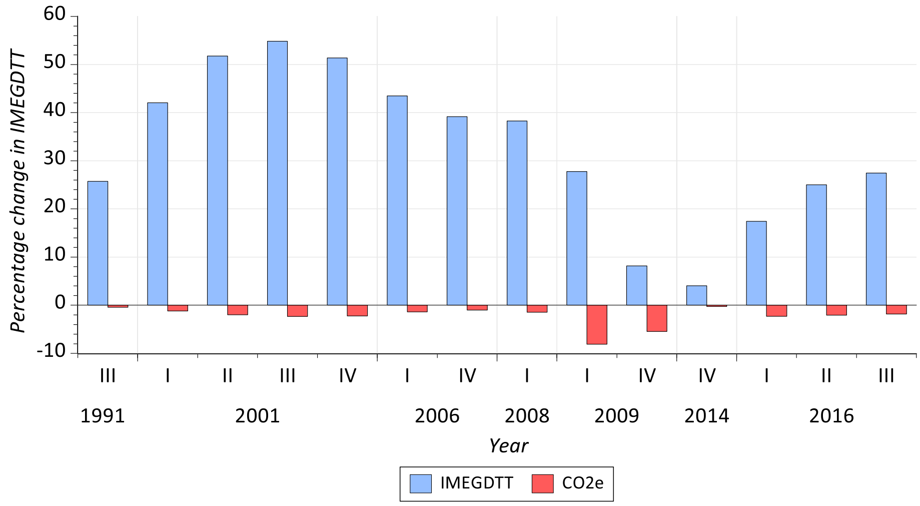


Fig. 10. Unparalleled association between IMEGDTT (%↑) and CO_{2e} (%↓).

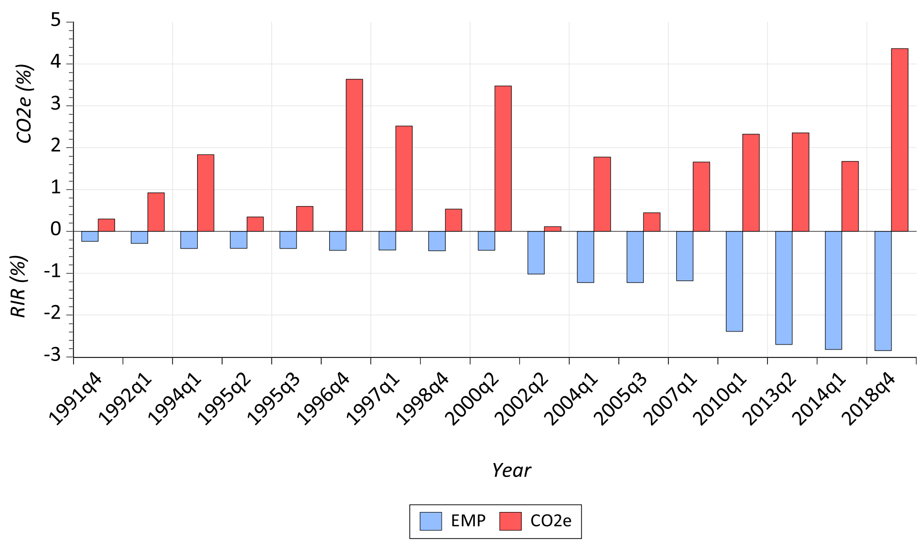


Fig. 11. Unparalleled association between RIR (%↓) and CO_{2e} (%↑).

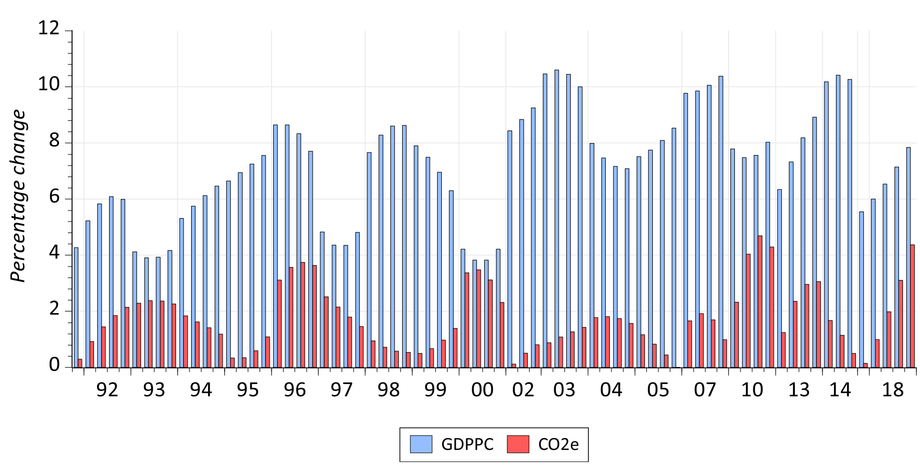


Fig. 12. Paralleled association between GDPPC (%↑) and CO_{2e} (%↑).

countries [209], Turkey [210], top renewable energy countries [211], Tunisia [212], emerging states [213] and Sub-Saharan Africa [214].

Fifth, the results show that an increase in TO contributed to higher CO_{2e}. Fig. 14 depicts the parallel association between TO (%↑) and CO_{2e} (%↑). This result is consistent with previous studies conducted in Tunisia [215], European countries [216], middle-income states [217], emerging

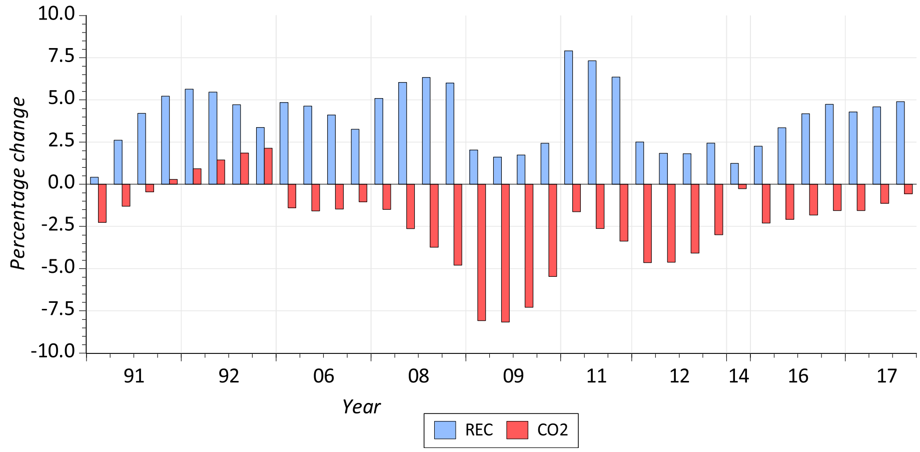


Fig. 13. Unparalleled association between REC (%↑) and CO_{2e} (%↓).

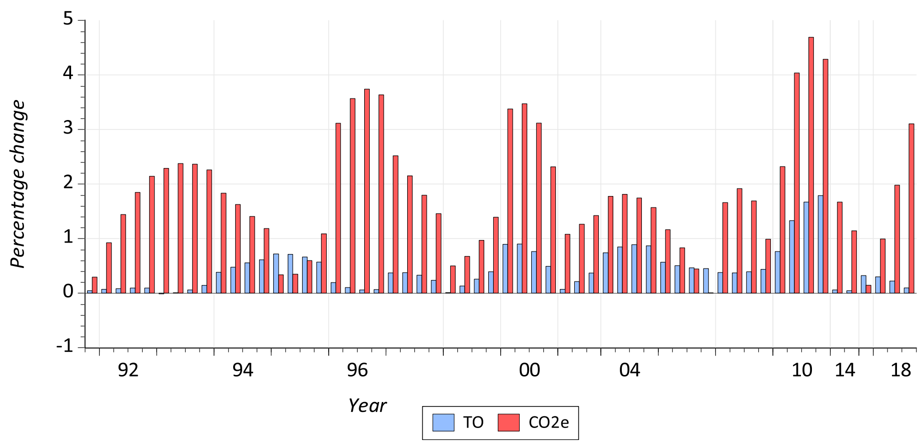


Fig. 14. Paralleled association between TO (%↑) and CO_{2e} (%↑).

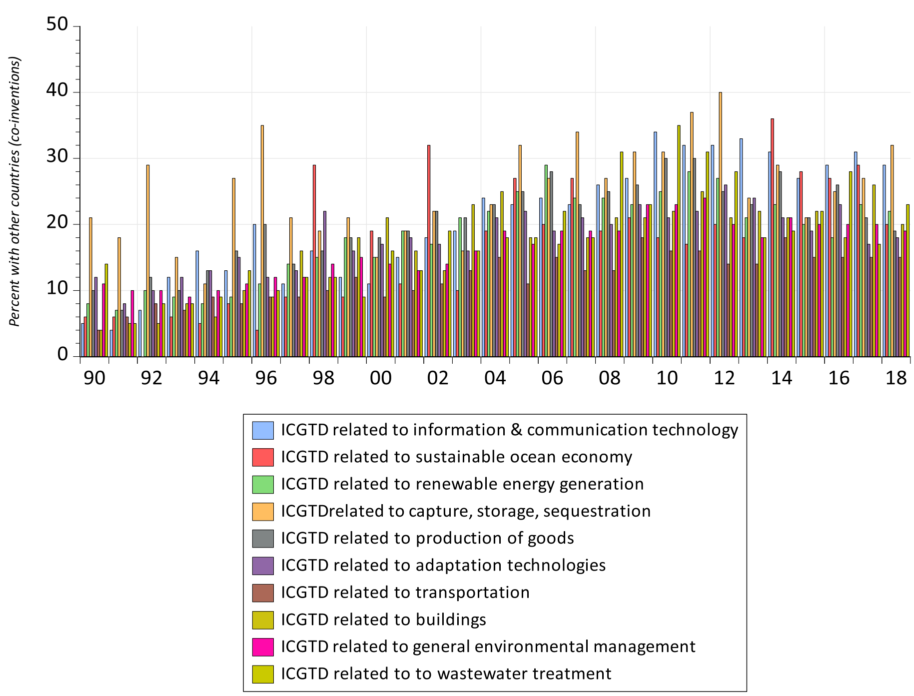


Fig. 15. Progress in ICGTD (percent with other countries co-inventions) at disaggregate level during 1990–2018.

countries [218], CIS states [219], China [220], D-8 nations [155], African states [221], emerging countries [222], developing states (Van Tran, 2020), and G-7 nations [223].

Lastly, the findings indicated that a 1% increase in ICGTD led to a decrease in CO_{2e} by 0.271% (CCR), 0.274% (FMOLS), and 0.266% (DOLS). This result suggests that continuous participation in ICGTD-related activities reduces reliance on fossil fuels and reduces CO_{2e}. International cooperation allows for more significant advancement in science and technology. Several indicators suggest that global scientists collaborate to advance green technology, establish shared standards, hold international meetings, exchange data, and collaborate on green research projects. The U.S. government expends significant finances on green research-related activities, including cross-border environmental-related research collaboration. These activities include advancements in standards, sustainable technology and databases, workshops, organizational support, technical assistance, and scientific cooperation in climate change mitigation and general technology development [224].

About 90% of all U.S.-funded partnership research is based on ICGTD. The Department of Energy (DOE) in the United States is responsible for conducting collaborative research related to global issues, especially in basic energy sciences and green and effective energy systems [139]. Over the last three decades, more than a trillion dollars has been spent on international collaboration studies on renewable energy, non-renewable energy, nuclear fusion, and power [224].

Fig. 15 indicates that the ICGTD (percent with other countries in co-inventions) related to information and communication technology surged from 5% (1990) to 29% (2018), ICGTD related to renewable energy generation increased from 8% (1990) to 22% (2018), ICGTD related to wastewater treatment rise from 14% (1990) to 23% (1980), ICGTD related to capture, storage, or sequestration expanded from 21% (1990) to 32% (2018), ICGTD related to production of goods increased from 10% (1990) to 19% (2018), ICGTD related to adaptation technologies 12% (1990) to 18% (2018), ICGTD related to transportation expanded from 4% (1990) to 15% (2018), ICGTD related to buildings increased from 4% (1990) to 20% (2018), ICGTD related to general environmental management expanded from 11% (1990) to 19% (2018) and ICGTD related to wastewater treatment surged from 4% (1990) to 20% (2018). Fig. 16 signifies the unparalleled association between ICGTD (%↑) and CO_{2e} (%↓). Accordingly, an increase in ICGTD by 10.18% (1991Q1), 0.73% (2011Q3), 7.28% (2012Q4), 10.74% (2015Q3) and 6.74% (2017Q2) led to decreased CO_{2e} by 2.27%, 2.62%, 2.99%, 3.07% and 1.13%, respectively.

Table 8 shows the results of the robustness tests from FMOLS, CCR, and DOLS in the presence of structural breaks. The findings confirmed

Table 8
Long-run estimates with structural break: Robustness check.

Variables	FMOLS	DOLS	CCR
ICGTD	−0.271***	−0.278***	−0.269***
	(-3.251)	(-4.274)	(-3.415)
GDPPC	0.278***	0.266***	0.275***
	(8.614)	(7.655)	(8.177)
IMEGDTT	−0.012**	−0.023**	−0.012**
	(-2.922)	(-2.068)	(-2.968)
TO	0.109**	0.133**	0.112**
	(2.114)	(2.184)	(2.248)
REC	−0.236***	−0.233***	−0.238**
	(-5.232)	(-3.986)	(-5.079)
EMP	0.025***	0.024***	0.024***
	(4.784)	(4.274)	(4.707)
Dummy_break years	−0.0009	0.004	−0.0007
	(-0.194)	(0.393)	(-0.974)
C	4.277***	4.334***	4.291***
	(16.087)	(14.901)	(14.675)

Note: ** and *** depict the 5% and 1% levels of significance, respectively.

negative relationships between IMEGDTT, REC, ICGTD, and CO_{2e}. In addition, the robustness tests also identified positive associations between EMP, TO, GDPPC, and CO_{2e}. These results are consistent with those shown in Table 7.

The results of the Granger causality are presented in Table 9. The findings indicated that there exists a bidirectional linkage between ICGTD and CO_{2e}. According to these findings, any economic policies that reduce or increase IMEGDTT result in corresponding decreases or

Table 9
Granger causality test.

Null hypothesis	F-statistic
ICGTD does not Granger Cause CO_{2e}	5.968**
CO_{2e} does not Granger Cause ICGTD	3.117*
GDPPC does not Granger Cause CO_{2e}	3.783*
CO_2e does not Granger Cause GDPPC	0.547
IMEGDTT does not Granger Cause CO_{2e}	5.358**
CO_{2e} does not Granger Cause IMEGDTT	0.872
TO does not Granger Cause CO_{2e}	10.907***
CO_{2e} does not Granger Cause TO	1.306
REC does not Granger Cause CO_{2e}	2.270
CO_{2e} does not Granger Cause REC	0.897
EMP does not Granger Cause CO_{2e}	6.316**
CO_{2e} does not Granger Cause EMP	0.427

Note: *, ** and *** depict the 10%, 5%, and 1% levels of significance, respectively.

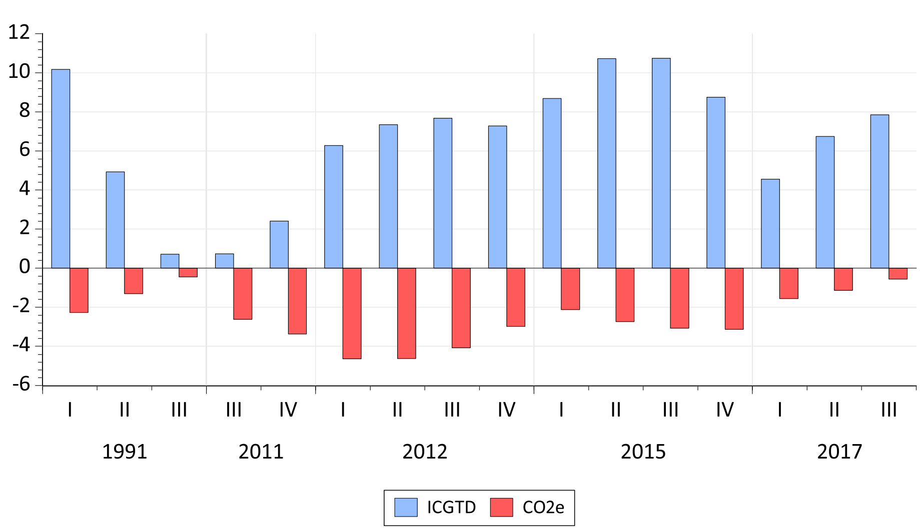


Fig. 16. Unparalleled association between ICGTD (%↑) and CO_{2e} (%↓).

increases in CO_{2e}. In addition, the results showed that economic policies that reduce or increase GDPPC, IMEGDTT, TO, and EMP lead to corresponding decreases or increases in CO_{2e}; this relationship was unidirectional.

5. Conclusion and policy implications

The study's main objective was to explore the nexus between IMEGDTT and CO_{2e}, along with control variables, such as GDPPC, ICGTD, TO, REC, and EMP in the United States, from 1990Q1 to 2018Q4. The Perron unit root test outputs (with breakpoints) showed that all the variables were integrated in the same order. The findings of the BT co-integration test validated the presence of long-run linkages among IMEGDTT, GDPPC, EMP, ICGTD, REC, TO, and CO_{2e}. According to the findings of CCR, FMOLS, DOLS, IMEGDTT, REC, and ICGTD was negatively linked with CO_{2e}. Furthermore, the results also showed that an increase in TO, EMP, and GDPPC was positively associated with CO_{2e}. The Granger causality test outputs validated a one-way relationship between IMEGDTT and CO_{2e}, GDPPC and CO_{2e}, TO and CO_{2e}, and EMP and CO_{2e}. Also, a two-way causality was observed between ICGTD and CO_{2e}.

The following policy implications are drawn from the results of this study. Based on the negative association between IMEGDTT and CO_{2e}, policymakers in the United States are encouraged to develop policies to facilitate businesses and industries in IMEGDT and increase the overall level of IMEGDTT. The relevant authorities should also identify and solve the barriers preventing private investors from making a total investment in the IMEGDTT. A consortium of US corporations, backed by universities and national laboratories, are making efforts to explore the global marine energy supply. Another critical concern is that the domestic marine energy businesses face the challenge of the ongoing requirement for private investment to fund innovation and first demonstrations during the precompetitive stages of technology development, owing to the tight timeframes and associated technical risks [12]. In this scenario, the related authority in the United States should initiate a green innovation funding program to provide financial and physical resources at lower interest rates to industrial research centers, universities, government research organizations, basic research institutes, laboratories, and high-tech enterprises.

Besides, small entrepreneurs with limited external support dominate marine energy technology development in the United States. Substantial federal funding is vital to sustaining the domestic maritime energy sector in light of the worldwide competitiveness in which US companies are significantly outmatched [12]. For example, European technology developers are not subject to stringent cost-sharing rules to match government financing. Jennifer Granholm, the United States Secretary of Energy, should consider leveling the playing field for all investors and entrepreneurs by eliminating the cost-share requirements for pre-commercial marine energy research and development awards.

While maritime energy generation and technological development in the United States are still in their infancy, they have significant growth and development potential. Marine energy technologies are seeing significant innovation. The widespread use of these technologies in the United States will boost exports of technology manufacturing and related services, generate thousands of high-wage jobs, and expand chances for localized economic growth.

Even though marine energy attracts less investment and is more expensive than other renewables, including wind and solar, resulting in less investment, yet in effect, it has high potential than solar energy. For example, exploiting just 1/10th of the current maritime resource would equal ¼ percent of the United States' coal fleet, about 6% of electrical generation, enough electricity to power 22 million households, and more than three times the United States' solar generation [12]. Costs associated with maritime energy generation can be reduced with the advancement of technology. The US government should grant subsidies or tax exemptions to enterprises that have engaged in or intend to engage in IMEGDTT activities.

Secondly, based on the negative relationship between ICGTD and CO_{2e}, it is suggested that the government of the United States should devise policies to further increase and strengthen ICGTD-related activities. Supporting policies related to ICERTD will help create a global consensus for achieving the objectives of sustainable production and consumption by lowering the overall costs of green R&D. They will also multiply private/public sector R&D capital, enhance green technology transfers and diffusion, and reduce the overall costs of green R&D. ICERTD-driven policies have the potential to help underdeveloped, emerging, and developed economies to make the transition to a green economy. Such cooperation will necessitate the development of well-designed and integrated systems and processes to transfer and share green resources. These include expertise, skills, scientists, data, and cutting-edge technologies. In this context, a trust-driven environment is urgently needed to facilitate resource exchange at the macro and micro levels and achieve long-term goals. New integrated green networks linking the public sector, industry stakeholders, and green projects should be developed and encouraged by policymakers.

Third, based on the positive relationship between EMP and CO_{2e}, it is suggested that the United States Department of State should formulate a green monetary policy. The Federal Reserve of the United States should use green monetary policies to encourage commercial banks to use "eco lending" practices. For example, the Federal Reserve of the United States could charge higher interest rates to companies or manufacturers who use at least 50% of fossil fuels in their production process. If adopted, this strategy is expected to mitigate CO_{2e} by inducing businesses to decrease their reliance on "dirty" technologies and enhance the development of renewable technologies.

Fourth, based on the negative link between REC and CO_{2e}, it is suggested that the United States Department of Energy and other related departments should promote renewable energy by enacting (a) regulations requiring solar panels to be installed in new homes, (b) interest-free loans for the purchase of renewable energy equipment, (c) relaxed planning restrictions for onshore wind farms, (d) regulated emission limits for power plants, (e) solar and biomass feed-in tariff schemes, and (f) a minimum carbon price flotation.

Lastly, based on the nexus between GDPPC, TO, and CO_{2e}, it is suggested that the United States Environmental Protection Agency should devise policies to encourage firms and industries to use clean technologies during production processes.

Regardless of the merits of this study, certain limitations remain relevant to future research directions. First, this study explores the connection between IMEGDTT, ICGTD, and CO_{2e} for the U.S. only. However, given the importance of IMEGDTT and ICGTD, an investigation may be conducted for other industrialized and developing economies. Second, this study used linear econometric techniques to examine the relationship between IMEGDTT and CO_{2e}. However, evidence suggests that innovative activities are pro-cyclical. The pro-cyclicality of innovative activities represents the fact that innovative activities rise during economic booms and fall during economic downturns. Subsequent studies could be conducted using non-linear econometric models to inspect cyclical or non-linear nexuses between IMEGDTT and CO_{2e}. Third, this study explores the connection between IMEGDTT and CO_{2e} at the aggregate level. This limitation can be overcome by examining the association between IMEGDTT and CO_{2e} at the individual level, i.e., the relationship among offshore wind, solar, tide, wave, current, and other marine energy and CO_{2e}.

Credit author statement

Xin Liguo: Conceptualization, Methodology, Software, and Supervision. **Manzoor ahmad:** Data curation, Writing – original draft preparation, Investigation, **Shoukat Iqbal Khattak:** Validation, Writing-Reviewing and Editing, Investigation.

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.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.rser.2022.112225.

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