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RESEARCH ARTICLE

Toward next-generation green solar cells and environmental sustainability: impact of innovation in photovoltaic energy generation, distribution, or transmission-related technologies on environmental sustainability in the United States

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Abstract
Photovoltaic is emerging as a cost-competitive source of energy generation and has experienced a decade of substantial cost decline. Recognizing that innovation in sustainable technologies can substantially contribute to the sustainable generation of energy, the federal government, universities, and industries in the USA have invested considerably in innovative solar technologies involving photovoltaic energy generation. However, the association between innovations in photovoltaic energy generation, distribution, or transmission-related technologies (IPVEGRT) and carbon dioxide emissions is unclear. The present study significantly contributes to energy economics by inspecting the nexus between IPVEGRT and carbon dioxide emissions, renewable energy consumption, the expansionary monetary policy, international collaboration in green technology development, gross domestic product per capita, and trade openness in the USA from 1990Q1 to 2018Q4. The results indicate that IPVEGRT helps reduce carbon dioxide emissions. International collaboration in green technology development and renewable energy consumption was negatively associated with carbon dioxide emissions, while expansionary monetary policy, gross domestic product per capita, and trade openness were positively associated with carbon dioxide emissions. The two-way causality between IPVEGRT and carbon dioxide emissions and between international collaboration in green technology development and carbon dioxide emissions was validated. Finally, a one-way causality between expansionary monetary policy, carbon dioxide emissions, gross domestic product per capita, and carbon dioxide emissions was validated.

Keywords Renewable energy consumption · Photovoltaic energy generation · Monetary policy · Carbon dioxide emissions · United States · Trade openness

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Nomenclature

IPVEGRT	Innovation in photovoltaic energy generation, distribution, or transmission-related technologies
PV	Photovoltaic
CO_2e	Carbon dioxide emissions
GDPPC	Gross domestic product per capita
EMP	Expansionary monetary policy
TRO	Trade openness
ICGTD	International collaboration in green technology development
REC	Renewable energy consumption
CCR	Canonical co-integration regression estimator
DOLS	Dynamic ordinary least squares estimator
FMOLS	Fully modified ordinary least squares estimator

OECD	Organization for Economic Cooperation and Development
K	Capital goods
I	Innovation activities
ERT	Environmentally related innovation
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	μ_t Error term
m	Lag operators
BY	Break years
BT	Bound test
MW	Megawatts

Introduction

The depletion of environmental and natural resources has shifted the focus of academics and authorities to factors that contribute to environmental problems to encourage sustainable production and consumption (Ahmad and Wu 2022b; Chen et al. 2021; Gyamfi et al. 2021). Achieving a clean environment has become a worldwide commitment (Raheem et al. 2020; Adedoyin et al. 2020; Bilgili et al. 2021). Nations worldwide have been affected by global-warming-induced issues, including severe weather events, which have a profound effect on the economy and lives (Sinha et al. 2020b). However, the ecological responses of nations have remained the same, based on indicators of socioeconomic development, monetary policy, trade openness, fossil fuel consumption, and a variety of other essential factors (Asiedu et al. 2021; Kirikkaleli et al. 2021). Furthermore, increasing globalization and the consequent rapid industrialization, infrastructure expansion, and enhanced business activity have increased the energy demands. This has continued to drive greenhouse gas emissions (Güngör et al. 2021; Razzaq et al. 2021). Global climate change is mostly caused by carbon dioxide (CO_2) emissions (CO_2e) from the combustion of fossil fuels (Bulut 2019; Cheng et al. 2021a). Global carbon emissions are a crucial driver of the worsening environmental quality. Over 45% increase in atmospheric CO_2 concentration has been recorded in ~130 years (Majeed and Asghar 2021; Qamar et al. 2022).

Energy depletion is critical to progress and development. Therefore, reducing energy expenditures could harm national/global economies, while also spurring the use of alternative energy sources (Chien et al. 2021; Ma et al. 2021). While higher energy use could boost efficiency, it is critical to limit fossil fuels that contribute to CO_2e and environmental deterioration. The use of fossil fuel energy should be limited in order to reduce CO_2e and slow down or even reverse environmental damage is a contentious issue (Abbasi et al. 2021; Jabeen et al. 2021). To minimize CO_2e, nations should support and encourage renewable energy use. Nevertheless, attempting to implement renewable energy in emerging economies may hinder industrialization and economic growth. This is because renewable energy is more expensive to implement as the dominant source of energy consumption. Emerging economies may require specific initiatives aimed at clean energy adoption (Abbasi et al. 2021).

Businesses and governments worldwide are exploring new ways to boost efficiency and lower the cost of existing renewable energy sources. Innovation in sustainable technologies is regarded as one of the most successful strategies to achieve more efficient delivery of renewable energy and reduce CO_2e emissions (Zhang et al. 2021). Among the various renewable energy sources, solar energy is a highly flexible technology, with numerous energy conversion technologies emerging globally. Standard photovoltaic (PV) cells are still the most viable and inexpensive technology. However, more commercial options are expected with time (Solar Nation 2021). Solar energy resources are abundant and widely distributed, and can be exploited anywhere there is sunlight. The quantity of solar radiation reaching the Earth's surface each hour (i.e., insolation) is greater than the amount of energy utilized annually by all human activities. Numerous variables, including geographic location, time of day, and weather conditions, influence the quantity of electricity that may be harnessed for power generation or cooking. Solar PV is the largest source of energy. By 2020, more than 139 GW of worldwide capacity will be added, bringing the total to approximately 760 GW and generating nearly 3% of electricity worldwide (Center for Climate and Energy Solutions 2021). Solar energy could have a positive effect on the emissions when it is used to replace or reduce the use of other energy sources with higher ecological consequences (U.S. Energy Information Administration 2021).

Recognizing innovation in environmental-related technologies (IERT) as a useful tool for counteracting global climate change and CO_2e, the federal government of the USA, as well as businesses and research institutions have invested considerable funds in the use of PV for innovation in PV energy generation, distribution, or transmission-related technologies (IPVEGRT). Between 1991 and 2018, IPVEGRT rose by an average of 78% in the USA. Notable annual increases were 200% in 1993, 33% in 1998, 57% in 2002, 90% in 2004, 56% in 2006, 54% in 2009, 40% in 2014, 46% in 2016, and 45% in 2018 (OECD 2021b). Given the advances in the capability of IPVEGRT from 1990 to 2018, it appears implausible to ignore the substantial environmental and technological consequences for the USA. However, despite this great progress, no study has addressed the connections between IPVEGRT and CO_2e. The present study was undertaken to address this knowledge gap in the USA by examining possible linkages between IPVEGRT and CO_2e.

The present study contributes to the existing literature in several ways. First, previous studies (cf. Ahmad et al. 2019, 2020a; Weimin et al. 2021; Xiaosan et al. 2021) have mainly investigated the total innovation–CO_2e nexus with total patents as a proxy for innovation, a weak variable to check the environmental effect of green innovation. Alternatively, some studies (cf. Ahmad and Zheng 2021; Khattak et al. 2021, 2022; You et al. 2021; Xin et al. 2021) have used total environmental patents (as a proxy) for understanding innovation in environmental-related technologies (IERT)–CO_2e nexus. Furthermore, some studies investigate the relationship between solar energy consumption and CO_2e. The possible impact of IERT, particularly the effect of IPVEGRT on CO_2e, remains widely unexplored. The present paper adds to environmental and energy economics by offering the first case study on the IPVEGRT–CO_2e nexus for the USA. Second, past works (cf. Alvarez-herranz et al. 2017; Chishti and Sinha 2022; Töbelmann and Wendler 2020; Wang et al. 2020) explored the influence of total innovation or total IERT on CO_2e, undermining how open innovation or international collaboration in green technology development (ICGTD) might contribute to CO_2e mitigation. The present study formulates the first environmental model for the potential ICGTD–CO_2e nexus and IPVEGRT–CO_2e nexus for the US economy, along with renewable energy consumption (REC), the expansionary monetary policy (EMP), ICGTD, gross domestic product per capita (GDPPC), and trade openness (TRO) as control variables. Third, the present estimates have taken structural breaks in the time-series data into account. Underestimation of structural breaks can result in incorrect regression results through a unique methodology. For example, the study first estimated several break years using the structural break unit-root test. After that, the paper adjusted the co-integration tests, including the Hansen Parameter Instability and Engle-Granger co-integration test for estimating break years. Furthermore, the long-run results were estimated with and without considering the break years. Compared to previous studies, this new methodology may yield more robust, consistent, and reliable findings. Fourth, prior studies, including Khattak et al. (2020), Ahmad et al. (2020a), Li et al. (2021b), Xiaosan et al. (2021), and Su et al. (2021) used the Environmental Kuznets curve conceptual framework to examine the nexus between economic factors and CO_2e. This study develops a novel conceptual and theoretical framework for examining the theoretical connection between IPVEGRT and CO_2e in the United States.

The rest of the study is organized in the following manner. The "Literature Review" section presents a review of related research on the nexus between innovation and CO_2e. The "Conceptual Framework" section outlines the study's theoretical model. The "Methodology" section explains the data sources, estimation methods, and strategies. The "Results and Discussion" section comprises of results and discussion . The "Conclusion and Policy Implications" section summarizes the major findings and their policy implications.

Literature review

IERT is frequently defined as an innovation that contributes to sustainable development goals by reducing the negative environmental effects of manufacturing processes, enhancing natural resilience to environmental issues, or generating more dependable and effective natural resource usage procedures. As explained previously, the USA has benefited significantly from environmental technologies, processes, services, and goods. These efforts have aided the USA in addressing common global concerns, such as resource scarcity, environmental degradation, and declining biodiversity. Apart from the macroeconomic benefits mentioned above, IERT allows private corporations to lower manufacturing costs, increase growth, and improve their market reputation (Hosseini and Azizi 2020).

Several researchers have scrutinized the nexus between innovation/IERT and CO_2e in diverse economies using econometric approaches and variables. For instance, the random and fixed-effect models were used to investigate the connection between CO_2e and province-level innovation patents (Li et al. 2021a). The findings revealed a negative linkage between the two variables in China. Xiaosan et al. (2021) investigated the role of IERT, renewable energy production, and hydroelectric generation in enhancing environmental quality in China from 1990 to 2018. The authors validated that IERT improved environmental quality based on autoregressive distributed lag (ARDL) estimates. In another research study concluded for India, Zameer et al. (2020) found that technology improvements are important for decreasing CO_2e and enhancing long-term economic growth. Hao et al. (2020) used the spatial lag model (SLM) to examine the nexus between innovation and CO_2e in China from 1998 to 2016. The findings confirmed that technological innovation helped reduce CO_2e. Yu and Du (2019) used the multiple regression (MR) approaches to analyze the link between technological innovation and CO_2e in China from 1997 to 2015. The researchers noted that technical progress resulted in a reduction in CO_2e.

Shahbaz et al. (2018) employed the ARDL approach to study the connection between FDI, financial development, and energy innovation in France from 1955 to 2016. The authors validated the pollution haven and EKC hypotheses, as well as a negative link between energy innovation and CO_2e. In another study, Yii and Geetha (2017) employed the vector error correction model (VECM) to assess the influence of technological innovation on CO_2e in Malaysia from 1971 to 2015. The estimates obtained indicated a negative correlation between technical advancement and CO_2e.

The link between IERT and environmental performances in China was evaluated by Long et al. (2017). The findings confirmed that technical innovation has a greater beneficial effect on environmental performance than on economic performance. Zhang et al. (2017b) examined the potential impact of IERT on CO_2e in China from 2000 to 2013. The system generalized method of moments (SGMM) estimator validated that IERT had a negative association with CO_2e. Lee and Min (2015) used the least square linear predictor (LSPL) analysis to explore the relationship between green IERT, financial success, and CO_2e in Japan from 2001 to 2010. These findings indicate an adverse link between the IERT and CO_2e emissions. Carrión-Flores and Innes (2010) used the generalized method of moments (GMM) estimator to analyze the link between IERT and CO_2e in the USA from 1989 to 2004. The findings established a bidirectional causal relationship between the two variables.

Numerous studies have scrutinized the effect of innovation/IERT on CO_2e in various regional groups. For example, Fernández et al. (2018) used the ordinary least squares (OLS) method to identify an inverse link between innovation and CO_2e in China, the European Union, and the USA from 1990 to 2013. Santra (2017) used the pooled regression modeling (PRM) approach to examine the connection between IERT and CO_2e for Brazil, Russia, India, China, and South (BRICS) from 2005 to 2014. The authors made a significant contribution in empirically establishing the favorable effect of IERT on production-related CO_2e and energy performance. Other studies conducted for 62 countries, the European Union, and 35 OECD member countries (Zhao et al. 2021; Cheng et al. 2021b, and Mongo et al. 2021) confirmed prior findings that IERT helps reduce the adverse effects of environmentally dirty technologies. In another study conducted for the OECD, Ahmad et al. (2020b) employed the two-step GMM approach to incorporate FDI, innovation, and energy–environment–growth equations utilizing a simultaneous equation modeling framework. These findings indicated that innovation increases the existing level of CO_2e. In a study on the BRICS nations from 1980 to 2016, Khattak et al. (2020) used the EKC framework to investigate the association between innovation and CO_2e. The common correlated effects mean group (CCEMG) approach was used by the authors, who found that innovation led to increased CO_2e. Rafique et al. (2020) employed the augmented mean group (AMG) estimator to establish the positive effect of innovation in reducing BRICS emissions. Fethi and Rahuma (2019) used the EKC framework to estimate the connections between income, IERT, energy use, and CO_2e for the top 20 refined oil-exporting countries from 2007 to 2016. The findings indicated that rising real income and CO_2e resulted in a reduction in higher energy consumption and promotion of IERT. The effect of IERT on CO_2e reductions in OECD member states from 1990 to 2015 was explored by Mensah et al. (2019). The ARDL estimations confirmed that both independent factors had a substantial effect on CO_2e. In addition, the FMOLS approach was utilized by Dauda et al. (2019) to assess the impact of IERT on CO_2e for the G6 and BRICS groups, as well as countries in the Middle East and North Africa (MENA) region, from 1990 to 2016. The findings showed that IERT reduced the G6 group's CO_2e and had a detrimental effect on environmental quality in the BRICS and MENA groups. Table 1 summarizes the selected studies on the relationship between IERT/innovation and CO_2e.

Conceptual framework

The linkage between capital input and final output can be represented by the following production function:

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

where Y_t is the final output or supply-sided economy, A_t is the level of technology, and K_t is the total quantity of capital inputs.

Economies of scale are a significant advantage for growing firms. Most entrepreneurs can effectively reduce unit costs as their production rises. Economies of scale are the cost advantages that a business can exploit by expanding its scale of production. To accomplish this goal, enterprises frequently engage in research and development (R&D) and innovation activities. Technological advancements and innovation will significantly change production methods, thereby lowering the overall cost per unit. Thus, innovation and R&D activities (I) can be inserted into the following production function (Weimin et al. 2021):

$$Y_t = A_t K_t^{\alpha} I_t^{\beta} \tag{2}$$

Innovation is necessary for success in any business. It can assist in resolving issues, generating revenue, edging out competitors, and expanding market share. Several of the most tangible advantages of innovation include increased productivity, increased economic growth, increased revenue and profitability, new partnerships and relationships, enhanced brand recognition and value, increased competitiveness, and cost savings.

Aggregate innovation can be divided into two categories: general innovation and environmentally related innovation (ERI). ERI can be viewed as a technique that promotes the development of new manufacturing and technology to mitigate environmental risks, such as carbon emissions and the negative effects of resource extraction (e.g., energy) (Borsatto et al. 2020). ERI has gained widespread acceptance as a means of enhancing the environmental performance and efficiency of enterprises

Table 1 Summary of selected studies on IERT/innovation and CO_2e

Authors	Year	Economy	Technique	INNOV–CO_2e nexus
Single country studies				
(Carrión-Flores and Innes 2010)	1989–2004	USA	Generalized method of moments	Negative
(Yii and Geetha 2017)	1971–2015	Malaysia	Vector error correction model	Negative
(Xiaosan et al. 2021)	1990–2018	China	Autoregressive distributed lag	Negative
(Long et al. 2017)	June 2015–March 2016	China	Factor analysis and correlation analysis	Negative
(Lee and Min 2015)	2001–2010	Japan	Least squares linear predictor	Negative
(Chen and Lee 2020)	2001–2016	China	System generalized method of moments	Negative
(Zameer et al. 2020)	1985–2017	India	Vector error correction model	Negative
(Li et al. 2021c)	2003–2016	China	Fixed effect Random effect	Positive
(Shahbaz et al. 2018)	1955–2016	France	Autoregressive distributed lag	Negative
(Yu and Du 2019)	1997–2015	China	Multiple regression	Negative
(Hao et al. 2020)	1998–2016	China	Spatial lag model	Negative
Group-level studies				
(Mongo et al. 2021)	1991–2014	Europe	Autoregressive distributed lag	Negative
(Dauda et al. 2019)	1990–2016	G-6	Fully modified ordinary least square	Negative
(Zhao et al. 2021)	2003–2018	62 nations	Mediation effect model	Negative
(Weimin et al. 2021)	1990–2016	Developing countries	Fully modified ordinary least square	Negative
(Ahmad et al. 2020a)	1993–2014	OECD	Differenced generalized method of moments	Positive
(Su and Moaniba 2017)	1976–2014	70 economies	Generalized method of moments	Positive
(Ahmad et al. 2019)	1990–2014	OECD	Fully modified ordinary least square	Negative
(Fethi and Rahuma 2019)	2007–2016	Top 20 refined oil-exporting nations	Dumitrescu–Hurlin panel causality test	Negative
(Khattak et al. 2020)	1980–2016	BRICS	Common correlated effects mean group	Positive
(Santra 2017)	2005–2014	BRICS	Panel quantile regression	Negative
(Ahmad and Wu 2022c)	1985–2017	G20	Panel quantile regression	Negative
(Ahmad and Wu 2022a)	1990–2017	OECD	Panel quantile regression	Negative
(Sinha et al. 2020a)	1990–2017	Next-11 nations	Panel quantile regression	Negative
(Chishti and Sinha 2022)	1990–2018	BRICS	Augmented Mean Group	Negative
(Zafar et al. 2021)	1990–2017	Asia-Pacific Economic Cooperation countries	Panel quantile regression	Negative
(Fernández et al. 2018)	1990–2013	China, EU, and the USA	Ordinary least square	Negative
(Mensah et al. 2019)	1990–2015	OECD	Autoregressive distributed lag	Negative
(Rafique et al. 2020)	1990–2017	BRICS	Augmented mean group	Negative
(Alvarez-herranz et al. 2017)	1990–2014	OECD	Lag distribution model	Negative
(Cheng et al. 2021a)	1996–2015	OECD	Panel quantile regression	Negative

as well as advancing to more sustainable business models (Szilagyi et al. 2018). Businesses implement ERI in response to stringent environmental regulations. Environmental regulations, for example, have a significant impact on ERI and contribute to CO_2e reduction (Borsatto et al. 2020). Hence, I_t can be replaced by ERI in the following equation:

$$Y_t = A_t K_t^{\alpha} ERI_t^{\gamma} \quad (3)$$

Along with ERI, some firms participate in international collaborations for green technology development (ICGTD) to co-develop green and sustainable technology. ICGTD entails the exchange of green knowledge, costs, and initiatives to promote and expedite technical green developments and the co-invention of sustainable technologies (Philibert 2004). International green partnerships can assist both developed and developing economies in becoming more productive by improving their skills in green R&D and promoting sustainable consumption and production (Dodgson 1992). Consequently, $ICGTD_t$ can be incorporated into the following equation:

$$Y_t = A_t K_t^{\alpha} ERT_t^{\gamma} ICGTD_t^{\zeta} \quad (4)$$

CO_2e from human activities is primarily caused by industrial production and the combustion of fossil fuels. A recent study found that industrial sectors are the primary source of CO_2e (Tian et al. 2014). The nexus between a firm's production (Y_t) and CO_2e can be depicted in the following mathematical expression (Qingquan et al. 2020; Xiaosan et al. 2021):

$$CO_2e_t = f(Y_t) \quad (5)$$

where $f(Y_t) = A_t K_t^{\alpha} ERT_t^{\gamma} ICGTD_t^{\zeta}$. Next, inserting Eq. (4) into Eq. 5:

$$CO_2e_t = A_t K_t^{\alpha} ERT_t^{\gamma} ICGTD_t^{\zeta} \quad (6)$$

In general, ERI can be classified as follows: PV energy generation distribution or transmission-related technologies, marine energy generation distribution or transmission-related technologies, mineral processing-related technologies, processing of goods-related technologies, combustion technologies with mitigation potential, information and communication technologies, wastewater treatment-related technologies, energy efficiency in building-related technologies, adaptation technologies, energy generation from non-fossil fuel-related technologies, energy efficiency in communication network-related technologies, and integration of renewable energy source-related technologies (OECD 2020). The present study assumes that firms initiate IPVEGRT to advance the green economy. Thus, ERI can be substituted for IPVEGRT to obtain the following CO_2e_t equation:

$$CO_2e_t = A_t K_t^{\alpha} IPVEGRT_t^{\gamma} ICGTD_t^{\zeta} \quad (7)$$

PV solar energy is an environmentally friendly and renewable source of energy that utilizes solar radiation. The PV breakthrough is built on a high-tech but relatively basic device that directly transforms sunshine into electricity (see Fig. 1). There are three classes of solar panels. PV panels generate energy for household use. Thermal panels mounted on houses receive direct sunlight. Third, thermodynamic panels function in different weather conditions, including at night, on rainy days, and on cloudy days. Solar panels have no moving parts, no external source of energy other than the sun, and no additional inputs or wastes (Sector 2014). When the PV technology was initially developed, it was utilized to power satellites. The installation of PV panels accelerated in the 1950s and has since evolved into a viable alternative to non-renewable and environmentally dirty fuels (Acciona 2021).

The shift to an electricity system that incorporates a significantly greater quantity of distributed solar energy has numerous benefits for both the energy grid and the environment. One of the greatest advantages of distributed solar energy is that it frequently produces energy when and where it is the most useful. In many places, power system demand peaks in the afternoon on warm, bright days, when

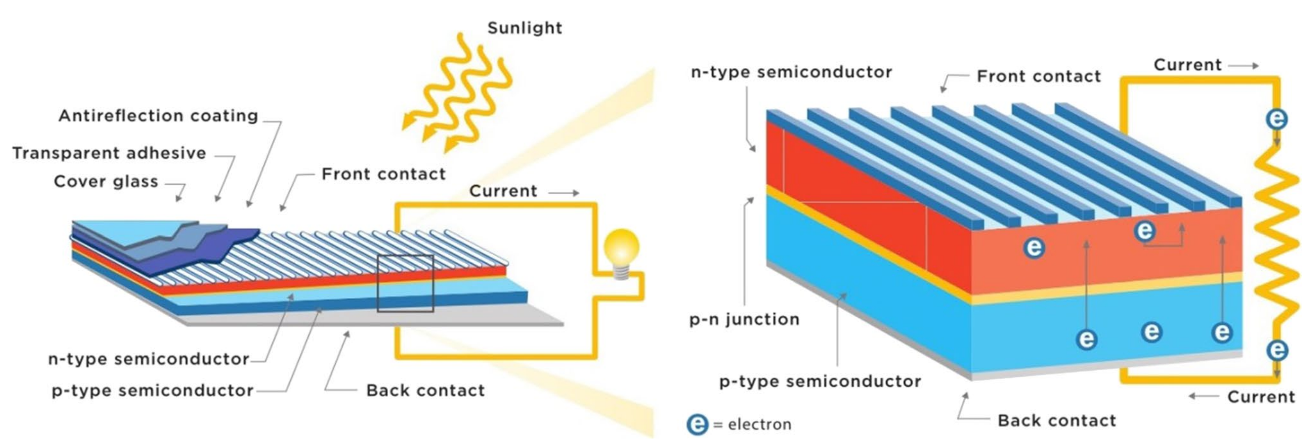


Fig. 1 Structure of a PV cell. Source: Sector 2014

air conditioning consumption has increased and solar PV is functioning well. This type of system allows utilities to satisfy peak demand while avoiding the costly and environmentally damaging use of oil-fired power plants that are infrequently used. Using PV systems improved through innovation allows houses and businesses to draw power from the grid before sending it to the grid. This reduces the load on the grid (Sector 2014).

The primary benefits of IPVEGRT include reduced manufacturing costs, increased efficiency and productivity, and improved accuracy of PV technologies. All these benefits contribute to the wider deployment of electricity generated directly from sunshine (Sector 2014). Thus, the introduction of new and better PV technologies increases efficiency and contributes to mitigating CO_2e. New and improved PV systems have the potential to play a significant role in reducing current and future CO_2e (Drennen et al. 1996). Because PV energy does not rely on the combustion of fossil fuels, it produces no CO_2e throughout the energy production process. Hence, it was expected that $\gamma < 0$.

Based on several studies (Qingquan et al. 2020; Chishti et al. 2021), K_t can be replaced by renewable energy consumption (REC_t) in the following equation:

$$CO_2e_t = A_t K_t^{\alpha} IPVEGRT_t^{\gamma} ICGTD_t^{\zeta} \tag{8}$$

Next, based on prior findings from Xin et al. (2021), Qingquan et al. (2020), and Ahmad and Zheng (2021), the present study also included gross domestic product per capita (GDPPC), expansionary monetary policy (EMP), and trade openness (TRO) in the following pollution equation:

$$CO_2e_t = A_t REC_t^{\alpha} IPVEGRT_t^{\gamma} ICGTD_t^{\zeta} EMP_t^{\eta} TRO_t^{\vartheta} GDPPC_t^{\lambda} \tag{9}$$

Following the studies of Xin et al. (2021), Qingquan et al. (2020), and Ahmad and Zheng (2021), it is expected that $\alpha < 0$, $\gamma < 0$, $\zeta < 0$, $\eta > 0$, $\vartheta > 0$ and $\lambda > 0$.

A linear model was obtained by taking the logarithm of Eq. (9):

$$\begin{aligned} \log CO_2e_t = \alpha_0 + \alpha logREC_t + \gamma logIPVEGRT_t + \zeta logICGTD_t \\ + \eta logEMP_t + \vartheta logTRO_t + \lambda logGDPPC_t \end{aligned} \tag{10}$$

An econometric model was obtained by adding an error term to Eq. (10)

$$\begin{aligned} \log CO_2e_t = \alpha_0 + \alpha logREC_t + \gamma logIPVEGRT_t + \zeta logICGTD_t \\ + \eta logEMP_t + \vartheta logTRO_t + \lambda logGDPPC_t + \mu_t \end{aligned} \tag{11}$$

Data sources and methodology

Data sources

The present study used the OECD database to collect data on international collaboration in green technology development (ICGTD; percent within country-co-inventions), patents relating to PV energy generation, distribution, real interest rate, and REC expressed as thousands of tons of oil equivalent (toes). Gross domestic product per capita (GDPPC), exports of goods, gross domestic product, and imports of goods were collected from the World Bank database. Positive changes in real interest rates and patents related to PV energy generation were used as proxies for EMP and IPVEGRT, respectively. Following Qingquan et al. (2020) and Chishti et al. (2021), the EMP was calculated using the following equation:

$$logEMP_t^+ = \sum_{j=1}^{t} \log \Delta EMP_j^+ = \sum_{j=1}^{t} logmax\left(\Delta EMP_j, 0\right) \tag{12}$$

Following Ahmad and Zheng (2021), the quadratic match sum approach (QMSA) was used to convert annual data into a quadratic series. All variables were transformed

Table 2 Description of the variables and data

Variables	Notation	Description	Source	Estimation method
Imports of goods	IMP	Constant US$	(World Bank 2021)	QMSA
Gross domestic product	GDP	Constant US$	(World Bank 2021)	QMSA
Innovation in PV energy generation, distribution, or transmission-related technologies	IPVEGRT	Number of patents related to energy generation, distribution, or transmission-related technologies	(OECD 2021b)	QMSA
International collaboration in green technology development	ICGTD	Patents on environment-related technologies (percent within country-co-inventions)	(OECD 2021b)	QMSA
Carbon dioxide emissions	CO_2e	Million tons	(OECD 2020)	QMSA
Exports of goods	EXP	Constant US$	(World Bank 2021)	QMSA
Trade openness	TRO	Sum of EXP and IMP divided by GDP	–	QMSA
Interest rates	IR	Percentage per annum	(OECD 2021a)	QMSA
Gross domestic product per capita	GDPPC	Constant US$	(World Bank 2021)	QMSA

to logarithms to improve the linearity between the response and predictor variables and to increase the validity of the econometric analysis. A summary of the data is provided in Table 2.

Methodology

Unit root tests

The unit root test was employed to determine the stationary nature of the time series data gathered for the research to minimize the risk of bias. The unit root test was used because numerous time series variables in the existing studies are non-stationary. Including non-stationary variables in the model may result in misleading regression (Babatunde 2018). The Augmented Dickey–Fuller (ADF) (Dickey and Fuller 1979) unit root test was used to determine whether a time series variable was stationary or not. The following model served as the basis for the ADF (Dickey and Fuller 1979) unit root test:

$$y_t = \beta_0 + \beta_1 y_{t-1} + \gamma_t + \varepsilon_t \tag{13}$$

Eq. (13) can also be written as follows:

$$\Delta y_t = \beta_0 + \left(\beta_1 - 1\right) y_{t-1} + \gamma_t + \varepsilon_t \tag{14}$$

where $\Delta y_t = y_t - y_{t-1}$. The ADF model is obtained by rewriting Eq. (14).

$$\Delta y_t = \beta_0 + \left(\beta_1 + \beta_2 - 1\right) y_{t-1} + \beta_2 \Delta y_{t-1} + \gamma_t + \varepsilon_t \tag{15}$$

The following is the hypothesis for the ADF test:

$$H_0 : \left(\beta_1 - 1\right) = 0$$

$$H_1 : \left(\beta_1 - 1\right) \neq 0$$

$(\beta_1 - 1) = 0$ indicates that the series is non-stationary. $(\beta_1 - 1) \neq 0$ indicates that it is stationary.

One disadvantage of the ADF test is that it becomes biased toward the non-rejection of the null hypothesis in the case of a structural break (Xin et al. 2021). Structural breaks can occur as a result of organizational, legislative, or technological changes, economic policies, or significant economic shocks. In time series analysis, structural breaks have a long-term impact on the structure of the time series (Byrne and Perman 2006). Thus, it is critical to consider structural breaks when performing unit root tests. The present study also used the Perron structural break unit root test (Perron 1989). There are certain advantages to testing the unit root hypothesis while allowing for structural breaks. One advantage is that it keeps test results from being biased toward the unit root. Another benefit is that it can determine the year in which the structural break occurs (Jiang et al. 2021).

Co-integration tests

The BCT can be used to determine the co-integration relationships between IPVEGRT, ICGTD, TRO, GDPPC, EMP, REC, and CO_2e. There are various advantages of using BCT. First, unlike many other classic co-integration approaches, BCT provides a variety of optimal variable lags. Second, regardless of the order of the integration series (i.e., I (0), I (1), or a mixture of both), the boundary test can be used to examine the co-integration association. Finally, this method is appropriate for a small sample size (Ahmad et al. 2020b). The BCT is determined using the following econometric specification:

$$\begin{aligned}\Delta logCO_2e_t = {} & \beta_0 + \sum_{i=1}^{m} \chi_1 logCO_2e_{t-i} + \sum_{i=1}^{m} \chi_2 logIPVEGRT_{t-i} \\ & + \sum_{i=1}^{m} \chi_3 \mathrm{log} ICGTD_{t-i} + \sum_{i=1}^{m} \chi_4 logTRO_{t-i} + \sum_{i=1}^{m} \chi_5 logREC_{t-i} \\ & + \sum_{i=1}^{m} \chi_6 logGDPPC_{t-i} + \sum_{i=1}^{m} \chi_7 logEMP_{t-i} \\ & + \lambda_1 logCO_2e_{t-i} + \lambda_2 logIPVEGRT_{t-i} \\ & + \lambda_3 logICGTD_{t-i} + \lambda_4 \mathrm{log} TRO_{t-i} \\ & + \lambda_5 logREC_{t-i} + \lambda_6 logGDPPC_{t-i} + \lambda_7 logEMP_{t-i} + \mu_t\end{aligned} \tag{16}$$

where β_0 depicts intercepts, m represents lag operators, μ_t signifies error terms, and Δ indicates the first difference operator. The F-statistic is used to test the following hypothesis after estimating Eq. (15):

$$H_0 : \lambda_2 = \lambda_3 = \lambda_4 = \lambda_5 = \lambda_6 = \lambda_7 = 0$$

$$H_1 : \lambda_2 \neq \lambda_3 \neq \lambda_4 \neq \lambda_5 \neq \lambda_6 \neq \lambda_7 \neq 0$$

In addition to BCT, the long-run and co-integration nexus between IPVEGRT, ICGTD, TRO, GDPPC, EMP, REC, and CO_2e was also examined using Engle–Granger and augmented Engle–Granger without structural break co-integration tests, Hansen parameter instability, and Engle–Granger with structural break co-integration tests.

Estimation of long-run coefficients: FMOLS, canonical co-integration regression (CCR), and dynamic OLS (DOLS)

Once co-integration was confirmed, the next step was to estimate the long-run coefficients using the FMOLS, CCR, and DOLS estimators. The FMOLS estimator introduced and developed by Phillips and Hansen (1990) uses the "Kernel" estimators of the nuisance parameters that affect the asymptotic distribution of the OLS estimator. FMOLS adjusts least squares to consider the effect of serial correlation and the presence of endogeneity among the IPVEGRT, ICGTD, TRO, GDPPC, EMP, and REC (due to the presence of co-integration between IPVEGRT, ICGTD, TRO, GDPPC, EMP, REC, and CO_2e), thereby ensuring asymptotic efficiency of the estimators. Consequently, the FMOLS approach generates consistent estimates and allows the assessment of the robustness of the results (Li et al. 2021b). By incorporating a differential term, the DOLS estimator can minimize non-normal residuals, concurrent bias, and autocorrelation, which may occur in the equation, and then estimate the coefficients of co-integration consistency (Anon. 2014). In comparison to the classic OLS estimator, DOLS has the advantage of correcting for regressor endogeneity in the residuals by incorporating the regressors' lags and leads in the first difference (Campos et al. 2020). Similar to DOLS and FMOLS, the CCR estimator also deals with the problem of endogeneity (Yawen et al. 2021).

Results and discussion

The basic properties of the data series are listed in Table 3. The average values of the levels of RIR (percentage), GDPPC (constant US$), CO_2e (million tons), IPVEGRT (green patents related to PV energy generation), TRO (percentage), ICGTD (green co-inventions), and REC (toe) were 4.591, 41,647.81, 5384.477, 362.489, 0.250, 79.681, and 11,7501.9, respectively. The minimum levels of RIR (percentage), GDPPC (constant US$), CO_2e (million tons), IPVEGRT (green patents related to PV energy generation), TRO (percentage), ICGTD (green co-inventions), and REC (toe) during 1990Q1–2018Q4 were 1.727, 23,851.36, 4894.552, 11.916, 0.198, 69.219, and 87,693.79, respectively. Likewise, the highest level of RIR (percentage), GDPPC (constant US$), CO_2e (million tons), IPVEGRT (green patents related to PV energy generation), TRO (percentage), ICGTD (green co-inventions), and REC (toe) in the USA during 1990Q1–2018Q4 were 8.775, 64,276.98, 5875.665, 1042.901, 0.312, 93.375, and 176,673.5, respectively.

Table 4 Unit root test without structural breaks

At level		At first difference		
Variables	t-statistic	Variables	t-statistic	Decision
CO_2e	−2.102	CO_2e	−6.253***	I(1)
ICGTD	−2.316	ICGTD	−10.378***	I(1)
IPVEGRT	−1.001	IPVEGRT	−8.443***	I(1)
GDPPC	−1.083	GDPPC	−4.234***	I(1)
EMP	−0.533	EMP	−3.866***	I(1)
REC	0.599	REC	−5.567***	I(1)
TRO	−1.834	TRO	−7.757***	I(1)

***depicts 1% levels of significance

The results of the unit root test without considering the structural breaks are presented in Table 4. The ADF unit root test's computed t-statistic values are less than the critical values at the level. Therefore, the alternative hypothesis of no unit root could be rejected for all variables, including GDPPC, IPVEGRT, REC, ICGTD, EMP, TRO, and CO_2e. This suggests that GDPPC, IPVEGRT, REC, ICGTD, EMP, TRO, and CO_2e are non-stationary at this level. Conversely, GDPPC, IPVEGRT, REC, ICGTD, EMP, TRO, and CO_2e became stationary at the first difference. Overall, the findings indicate that the computed values of the ADF test are more than the critical values at the first difference. Consequently, the null hypothesis of non-stationarity was rejected at the 1%, 5%, and 10% levels of significance. Although the US economy has experienced numerous economic shocks or structural breaks over the past several decades, the ADF test cannot consider structural breaks in the data set. The results of the ADF test could be dubious, incorrect, and inconsistent in the presence of structural breaks. For this reason, a unit root test with structural breaks, especially the Perron (1989) unit root test, was employed.

Table 5 presents the results of the unit root test with structural breaks. The findings confirmed that GDPPC, IPVEGRT, REC, ICGTD, EMP, TRO, and CO_2e have unit roots at this level. The single break duration was identified

Table 3 Descriptive statistics

Variable	CO_2e	IR	ICGTD	IPVEGRT	REC	GDPPC	TRO
Mean	5384.477	4.591	79.681	362.489	117,501.9	41,647.81	0.250
Median	5332.892	4.486	79.063	172.627	106,760.2	41,707.00	0.247
Maximum	5875.665	8.775	93.375	1042.901	176,673.5	64,276.98	0.312
Minimum	4894.552	1.727	69.219	11.916	87,693.79	23,851.36	0.198
Std. Dev.	298.1728	1.881	6.126	348.620	23,180.97	11,607.82	0.035
Skewness	0.089311	0.254	0.392	0.571	0.940	0.068	0.125
Kurtosis	1.707047	2.075	2.401	1.807	2.581	1.820	1.835
Observations	112	112	112	112	112	112	112

Table 5 Unit root test with structural breaks

At level			At first difference		
Variables	t-statistic	Break year	Variables	t-statistic	Break year
CO_2e	−3.786	2008Q1	CO_2e	−5.429***	1993Q1
ICGTD	−2.501	2001Q1	ICGTD	−6.891***	1992Q1
IPVEGRT	−4.142	1996Q1	IPVEGRT	−6.265***	1992Q1
GDPPC	−2.809	1991Q4	GDPPC	−4.866**	2009Q1
EMP	−3.438	2007Q1	EMP	−7.456***	2009Q1
REC	−1.481	2009Q1	REC	−5.267***	2001Q1
TRO	−3.473	2003Q1	TRO	−6.012***	1993Q1

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

in GDPPC (1991Q4), IPVEGRT (1996Q1), REC (2009Q1), ICGTD (2001Q1), EMP (2007Q1), TRO (2003Q1), and CO_2e (2008Q1). The results also showed that all the variables, including GDPPC, IPVEGRT, REC, ICGTD, EMP, TRO, and CO_2e, are stationary at the first difference. Hence, the null hypothesis of non-stationarity in the presence of structural break was rejected at the 1%, 5%, and 10% levels of significance. The same integrating order of GDPPC, IPVEGRT, REC, ICGTD, EMP, TRO, and CO_2e in the absence and presence of structural breaks allowed us to examine the co-integration nexus between variables in both cases.

The findings of the co-integration tests without structural breaks are presented in Table 6. The estimated bound F-statistic value was greater than the upper bound value. Hence, the alternative hypothesis of co-integration among GDPPC, IPVEGRT, REC, ICGTD, EMP, TRO, and CO_2e in the absence of structural break was accepted at the 1%, 5%, and 10% levels of significance. In addition, the computed values of the z-statistic and t-statistic are also statistically significant; therefore, the null hypothesis of no co-integration among GDPPC, IPVEGRT, REC, ICGTD, EMP, TRO, and CO_2e in the absence of structural breaks is rejected. The co-integration tests with a structural break were used to determine whether integrating structural breaks changed the results of co-integration between GDPPC, IPVEGRT, REC, ICGTD, EMP, TRO, and CO_2e.

Table 7 shows the findings of the co-integration tests in the presence of structural breaks. The estimated value of the LC statistic was less than the critical values. Hence, the null hypothesis of co-integration among GDPPC, IPVEGRT, REC, ICGTD, EMP, TRO, and CO_2e in the presence of structural breaks was accepted. Furthermore, the computed values of the Tau-statistic and Z-statistic were greater than the critical values, and the alternative hypothesis of co-integration among GDPPC, IPVEGRT, REC, ICGTD, EMP, TRO, and CO_2e in the presence of structural breaks was accepted. After validating the co-integration and long-run nexus between GDPPC, IPVEGRT, REC, ICGTD, EMP, TRO, and CO_2e, the next step was to use FMOLS, DOLS, and CCR to estimate the long-run coefficients.

Table 6 Co-integration tests without structural breaks

Variables	Optimal lag length	Bound F-statistic
BT co-integration	AIC [2, 0, 0, 2, 1, 2, 1]	4.967***
Engle–Granger Co-integration Test	z-statistic	Decision
CO_2e → IPVEGRT	−1.838**	Co-integration
CO_2e → EMP	−3.805***	Co-integration
CO_2e → REC	−3.491***	Co-integration
CO_2e → TRO	−1.394*	Co-integration
CO_2e → GDPPC	−1.632*	Co-integration
CO_2e → ICGTD	−2.276**	Co-integration
Augmented Engle–Granger Co-integration Test	t-statistic	Decision
CO_2e → IPVEGRT	−1.967**	Co-integration
CO_2e → EMP	−2.447***	Co-integration
CO_2e → REC	−2.443***	Co-integration
CO_2e → TRO	−1.792**	Co-integration
CO_2e → GDPPC	−1.869**	Co-integration
CO_2e → ICGTD	−1.952**	Co-integration

Table 7 Co-integration tests with structural breaks

Co-integration test—Hansen Parameter Instability					
Null hypothesis: Series are co-integrated					
Structural Breaks: 1991Q4, 1996Q1, 2001Q1, 2003Q1, 2007Q1, 2008Q1, 2009Q1					
FMOLS		DOLS		CCR	
LC statistic	Stochastic trends	LC statistic	Stochastic trends	LC statistic	Stochastic trends
0.449					
(>0.2)	7	0.019			
(>0.2)	7	0.537			
(>0.2)	7				
Co-integration test—Engle–Granger					
Null hypothesis: Series are not co-integrated					
Structural breaks: 1991Q4, 1996Q1, 2001Q1, 2003Q1, 2007Q1, 2008Q1, 2009Q1					
FMOLS		DOLS		CCR	
Tau-statistic	**Z-statistic**	**Tau-statistic**	**Z-statistic**	**Tau-statistic**	**Z-statistic**
−5.505**					
(0.043)	−239.968***				
(0.000)	−5.505**				
(0.043)	−239.968***				
(0.000)	−5.505**				
(0.043)	−239.968***				
(0.000)					

** and *** depict the 5% and 1% levels of significance, respectively; the *p* values are reported within parentheses

Table 8 Long-run estimates

Variables	FMOLS	DOLS	CCR
ICGTD	−0.199**	−0.200**	−0.198**
	(−2.413)	(−2.245)	(−2.537)
IPVEGRT	−0.020***	−0.022***	−0.011***
	(−2.847)	(−2.865)	(−3.012)
GDPPC	0.282***	0.294***	0.280***
	(8.493)	(8.232)	(8.113)
EMP	0.018***	0.020***	0.018***
	(3.021)	(3.054)	(3.141)
REC	−0.293***	−0.292***	−0.293***
	(−5.405)	(−4.967)	(−5.471)
TRO	0.185***	0.192***	0.186***
	(2.951)	(2.838)	(3.108)
C	4.479***	4.428***	4.481***
	(15.102)	(13.774)	(14.303)

** and *** indicate significance at the 5% and 1% levels, respectively; the t-statistics are reported within parentheses

The findings of CCR, FMOLS, and DOLS are shown in Table 8. First, the findings signified that an upsurge in IPVEGRT led to a decrease in CO_2e in the USA. This finding shows that IPVEGRT can significantly reduce CO_2e emissions associated with power generation, paving the way for a more sustainable and eco-friendly energy future. The IPVEGRT helps to mitigate CO_2e in the sense that the production of solar energy employing the most advanced PV technologies increases the consumption of renewable energy and reduces dependence on the use of dirty fuels.

The economic and environmental well-being of the USA is dependent on a significant transition toward power supplied from abundant, reliable, and generally clean fuels. Solar energy can create electricity without contributing to climate change, without emitting other pollutants, without bearing fuel expenditures, and without the risk of fuel price increases. The sun is a mostly equal-opportunity renewable energy source, with sufficient sunshine across the country to make solar an appealing alternative in every state. Solar energy generation options include a variety of technologies with varying features and benefits for utilities, businesses, and homeowners. Solar PV systems of a small size account for the majority of solar installations in terms of installed capacity, whereas concentrating solar power systems and large-scale PV systems account for the bulk of solar total electricity-generating capacity. All three factors contribute environmentally and economically to the stabilization and resilience of the energy system of the USA (Sector 2014). Solar power has grown at a remarkable pace in the USA over the past several decades. For instance, there was a 485% increase in solar PV installations in the USA between 2010 and 2013 (GTM Research and Solar Energy Industries Association (SEIA) 2014). With an average yearly installation rate of 16% from 2011 to 2013, solar energy contributed almost 30% of the new energy capacity in the USA (Energy

Information Administration (EIA) 2011). By the beginning of 2014, the USA had more than 480,000 solar energy systems installed, totaling 13,400 megawatts (MW), which was sufficient to power approximately 2.4 million typical households for an entire year (GTM Research and Solar Energy Industries Association (SEIA) 2014). While solar power still accounts for a small portion of total electricity generation, it currently accounts for 2% of electricity generation in the leading states of Nevada, California, and Arizona. In June 2014, California set a 1-day record for solar energy production equal to 8% of the total electricity demand (Energy Information Administration (EIA) 2014). The transformation toward affordable, reliable, and clean electricity in the USA is most evident in the swift increase of solar panels fixed on the roofs of businesses and homes. The institutional, commercial, and residential rooftop PV solar expanded by an average of more than 50% per annum between 2008 and 2013.

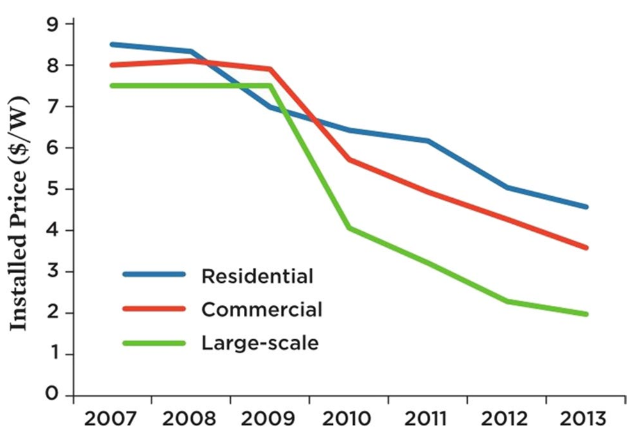


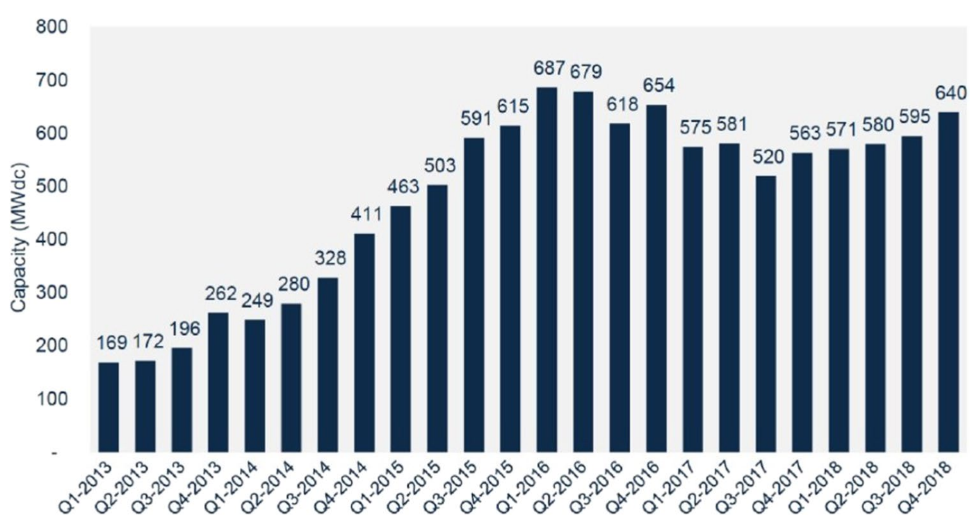
Fig. 2 Installation costs of PV solar systems in the USA. Source: Sector 2014

Technical advancements and investment will continue to promote increased solar investment by lowering installation costs, increasing generation efficiency, and lowering component costs. The continued growth in IPVEGRT results in the development of new and improved PV technology that is efficient in generating electricity and cost-competitive (Sector 2014). Because of innovation, PV solar systems are becoming increasingly economical for business owners, homeowners, and their communities in the USA, as depicted in Fig. 2. In the fourth quarter of 2018, the solar market in the USA installed 4.2 gigatons (GWdc) of solar PV, representing a 139% rise from the third quarter of 2018 and a 4% increase from the fourth quarter of 2017. Currently, the cumulative operating solar photovoltaic capacity is 62.4 GWdc, which is approximately 75 times greater than the capacity built at the end of 2008 (Solar Energy Industries Association 2018).

Following a year in which the domestic solar market witnessed a 15% drop, 2018 represented a year of recovery, with the market growing by 7%. The home solar segment experienced its best quarter in more than 2 years in Q4, indicating that the residential market has reached a point of stability (Solar Energy Industries Association 2018). As shown in Fig. 3, 314,600 new home PV systems were installed in the USA in 2018.

Among the highest penetration markets in the country, residential growth rates varied in 2018, as depicted in Fig. 4, Nevada was the sole exception, experiencing a threefold increase after net metering was resumed in 2017 following its suspension in 2016, which resulted in a market contraction of 61% from 2016 to 2017. Due to this political turmoil, 2018 saw an exceptionally high number of installations due to pent-up demand. Apart from stabilizing large markets, expansion in low-penetration emerging markets, such as Florida and Texas, continues to diversify the residential

Fig. 3 Installation of residential PV solar system during 2013–2018. Source: Solar Energy Industries Association 2018



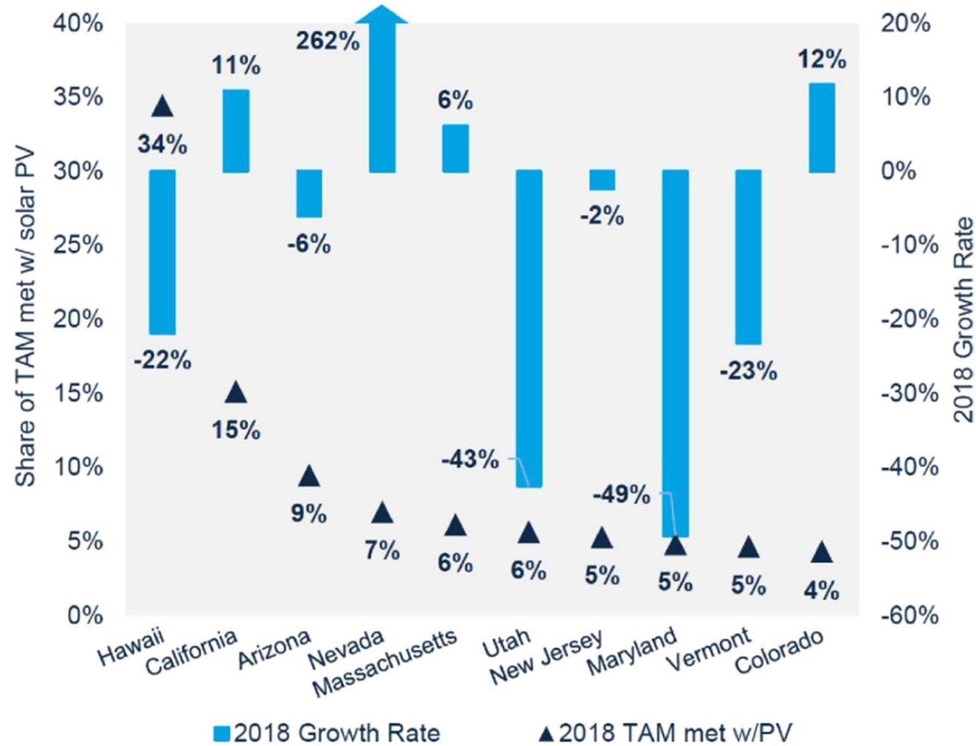


Fig. 4 Year-over-year increase by highest penetration. Source: Solar Energy Industries Association 2018

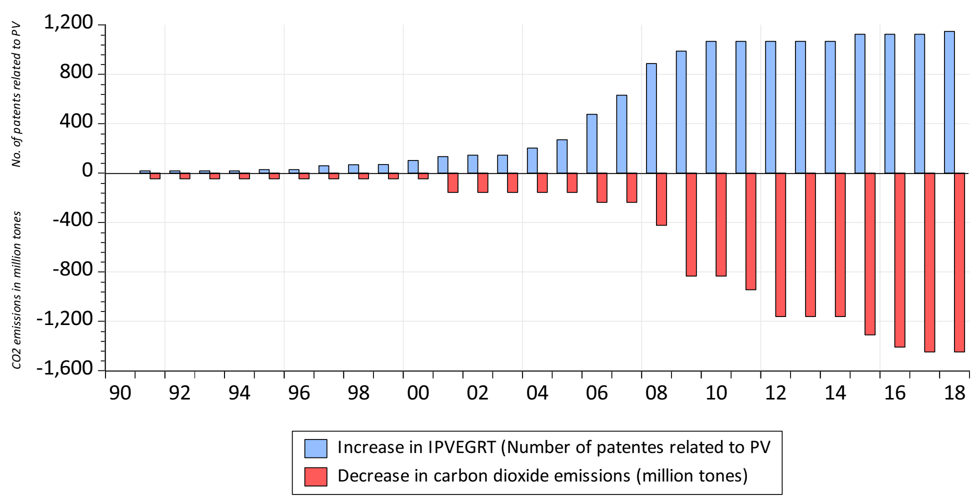


Fig. 5 Unparalleled association between IPVEGRT (%↑) and CO_2e (%↓). Data source: OECD 2020

market outside of the Northeast and California (Solar Energy Industries Association 2018).

Overall, IPVEGRT increases the use of PV energy systems in the USA, consequently decreasing the use of fossil fuels and CO_2e. As shown in Fig. 5, an upsurge in the number of patents related to new PV technology (17 in 1995, 133 in 2001, 474 in 2006, 886 in 2008, 986 in 2009, 1065 in 2010, 1123 in 2015, and 1146 in 2018) led to a decrease in CO_2e (million tons) by 46.15157.6, 237.8, 423, 885, 835, 1310, and 1449 in the respective years.

The findings also indicate that a 1% increase in ICGTD led to a 0.20% decrease in CO_2e. This shows that continued engagement in ICGTD-related actions minimizes reliance on non-renewable energy and also lessens CO_2e. Global cooperation has allowed significant advancements in green and sustainable technologies. Numerous studies indicate that worldwide specialists interact more effectively to improve environmental technology, build shared standards, convene worldwide conferences, transmit information, and collaborate on sustainable research projects. The US government spends a substantial amount of money on sustainable research-related initiatives, notably cross-border green, and sustainable-related research partnerships. These efforts include developments in standardization, ecological technology, datasets, symposia, management culture, technical support, and intellectual engagement in the areas of environmental innovation and general technological innovation (Wagner et al. 2001).

Approximately 90% of all collaborative research financed by the USA is based on ICGTD. The United States Department of Energy conducts collaborative research on issues of increasing concern, particularly in available energy sciences and green and efficient energy systems. Between 1960 and 2018, the United States greatly enhanced ICGTD operations, focusing primarily on alliance in the fields of transportation, sustainable energy (generation and transmission), ICT, green ocean economy, industrial goods production, wastewater management, general ecological management, buildings and construction, and adaptation to climate change technologies. Figure 6 shows the progress made by the USA in ICGTD from 1972 to 2018 in various sectors. From 1972 to 2018, ICGTD increased from 1 to 1097 for ICT, from 3 to 61 for discarding of greenhouse gases, from 20 to 484 for climate change adaptation technologies, from 111 to 1340 for general environmental management; from 6 to 78 for sustainable ocean economies, from 17 to 2056 for transportation, from 5 to 576 for buildings, from 15 to 127 for wastewater treatment or waste management, from 44 to 1698 for energy generation, transmission, or distribution, and from 22 to 870 for production or processing of goods. This advancement in ICGTD across a variety of industries and companies has contributed to a reduction in CO_2e emissions.

The third implication of the results is that the execution of an EMP causes an upsurge in CO_2e. This suggests that reducing interest rates through monetary policy in the United States leads to an increase in CO_2e. One probable explanation is that the recession in the USA during 2009 and 2010 had a major influence on economic activities, household consumption, production, energy consumption, aggregate supply and demand, international trade, purchasing power, and investments. The United States Central Bank adopted an EMP to boost domestic investment, exports, and firms' production, demand, and supply. For example, during the recession that occurred in the late 2000s, an EMP was implemented in the USA. As housing prices declined and the economy weakened, the Federal Reserve cut its interest rate from 5.25% in June 2007 to 0% by the end of 2008. Reduced real interest rates enhanced industrial production, aggregate supply and demand, non-renewable energy use, and CO_2e. This finding confirms previous studies conducted in BRICS nations (Chishti et al. 2021) and Asian economies (Qingquan et al. 2020).

Fourth, the results show that a 1% increase in TRO has led to an increase in CO_2e by 0.19%. This finding shows that the steady increase in the purchase of imported and exported goods contributes to the rise in CO_2e in the USA. This finding validates the previous studies conducted in OECD states (Ahmad et al. 2019), South Africa (Ahmad and Khattak 2020), the BRICS nations (Ahmad and Zheng 2021), the USA (Xin et al. 2021), developing countries (Van

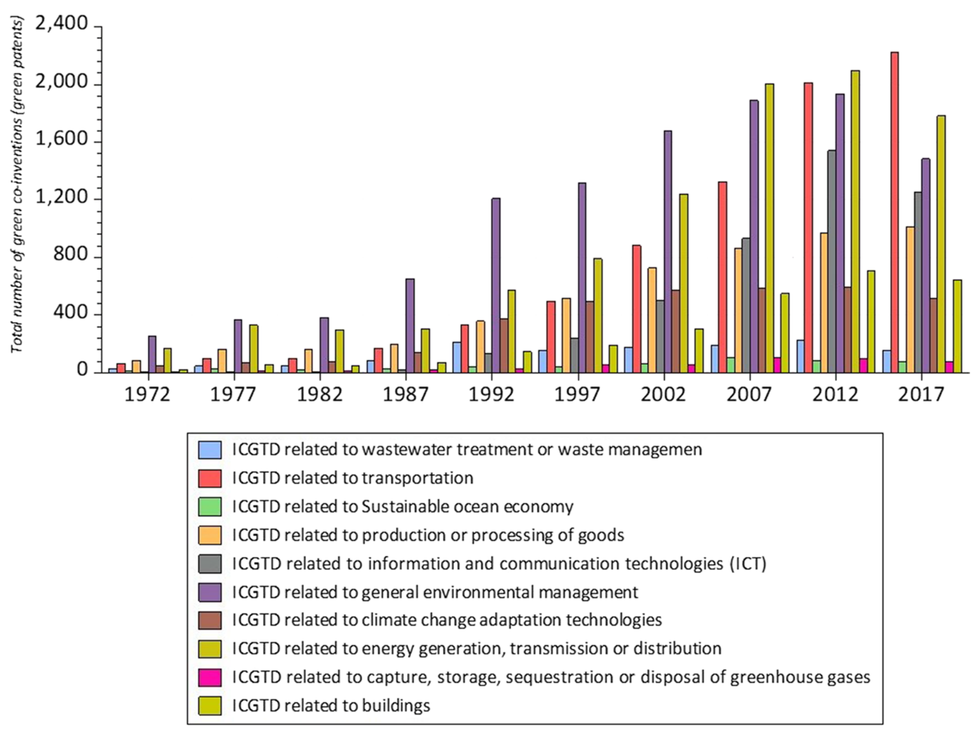


Fig. 6 ICGTD (co-inventions) between 1972 and 2018. Data source: OECD 2020

Table 9 Long-run estimates with structural breaks: robustness check

Break years: 1991Q4, 1996Q1, 2001Q1, 2003Q1, 2007Q1, 2008Q1, 2009Q1

Variables	FMOLS	DOLS	CCR
ICGTD	−0.199**	−0.191**	−0.197**
	(−2.391)	(−2.214)	(−2.480)
IPVEGRT	−0.020***	−0.022***	−0.020***
	(−2.835)	(−2.852)	(−2.999)
GDPPC	0.282***	0.294***	0.280***
	(8.472)	(8.186)	(8.045)
EMP	0.019**	0.020**	0.019**
	(3.029)	(3.039)	(3.127)
REC	−0.293***	−0.292***	−0.293***
	(−5.374)	(−4.937)	(−5.448)
TRO	0.185**	0.193**	0.187**
	(2.936)	(2.816)	(3.039)
Dummy	0.0005	0.0004	0.0008
	(0.095)	(0.065)	(0.099)
C	4.475***	4.427***	4.478***
	(15.011)	(13.675)	(14.230)

** and *** indicate significance at the 5% and 1% levels, respectively; the t-statistics are reported within parentheses

Table 10 Granger causality test

Null hypothesis	F-statistic
ICGTD → CO_2e	5.968**
CO_2e → ICGTD	3.117*
GDPPC → CO_2e	3.783*
CO_2e → GDPPC	0.547
IPVEGRT → CO_2e	9.644***
CO_2e → IPVEGRT	11.297***
TRO → CO_2e	10.907***
CO_2e → TRO	1.306
REC → CO_2e	2.270
CO_2e → REC	0.897
EMP → CO_2e	6.316**
CO_2e → EMP	0.427

*, **, and *** represent the 10%, 5%, and 1% levels of significance, respectively

Tran 2020), and South Asian states (Murshed 2020). Fifth, the findings indicate that a 1% upsurge in REC has resulted in a decline in CO_2e by 0.29%. This result confirms previous studies carried out for emerging market economies (Ummalla and Samal 2019), developing states (Dimitriadis et al. 2021), the USA (Pata 2020), Pakistan (Zaidi et al. 2018), and China (Li et al. 2021c). Lastly, the results show that a 1% upsurge in GDPPC has caused an increase in CO_2e by 0.28%. This result confirms the results of previous studies conducted in Pakistan (Ali et al. 2021), Belt and Road Initiative Economies (Anwar et al. 2020), OECD nations (Mensah et al. 2018), E7 countries (Gyamfi et al. 2020), China (Boamah et al. 2017), and newly industrialized nations (Zhang et al. 2017a).

Table 9 summarizes the findings of the robustness tests in the presence of structural breakdowns. The results validate the positive nexus between GDP, EMP, TRO, and CO_2e. Furthermore, the findings also validated the negative association between REC, ICGTD, IPVEGRT, and CO_2e. These findings are consistent with those presented in Table 8.

The findings of Granger causality are presented in Table 10. The results reveal the unidirectional nexus between GDPPC and CO_2e, TRO and CO_2e, and EMP and CO_2e. These results show that any government policies that upsurge or reduce GDPPC, TRO, and EMP results in a parallel increase or mitigation of CO_2e. Conversely, government policies that increase or mitigate CO_2e do not increase or decrease GDPPC, TRO, and EMP. The findings also indicate a bidirectional association between ICGTD and CO_2e and IPVEGRT and CO_2e, suggesting that any government policies that increase or reduce ICGTD and IPVEGRT result in a parallel respective increase or mitigation of CO_2e. In addition, government policies that increase or mitigate CO_2e lead to an increase or decrease, respectively, in ICGTD and IPVEGRT.

Conclusion and policy implications

This study evaluates the effects of IPVEGRT and ICGTD on CO_2e in the USA. An environmental model that captures the theoretical relationships between GDPPC, IPVEGRT, REC, ICGTD, EMP, TRO, and CO_2e was used. CCR, FMOLS, DOLS, and Granger causality techniques were employed. The findings validate the positive impact of EMP, GDPPC, and TRO on CO_2e. Conversely, the results also show the positive linkage of upsurges in REC, IPVEGRT, and ICGTD with CO_2e. The findings from the Granger causality test reveal a one-way connection between the nexus between GDPPC and CO_2e, TRO and CO_2e, and EMP and CO_2e. The two-way linkage is between a bidirectional nexus between ICGTD and CO_2e and between IPVEGRT and CO_2e.

The study's findings have the following policy implications. The first is based on the negative nexus between IPVEGRT and CO_2e. The US federal government could consider enacting policies that make it possible for corporations and industries to engage in IPVEGRT and boost the total level of IPVEGRT participation. For instance, the green innovation funding program should be supported by providing both financial and physical resources at lower interest rates to industrial research centers, universities, government research organizations, basic research institutes, laboratories, and high-tech enterprises. Barriers specific to IPVEGRT policymaking, execution, and fund provision may further hamper IPVEGRT activities. Examples of these are shortfalls in awareness and information, the number of trained and educated employees to match developing PV energy generation technologies, and the resources to integrate marine energy into current systems. The widespread adoption of PV energy generation technologies would necessitate policies to resolve these obstacles and help overcome such obstacles. Furthermore, policy frameworks enacted to support IPVEGRT are diverse and can be applied to all energy sectors. They include regulations like quotas and price-driven policies (i.e., biofuel blending requirements, heat obligations, and feed-in tariffs for energy) and fiscal incentives (i.e., low-interest loans, tax credits, and rebates).

Second, given the negative linkage between ICGTD and CO_2e, the US federal government could consider developing policies to expand and develop ICGTD-related efforts. Supporting ICGTD policies will play a vital role in the development of a worldwide understanding of accomplishing the goals of achieving sustainability by reducing the total costs of green R&D. In addition, they will double private/public sector R&D funding, accelerate the adoption and diffusion of green technologies, and lower the overall cost of green R&D. Policies driven by the ICGTD can contribute to developing, growing, and industrialized economies in transitioning to a green economy. Cooperation in this area will entail the creation of elegant and inclusive systems and processes for the transmission and exchange of sustainable resources. These include knowledge, competence, scientists, statistics, and cutting-edge technologies. In this respect, a trust-based ecosystem is critical for facilitating macro- and micro-level resource exchange and accomplishing long-term goals. Policymakers should build and promote novel cohesive green networks that connect the government sector, technology companies, and green projects.

The present study does have limitations that are significant for future research directions. First, this study examined the link between IPVEGRT and CO_2e using linear econometric approaches. Nevertheless, there is evidence that innovative activities are pro-cyclical during the business cycles. The pro-cyclical nature of R&D activities indicates that these activities increase during an economic boom and decline during a recession. This limitation can be addressed by examining the cyclical and asymmetrical nexus between IPVEGRT and CO_2e. Second, this study only examined the association between IPVEGRT and CO_2e in the USA. However, considering the significance of IPVEGRT, studies conducted elsewhere are warranted, including European Union states, BRICS economies, G7, newly industrialized states, and African economies.

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Declarations

Conflict of interest The authors declare no competing interests.

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