sustainability

Article

Economic Growth, CO_2 Emissions Quota and Optimal Allocation under Uncertainty

Chiu-Ming Hsiao

Department of Finance, College of Management, National Yunlin University of Science & Technology, Yunlin 64002, Taiwan; shiaucm@yuntech.edu.tw

Abstract: This study attempts to link greenhouse gas emissions and economic development, and under the premise of considering economic development, proposes an optimal quota of greenhouse gas emissions. Based on the environmental Kuznets curve hypothesis, the logarithmic value of greenhouse gas emissions is an inverted U-shaped function of the logarithmic value of GDP per capita. The empirical results showed that most countries in the world support the Kuznets curve hypothesis. Moreover, using data collected from Our World in Data, the optimal allocation of a greenhouse gas emissions quota can be found by minimizing the uncertainty risk subject to a prespecified global economic growth rate. For government policymakers, they may apply the framework in this study to determine an optimal allocation of greenhouse gas emissions for each sector that will ensure the intended level of domestic economic growth.

Keywords: greenhouse gases; CO_2 emission equivalent; environmental Kuznets curve; modern portfolio theory

check for updates

Citation: Hsiao, C.-M. Economic Growth, CO_2 Emissions Quota and Optimal Allocation under Uncertainty. *Sustainability* **2022**, *14*, 8706. https://doi.org/10.3390/su14148706

Academic Editors: Guo Wei, Ehsan Elahi and Tasawar Nawaz

Received: 16 June 2022
Accepted: 4 July 2022
Published: 16 July 2022

1. Introduction

Following the Industrial Revolution in the 18th century, for more than 260 years, human beings have invented tools and innovative technologies in order to both improve their lives and improve their economic standards. Therefore, original resources (such as fossil energy, minerals, and virgin forests) have almost been exhausted, and the destruction of the environment (the shrinking of the ice caps in the Arctic and Antarctic, the deforestation of rainforests leading to biological extinction, etc.) has changed the ecological system, making the Earth no longer able to accept such man-made destruction, and it has begun to remind mankind in its own way (Guggenheim and Al Gore, 2006 [1]; TVBS Sisy's World News Group, 2010 [2]).

1.1. Climate Change Impacts

On 25 August 2005, a categorized level 5 hurricane, Katrina, caused severe damage in New Orleans, Louisiana, United States. The hurricane made landfall in Florida as a category 1 hurricane, and at dawn on 29 August, it made landfall again on the outer coast of New Orleans, Louisiana, on the Gulf Coast of the United States as a category 3 hurricane. It weakened to a tropical storm more than 12 h after making landfall. According to the United States National Catastrophe Center, Hurricane Katrina was the hurricane/tropical depression that caused the worst damage in the continental United States (Table 1).

Table 1. America's historical top-10 costliest Atlantic hurricanes.

Rank	Name	Pressure (mbar)	Category (USA)	Year	Damage (Billion USD)	Dead
1	Katrina	920	5	2005	125.0	1836
2	Harvey	937	4	2017	125.0	107
3	Maria	920	5	2017	91.6	3059
4	Irma	914	5	2017	77.6	134
5	Ida	929	4	2021	75.3	107
6	Sandy	940	3	2012	68.7	233
7	Ike	935	4	2008	38.0	214
8	Andrew	922	5	1992	27.3	65
9	Michael	919	5	2018	25.5	74
10	Florence	927	4	2004	24.2	54

Source: United States National Catastrophe Center.

In the summer of 2021, the Northern Hemisphere of the Earth was facing a flood. In Western Europe, heavy rains caused flooding in Germany, Belgium, the Netherlands, Luxembourg, and Switzerland. Not only was transportation blocked, but businesses were unable to operate normally, and more complications caused heavy casualties. According to EU statistics, this flood not only extended to five Western European countries, resulting in 228 deaths and 166 missing, but the economic damage was at least 3 billion US dollars.

Moreover, in Asia, from mid-May to mid-July 2018, southwestern China suffered frequent floods in Sichuan, Gansu, and Shaanxi provinces due to the fact of heavy rains for many days, resulting in 3.526 million people being affected, with 16 dead, 4 missing, and a direct economic loss of 1.58 billion Chinese yuan. Two years later, from late May 2020, severe floods were caused by continuous heavy precipitation that occurred in the middle and lower reaches of the Yangtze River, the Huaihe River Basin, Southwest China, South China, and the southeast coast of China. According to China's official statistics, 63.46 million people were affected by the flood, with more than 54,000 houses collapsed, 247 people dead, and 33 people missing, and the economic damage was over 225.56 billion Chinese yuan.

Deadly floods in Asia, the Arctic melting, droughts in Taiwan, and wildfires in California and Australia—real-life examples of extreme weather—sounded the alarm on climate change in 2020 and 2021. Although 2020 coincided with the "La Niña" phenomenon that will cool down the atmosphere, and the COVID-19 epidemic has significantly dragged down the economies of various countries (Le Quéré et al., 2020 [3]; Hsiao, 2022 [4]), it was still one of the three warmest years in history, hotter than the pre-industrial era (1850–1900) by 1.2 °C. The most significant warming in this year was in northern Asia, especially the Siberian Arctic, which was a full 5 °C above the average of previous years. Witnessing the impact of a string of extreme weather events is a further reminder of why we cannot ignore the climate crisis (Abbass et al., 2022 [5]).

As former US Vice President Al Gore said in *An Inconvenient Truth*, the phenomenon of climate change that causes the Earth's severe climate is due to global warming, and the excessive production of greenhouse gases by humans is an important cause of global warming. According to the IPCC AR6, no matter what the emission scenario is, the global surface will continue to warm until at least the middle of the 21st century. In the 21st century, it will exceed an increase of 1.5 or 2.0 °C, which will cause an increase in the proportion of extreme climates.

1.2. Global Warming and Greenhouse Gases

A greenhouse gas (GHG) is a gas that absorbs and emits radiant energy within the thermal infrared range, causing the greenhouse effect. The primary greenhouse gases in the Earth's atmosphere are water vapor (H_2O), carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and ozone (O_3). The amount of water vapor in the atmosphere is also related to temperature. The higher the temperature, the more water vapor accumulates.

Therefore, water vapor is considered to be part of a feedback loop rather than the cause of the greenhouse effect. Carbon dioxide (CO_2) is the primary GHG emitted through human activities. In 2020, CO_2 accounted for approximately 79% of all US greenhouse gas emissions from human activities. The following Table 2 lists the sources of GHGs.

Table 2. Emission sources of GHGs.

GHG	Molecular Formula	Emission Sources
Water vapor	H_2O	Boiled water
Ozone	O_3	Light causes O_2 to act photochemically.
Carbon dioxide	CO_2	1. Human burning of fossil fuels 2. Deforestation 3. Biological respiration
Methane	CH_4	1. Enteric fermentation (for example, from animal husbandry and cattle raising) 2. Rice 3. Small leakage of fossil fuel transportation
Nitrogen oxides	NO, NO_2, N_2O, N_4O, NO_3, N_2O_3, N_2O_4, N_2O_5, $N(NO_2)_3$	1. Combustion of biomass 2. Fuel 3. Fertilizer production
Chlorofluorocarbons	Chlorofluorocarbons (CFCs) Hydrochlorofluorocarbons (HCFCs) Hydrofluorocarbons (HFCs)	Refrigerant escape
Perfluorocarbons	CF_4, C_2F_6, SF_6, NF_3	Insulator

Source: United States Environmental Protection Agency (https://www.epa.gov/ghgemissions/overview-greenhouse-gases, accessed on 16 May 2022).

Under the Kyoto Protocol, in 1997 the Conference of the Parties standardized international reporting by deciding (decision 2/CP.3) that the values of the GWP calculated for the IPCC AR2 were to be used for converting the various GHG emissions into comparable CO_2 equivalents (CO_2e). After 2013, this standard was updated at the Warsaw meeting of the UN Framework Convention on Climate Change (UNFCCC, decision 24/CP.19), in which researchers are required to use a new set of 100 year global warming potential (GWP) values. They published these values in Annex III, and they took them from IPCC AR4, which was published in 2007.

The GWP value depends on both the efficiency of the molecule as a GHG and its atmospheric lifetime. The GWP value is defined as the ratio of the time-integrated radiative forcing from the instantaneous release of 1 kg of a trace substance relative to that of 1 kg of a reference gas (here, it was CO_2). As a result, the GWP is measured relative to the same mass of CO_2 and evaluated for a specific timescale. When a gas has a high (positive) radiative forcing but also a short lifetime, it will have a large GWP on a 20 year scale but a small one on a 100 year scale. Conversely, if a molecule has a longer atmospheric lifetime than CO_2, its GWP will increase when the timescale is considered. CO_2 is defined to have a GWP of 1 over all time periods. The GWP values of GHGs are shown in the following Table 3 from the United States Environmental Protection Agence.

Table 3. Global warming potential of greenhouse gases.

GHG	Lifetime (Years)	Global Warming Potential (GWP) [a]		
		20 Years	100 Years	500 Years
Carbon dioxide (CO_2)	20~200	1	1	1
Methane (CH_4)	12.4	82.5	32	7.6
Nitrous oxide (N_2O)	109	273	273	130
HFC-134a (CH_2FCF)	14	1390	1526	436
CFC-11 (CCl_3F)	52	8321	6226	2093
CFC-12 (CCl_2F_2)	100	10,800	10,200	5200
HCFC-22 ($CHClF_2$)	12	5280	1760	549
Carbon tetrafluoride (CF_4, PFC-14)	50,000	5301	7380	10,587
HFC-32 (CH_2F_2)	5	2693	771	220
Hexafluoroethane (C_2F_6)	10,000	8210	11,100	18,200
Nitrogen trifluoride (NF_3)	500	12,800	19,100	20,700
Sulfur hexafluoride (SF6) [b]	3200	17,500	23,500	32,600

[a] It is estimated according to IPCC AR6 WG1 Ch7 2021, contributed by Forster et al., (2021) [6]. [b] It is estimated according to IPCC AR5 WG1 Ch8 2013, contributed by Myhre et al., (2013) [7]. Source: United States Environmental Protection Agency, 16 May 2022.

1.3. Motivations

The purpose of conducting GHG inventory is to understand the hot spots of its emission sources, so as to determine the reduction plan, such as process improvement, equipment renewal, purchase of green power energy, or addition of carbon sequestration equipment, or even carbon rights trading. Furthermore, with this GHG emission information in the base year can also be used as the basis for the government to formulate GHG emission management measures and impose a carbon tax.

However, are the current emissions just too high? What is the baseline? In general, the most fundamental question is: what is the allowable carbon emission benchmark quota? Since 2013, there have been many studies which have sought to investigate this issue (For instance, Golombek et al., (2013) [8], Zhou et al., (2013) [9], Wei et al., (2014) [10], Pan et al., (2014a [11], 2014b [12]), Zhang et al., (2014) [13], Hao et al., (2015) [14], Pang et al., (2015) [15], Carretero et al., (2016) [16], Miao et al., (2016) [17], Han et al., (2016) [18], Chang et al., (2016) [19], An et al., (2017) [20], and Zhou et al., (2018) [21]), some of them use the efficiency analysis, and some others use mathematical/statistical approach to find a reasonable emission quota for countries or regions.

If the quota of carbon emission rights of enterprises/organizations cannot be reasonably determined, or the quotas set cannot be achieved, it should be difficult for enterprises/organizations to achieve carbon reduction targets regardless of whether it is a carbon tax or a carbon price set by the carbon trading market. Organizational protests cause social disputes and affect economic development (Crémieux, 2018 [22]). Moreover, for smaller economies, blindly formulating consistent emission reductions by the government in order to follow international standards, ignoring their domestic economic development, is a very dangerous decision.

This study attempts to link GHGs emissions and economic development, and then to propose an optimal quota of GHG emissions for the countries by considering the economic development and uncertainty. Using the mathematical framework in Markowitz (1952) [23], Chen, Jang, and Peng (2010) [24], and Hsiao (2017) [25], an optimal allocation can be found that minimizes the uncertainty risk of economic growth subject to a lower bound of economic growth rate. Such that, based on this, countries can implement reasonable policies for GHGs emissions, namely, the over-emitting countries should implement emission reduction policies, such as energy efficiency and energy conservation enhance, fuel switching, carbon capture and sequestration, land management practices, and so on. The countries with lower emissions can trade its carbon rights to promote national GDP.

The structure of this study is as follows. Section 2 is a literature review, which discusses the literature and research results on the topic of GHG emissions and economic development. Section 3 is the research model of this study. Through the environmental Kuznets curve hypothesis (EKC), the nexus between GHG emissions and economic growth can be established. Hence fore, a model can be further established: when considering the lowest rate of regional economic growth, an optimal proportion of greenhouse gas emissions in each economy that minimizes the uncertainty risk can be found. Thus, it can convert the optimal GHG emissions of all economies in the region. Section 4 is the empirical results and analysis. In this study, the source of the empirical data is downloaded from the database of Our World in Data. It is an open resource, and its data collection is rich and has certain credibility. Therefore, this study used empirical results based on the data in that database. Section 5 is the conclusion and suggestion of this study.

2. Literature Review

2.1. GHGs and CBAM

In 2019, the European Commission (EC) announced the European Green Deal. The goal is to reduce GHGs (compared to 1990) by 55% by 2030. Moreover, in the future, in 2050, Europe should achieve medium- and long-term reduction targets of climate neutrality. Recently, in July 2021, on the eve of the 26th United Nations Climate Conference (COP26) in Glasgow, Scotland, the EC proposed the implementation of 12 measures in the “Fit for 55 Package”. The package not only ensures that future climate and energy policies can meet the goals set by the European Climate Law but also covers climate, energy, construction, carbon trading, transportation, and other aspects. More importantly, it pushed other countries that were able to follow suit at COP26.

On the other hand, in March 2020, the European Parliament adopted a resolution on the Carbon Border Adjustment Mechanism (CBAM). The so-called “carbon border tax” has thus became one of the focal points of the European Green Deal. On 14 July 2021, the EC presented a draft regulation that defined the framework for the operation of the border tax. It is to apply from 1 January 2023 onwards, and is supposed to prevent the shifting of production, especially high-carbon industry, to countries where companies do not pay for greenhouse gas emissions (so-called “carbon leakage”) and to level the chances of EU and non-EU producers. An additional fee is to be levied on goods imported into the EU, the production of which is associated with high CO_2 emissions.

After COP26, countries successively proposed the Climate Change Response Act or the Amendment Law on GHG reduction. For example, on 28 May 2022, the Legislative Yuan of Taiwan first reviewed the draft amendment of the Greenhouse Gas Reduction and Management Law and completed the first trial under the name of the Amendment Draft of the Climate Change Response Act. As of 2021 June, 132 countries in the world have proposed to achieve the goal of “net-zero carbon emissions” by 2050 (or earlier). However, without “carbon pricing”, net-zero will remain a castle in the air and out of reach (Bashir, Shahbaz, and Jiao, 2020 [26]).

Carbon pricing is an instrument that captures the external costs of GHG emissions—the costs of emissions that the public pays for such as damage to crops, health care costs from heat waves and droughts, and loss of property from flooding and sea level rise—and ties them to their sources through a price, usually in the form of a price on the CO_2 emitted (https://carbonpricingdashboard.worldbank.org/what-carbon-pricing, accessed on 30 June 2022). Global carbon pricing revenue in 2021 increased by almost 60% from 2020 levels, to around 84 billion US dollars, providing an important source of funds to help support a sustainable economic recovery, finance broader fiscal reforms, or invest in communities as part of a low-carbon transition future (World Bank, 2022 [27]). Among the types of carbon pricing methods, including carbon taxes (CTs), emissions trading systems (ETS), offsets, and results-based financing (RBF), most advanced countries mainly adopt two ways to price carbon: CT and ETS. According to Carbon Disclosure Project (CDP) statistics, there are 61 carbon pricing mechanisms in the world including 30 CTs and 31 carbon ETSs.

Figure 1 shows that the world's current 64 carbon pricing mechanisms cover 45 countries and 35 states or provinces, accounting for 21.5% of total global GHG emissions (World Bank, 2022 [27]).

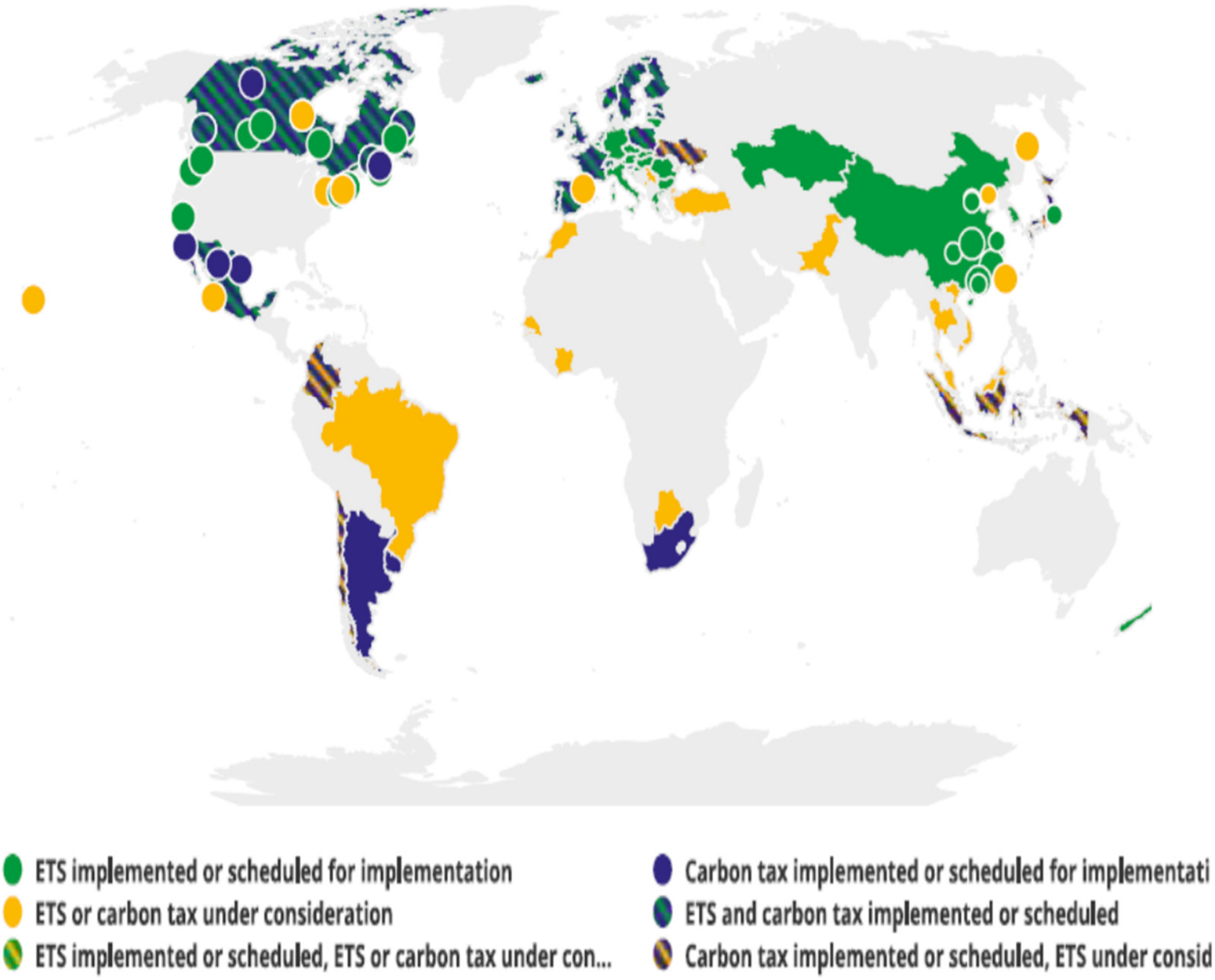

Figure 1. Global carbon pricing mechanisms. Reprinted with permission from Ref. [27]. 2022, World Bank.

In addition, CT refers to the taxation measures offered by the government for large carbon emitters, and the price is determined by the government, for example, CBAM, which will be adopted by the EU in 2023. On the other hand, the ETS is a market mechanism to create more "carbon value" by setting the cap, quota, trading, and flow of carbon emission rights. Furthermore, the price of CT or ETS varies greatly from place to place. For example, Sweden's carbon tax in 2021 was USD 137/tCO_2e, the highest in the world. The amount of Sweden's carbon tax was 45.7 times that of Japan's carbon tax (USD 3/tCO_2e) during the same period. In 2021, Switzerland's carbon tax was USD 101/tCO_2e, France's was USD 52/tCO_2e, and Singapore's was USD 4/tCO_2e. Later, Taiwan would also impose a carbon tax in the preliminary review of the Climate Change Response Act in 2022, which was also approximately USD 3/tCO_2e. The following figure (Figure 2) shows the carbon prices. It can be seen that most carbon prices in 2020 fell in the range of USD 40–80/tCO_2e.

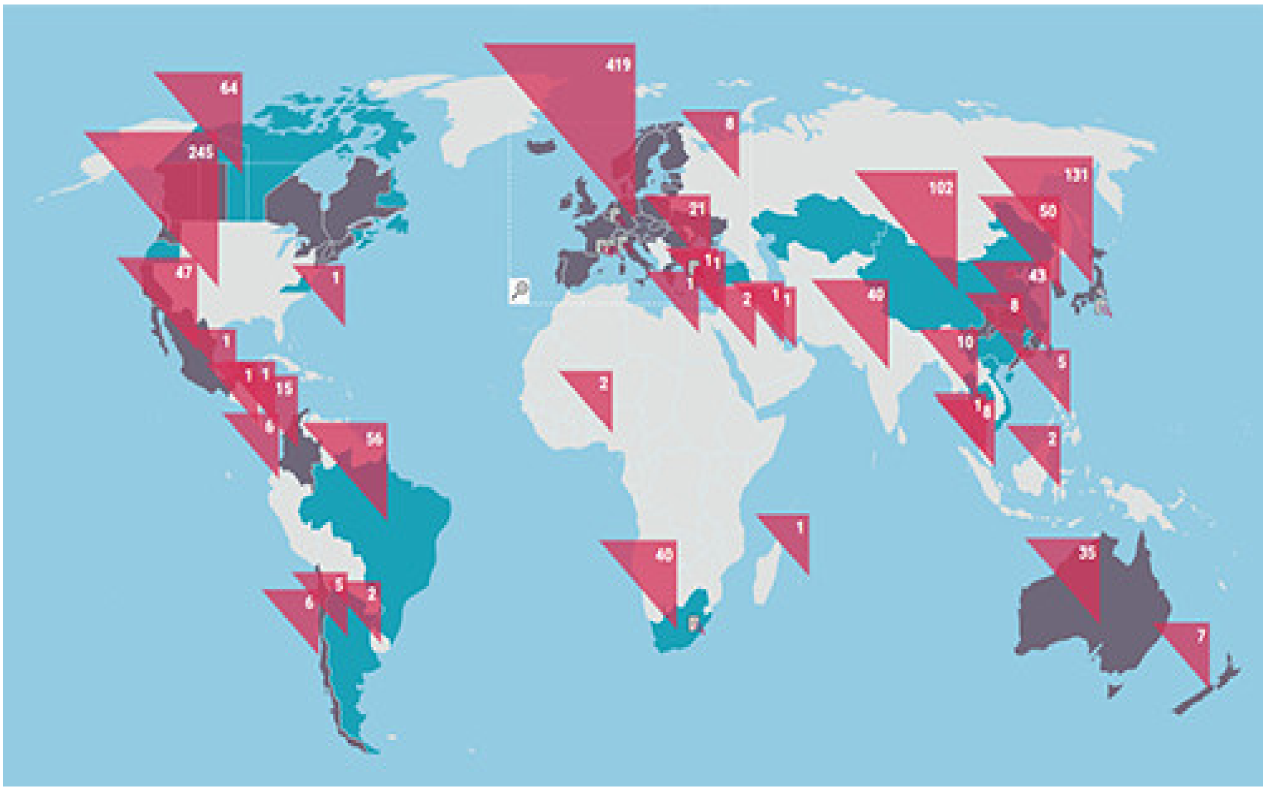

Figure 2. Carbon prices. Reprinted with permission from Ref. [27]. 2022, World Bank.

2.2. GHGs and Economic Growth

GDP growth is one of the primary macroeconomic factors for a country's policymaking, as reaching a desired growth rate is considered a main economic objective. However, ecological and environmental costs cannot be ignored. Therefore, the linkage of economic growth and CO_2 emissions has gained the attention of policymakers, practitioners, and researchers in recent times (Bashir et al., 2020 [26]).

To investigate the relationship between environmental degradation and economic growth, Grossman and Krueger (1991) [28] and Selden and Song (1994) [29] were among the pioneer researchers to imply that economic growth contributes to environmental degradation initially, and after reaching a certain economic threshold, environmental quality improves. However, the findings of Bashir et al., (2020) [26] suggest that CO_2 emissions increase in parallel with economic growth, which contradicts the former studies.

Furthermore, the environmental Kuznets curve (EKC) is a milestone hypothesized relationship among various indicators of environmental degradation and per capita income proposed by Kuznets (1955) [30]. According to Kuznets (1955) [30], the economic development of a country has an inverted U-shaped relationship with its environmental degradation index. That is, in the process of economic development, environmental degradation will increase due to the exploitation of natural resources or the use of industrial equipment. However, when economic development reaches a certain level, the degree of degradation of the environment will decrease due to the fact of R&D of processes or the relocation of manufacturing departments, or even improvement in domestic environmental awareness. In short, the EKC hypothesis states that "the solution to pollution is economic growth". As a result, the model of EKC is given as follows:

$$\ln E_{n,t} = \beta_{n,0} + \beta_{n,1} \cdot \ln Y_{n,t} + \beta_{n,2} \cdot (\ln Y_{n,t})^2 \tag{1}$$

where, $E_{n,t}$ is the indicator of environmental degradation, $Y_{n,t}$ is the nth country's income per capita in t years. In Kuznets' results, the coefficient of linear term $\beta_{n,1} > 0$ and the coefficient of quadratic term $\beta_{n,2} < 0$. As a result, the relationship between the environmental indicator and national income per capita is an inverted U-shaped curve as shown in the following figure.

According to the inverted U-shaped curve in Figure 3, there is a per capita income level Y^*, so that when the per capita income does not reach Y^*, the environmental degradation index will increase with the increase of the per capita income level. When the per capita income exceeds Y^*, the environmental degradation index will decrease with the increase of the per capita income level.

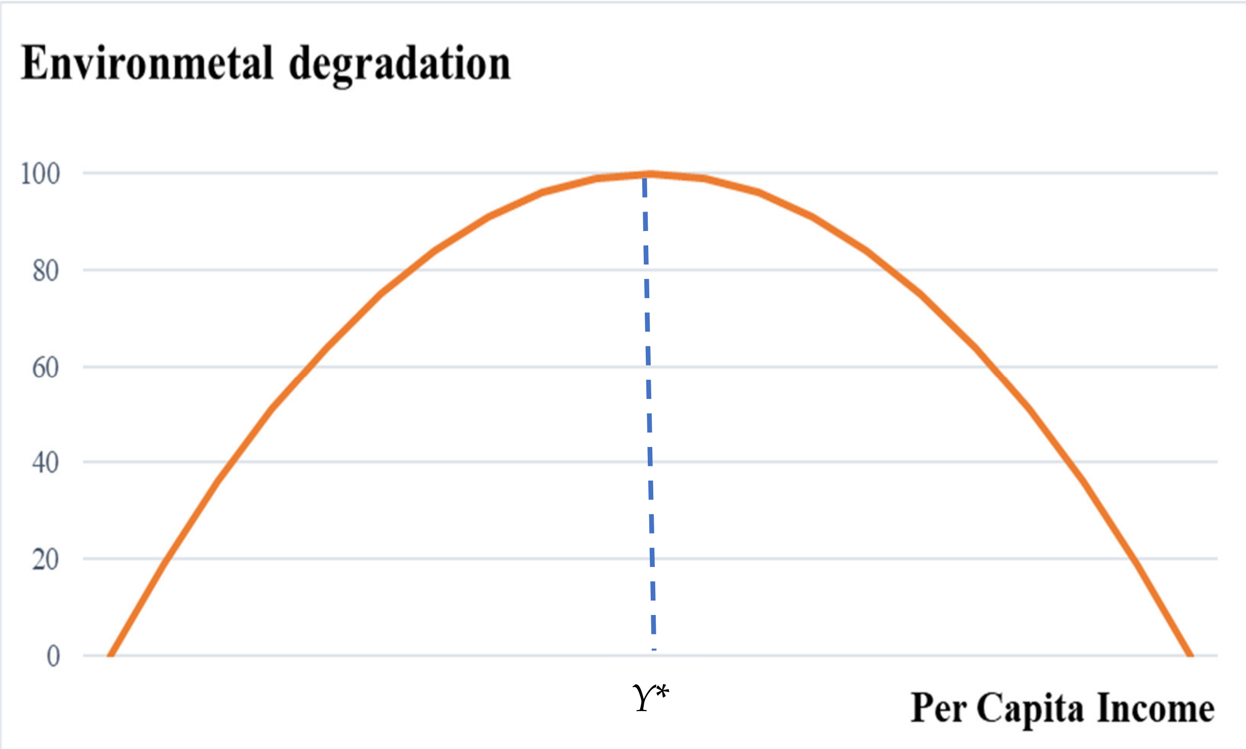

Figure 3. Environmental Kuznets curve. Source: Stern, Common, and Barbier (1996) [31].

In summary, there are many researches in studying the relationship linking the carbon dioxide emissions to economic growth from 2013 on. Some researches investigate the EKC hypothesis by using a single-country data, for instance, Shahbaz et at. (2013) [32] for Romania, Wang et al., (2016) [10] and Sun et al., (2021) [33] for China, Ahmad et al., (2017) [34] for Croatia, Bekhet and Othman (2018) [35] for Malaysia, Uzar and Eyuboglu (2019) [36] for Turkey, and Koc and Bulus (2020) [37] for South Korea.

Moreover, some researches investigate it by using regional data. For example, Salahuddin and Gow (2014) [38] for GCC countries, Lin et al., (2016) [39] for 5 African countries, Lu (2017) [40] for 16 Asian countries, Mensah et al., (2019) [41] for 22 African countries, Balsalobre-Lorente, and Leitão (2020) [35] for 28 EU countries, and Aslan, Altinoz, and Özsolak (2021) [42] for Mediterranean countries. In addition, some other researches test the EKC hypothesis by using some major countries, such as Azam et al., (2016) [43] for USA, China India and Japan; Bashir et al., (2020) [26] and Dogru et al., (2020) [44] for OECD economies; Kongkuah et al., (2021) [45] for Belt and Road countries and OECD economies. Their empirical results are shown in the following table (Table 4).

Table 4. Researches on the CO_2 emission and economic development.

Reference	Study Area/Period	Interpretations
Shahbaz et al., (2013) [32]	Romania/1980–2010	EKC is found both in long- and short-runs in Romania.
Salahuddin and Gow (2014) [38]	GCC countries/1980–2012	No significant relationship is found between economic growth and CO_2 emissions.
Wang et al., (2016) [10]	China/1990–2012	Shocks in CO_2 emissions has a small effect on energy consumption and GDP.
Azam et al., (2016) [43]	USA, China, India, Japan/1971–2013	Positive relationship between CO_2 emissions and GDP in USA, China and Japan
Lin et al., (2016) [39]	Five African countries/1980–2011	There is no evidence of the validity of the hypothesis in Africa
Lu (2017) [40]	16 Asian countries/1990–2012	In the long run, bidirectional Granger causality between energy consumption, GDP and GHG emissions is established.
Ahmad et al., (2017) [34]	Croatia/1992Q1–2011Q1.	Support to EKC for long-run and bidirectional causality for short-run.
Bekhet and Othman (2018) [46]	Malaysia/1971–2015	The inverted N-shaped EKC hypothesis holds in Malaysia and the GDP growth will be a remedy for environmental pollution problems.
Uzar and Eyuboglu (2019) [36]	Turkey/1984–2014	Income inequality has a positive effect on CO_2 emissions and the EKC is valid in Turkey.
Mensah et al., (2019) [41]	22 African countries/1990–2015	A unilateral causality from carbon emissions to economic growth in long-term
Koc and Bulus (2020) [37]	South Korea/1971–2017	An N-shaped relationship has been identified between per capita CO_2 emissions and per capita GDP. This indicates that our empirical findings do not support the EKC hypothesis in South Korea.
Balsalobre-Lorente, and Leitão (2020) [35]	EU-28/1995–2014	CO_2 emissions are positively correlated with economic growth, showing that growth is directly correlated by climate change and GHG.
Bashir et al., (2020) [26]	OECD economies/1995–2015	Economic growth impedes environmental quality by increasing carbon emissions.
Dogru et al., (2020) [44]	OECD	Tourism development has negative and significant effects on CO_2 emission in Canada, Czechia, and Türkiye, while it has positive and significant effects on CO_2 emission in Italy, Luxembourg, and the Slovak Republic.
Kongkuah et al., (2021) [45]	Belt and Road Countries, OECD	Both CO_2 emissions and economic growth positively and significantly affect energy consumption.
Aslan, Altinoz, and Özsolak (2021) [42]	Mediterranean countries/1995–2014	Energy consumption supports economic growth at low and medium growth levels. Short-run causality test results illustrated that there is bidirectional causality between GDP and CO_2 emission.
Sun et al., (2021) [33]	China/1990–2017	In the long-run, the relationship between economic growth and carbon emissions is inverted U-shaped.

Such that, if the EKC hypothesis holds, then the annual amount of CO_2 emission equivalent, Q_t is an inverted U-shaped function of national income per capita. Therefore, we have,

$$\frac{\Delta Q_t}{Q_{t-1}} = (b_1 + 2 \cdot b_2 \cdot \ln Y_{t-1}) \cdot \frac{\Delta Y_t}{Y_{t-1}} \tag{2}$$

It means that the change of the amount of CO_2 emissions is correlated to the rate of economic growth.

3. The Model

3.1. Optimal Allocation with Economic Growth

Suppose the rate of economic growth for economy n is defined by

$$R_{n,t} \equiv \frac{\Delta GDP_{n,t}}{GDP_{n,t-1}} \times 100 = \frac{\Delta \text{GDP per Capita}_{n,t}}{\text{GDP per Capita}_{n,t-1}} \times 100 \tag{3}$$

then the average of the rate of economic growth (sample mean) is

$$\overline{R}_n \equiv \frac{1}{T} \cdot \sum_{t=1}^{T} R_{n,t} = \left(J_T{}' \cdot J_T\right)^{-1} \cdot J_T{}' \cdot R \tag{4}$$

where, R be the vector of the economic growth rate of the N economies and J_T is the ones vector in $\Re^T$. In addition, the volatility of the rate of economic growth (sample variance) is given as follows:

$$\sigma_n = \sqrt{\frac{1}{T-1} \cdot \sum_{t=1}^{T} \left(R_{n,t} - \overline{R}_n\right)^2} \tag{5}$$

Next, the covariance matrix can be found as follows:

$$\Sigma \equiv Var(R) = (\sigma_{k,m}) \in M_{N \times N}(\Re) \tag{6}$$

where, $\sigma_{k,m} \equiv \frac{1}{T-1} \cdot \sum_{t=1}^{T} \left(R_{k,t} - \overline{R}_k\right) \cdot \left(R_{m,t} - \overline{R}_m\right)$ is the sample covariance of R_k and R_m.

Furthermore, assume that w_n is the share of global economic growth of the nth economy, then the rate of the global economic growth is the weighted average of economic growth rate of all economies, that is,

$$R_G = \sum_{n=1}^{N} w_n \cdot \overline{R}_n = W' \cdot R \tag{7}$$

where $W = (w_1, w_2, \cdots, w_N)' \in \Re^N$. In addition, the volatility of the global economic growth is

$$\Sigma_G \equiv Var\left(W' \cdot R\right) = W' \cdot \Sigma \cdot W \tag{8}$$

Such that, an optimal share for each economy is to minimize the volatility of the global economic growth subject to a lower bound of global economic growth. In other words, the mathematical model is given by

$$\min_W \frac{1}{2} \cdot \Sigma_G = \frac{1}{2} \cdot W' \cdot \Sigma \cdot W \tag{9}$$

$$\text{s.t. } W' \cdot R \geq \mu_0 \tag{10}$$

$$J_N{}' \cdot W = 1 \tag{11}$$

where, J_N is the ones vector in $\Re^N$ and μ_0 is a pre-specified growth rate. Using the Lagrange multipliers method (See Markowitz (1952) [23], Merton (1972) [47], Jang and Chen (2008) [48], Chen, Jang, and Peng (2010) [24], and Hsiao (2017) [25]), we have,

$$W^* \equiv Arg\left(\min_W \frac{1}{2}\cdot\Sigma_G\right) = \lambda_1\cdot\Sigma^{-1}\cdot R + \lambda_2\cdot\Sigma^{-1}\cdot J_N \tag{12}$$

where, $\lambda_1 = \frac{1}{D}\cdot(C\cdot\mu_0 - B)$ and $\lambda_2 = \frac{1}{D}\cdot(A - B\cdot\mu_0)$. In addition, $A = R'\cdot\Sigma^{-1}\cdot R$, $B = J_N{}'\cdot\Sigma^{-1}\cdot R$, $C = J_N{}'\cdot\Sigma^{-1}\cdot J_N$, and $D = A\cdot C - B^2$.

As shown in Hsiao (2017) [25], the expected global economic growth rate is

$$R_G^* = W^{*\prime}\cdot R = \left(\lambda_1\cdot\Sigma^{-1}\cdot R + \lambda_2\cdot\Sigma^{-1}\cdot J_N\right)'\cdot R = \mu_0 \tag{13}$$

and the volatility of change of the amount of CO_2 emission is

$$Var(R_G^*) = W^{*\prime}\cdot\Sigma\cdot W^* = \frac{C}{D}\cdot\left(\mu_0 - \frac{B}{C}\right)^2 + \frac{1}{C} \equiv (\sigma_G^*)^2 \tag{14}$$

Hence, the relationship between the volatility of the economic growth rate (σ_G^*) and global economic growth (μ_0) is a hyperbola shown in the following figure (Figure 4).

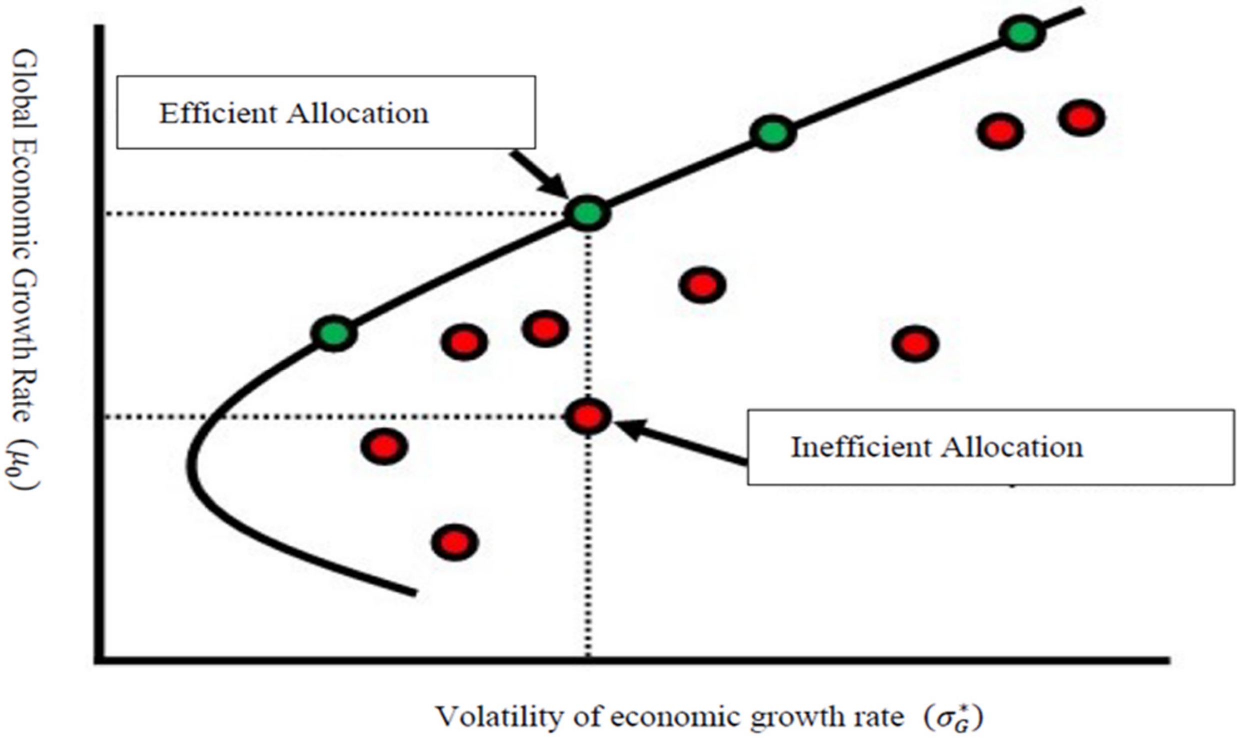

Figure 4. Efficient frontier under uncertainty. Source: Hsiao (2017) [25].

3.2. Optimal Allocation with CO_2 Emissions

Hereinafter, assuming that the EKC hypothesis does hold, that is, the Equation (2) can be rewritten as follows:

$$EM_{n,t} = \left(b_{n,1} + 2\cdot b_{n,2}\cdot \ln \text{GDP per Capita}_{n,t-1}\right)\cdot R_{n,t} \tag{15}$$

where, $EM_{n,t} \equiv \frac{\Delta Q_{n,t}}{Q_{n,t-1}} \times 100$, is the annual rate of change of CO_2 emissions of the nth country in the tth year.

Next, by letting

$$K_n \equiv \left(b_{n,1} + 2b_{n,2}\cdot \ln \text{GDP per Capita}_{n,0}, \cdots, b_{n,1} + 2b_{n,2}\cdot \ln \text{GDP per Capita}_{n,T-1}\right)'$$

then, we have, $EM_{n,t} = K_n{}'\cdot R_{n,t}$ and

$$\overline{EM}_n \equiv \frac{1}{T}\cdot\sum_{t=1}^{T} EM_{n,t} = \left(J_T{}'\cdot J_T\right)^{-1}\cdot J_T{}'\cdot K_n{}'\cdot R_{n,t} \tag{16}$$

Moreover, let $K \equiv \text{Diag}(K_1, K_2, \cdots, K_N)$, an $N \times N$ diagonal matrix, then the

$$EM \equiv \left(\overline{E}_1, \overline{E}_2, \cdots, \overline{E}_N\right)' = \left(J_T{}'\cdot J_T\right)^{-1}\cdot J_T{}'\cdot K'\cdot R. \tag{17}$$

In addition, the covariance matrix

$$\begin{aligned} Var(EM) &= Var\left(\left(J_T{}'\cdot J_T\right)^{-1}\cdot J_T{}'\cdot K'\cdot R\right) \\ &= \left(J_T{}'\cdot J_T\right)^{-1}\cdot J_T{}'\cdot K'\cdot\Sigma\cdot K\cdot J_T\cdot\left(J_T{}'\cdot J_T\right)^{-1} \end{aligned} \tag{18}$$

As a result, the optimal allocation with CO_2 emissions is given as follows:

$$W_E^* = W^*\cdot K^{-1} \tag{19}$$

where, W^* is given by the Equation (12).

Hence, the global growth rate of CO_2 emission with the optimal allocation is given as follows:

$$EM_G^* = W_E^{*\prime}\cdot EM = \left(W^*\cdot K^{-1}\right)'\cdot(K\cdot R) = W^{*\prime}\cdot R = \mu_0. \tag{20}$$

And, the volatility of the global growth rate of CO_2 emission can be found by

$$Var(EM_G^*) = Var\left(W_E^{*\prime}\cdot EM\right) = \frac{C}{D}\cdot\left(\mu_0 - \frac{B}{C}\right)^2 + \frac{1}{C} = \left(\sigma_G^*\right)^2 \tag{21}$$

Furthermore, the optimal quota of CO_2 emission for the country n in the next year is given as follows:

$$Q_{n,t+1}^* = Q_{n,t}\cdot\left(1 + \mu_0\cdot e_n{}'\cdot W_E^*\right) \tag{22}$$

where, e_n is the nth column vector of an $N \times N$ identity matrix.

4. Empirical Evidence

4.1. Data

This study collects the global CO_2 emission from the database of Global Carbon Project (https://www.globalcarbonproject.org/carbonbudget/21/data.htm, accessed on 10 May 2022), s and GDP per capita is from World Bank (https://data.worldbank.org/indicator/NY.GDP.PCAP.CD, accessed on 10 May 2022), respectively. Moreover, Taiwan's macroeconomic data is downloaded from Republic of China (Taiwan) National Statistics (https://eng.stat.gov.tw/point.asp?index=1, accessed on 12 May 2022). Then the descriptive statistics for the variables are shown in the following table (Table 5).

Table 5. Descriptive statistics for variables.

Variable	Obs.	Mean	Median	St. Dev.	Min	Max
CO_2eton (Mtons)	1582	423.25	100.93	1124.67	1.87	9528.20
GDP per capita (1000$)	1582	24.41	18.20	22.00	0.37	129.36

Source: Global Carbon Project and World Bank.

4.2. Test for EKC Hypothesis

On the other hand, the database of Our Data in World collects more comprehensive country-level data including CO_2 emission and macroeconomic data, for instance, population, population density, etc. Excluding the countries with incomplete data, this study collects a total of 3402 country-year data from Our World in Data database.

To test the EKC hypothesis for each country, the model:

$$\ln CO2eton_{i,t} = b_{i,0} + b_{i,1} \cdot \ln \text{GDP per Capita}_{i,t} + b_{i,2} \cdot \left(\ln \text{GDP per Capita}_{i,t}\right)^2 + \varepsilon_{i,t} \quad (23)$$

where, $CO2eton_{i,t}$, the dependent variable, is the CO_2 emission equivalent in million tons of weight and GDP per $\text{Capita}_{i,t}$, the independent variable, is the annual GDP per capita in thousands of US dollars of country i in t year. $\varepsilon_{i,t}$ is a disturbance term with mean zero and constant variance $\sigma^2_{\varepsilon,i}$. Such that, the null hypothesis and alternative hypothesis are

$$H_0 : \ b_{n,2} < 0 \text{ versus to } H_1 : \ b_{n,2} \geq 0 \quad (24)$$

The test results are shown in the following table (Table 6).

Table 6. Test results for the EKC hypothesis for each country.

Continent	Support to EKC Hypothesis	Reject the EKC Hypothesis
Europe	Albania (−1.4487 ***) Austria (−0.4760 ***) Belarus (−1.8549 ***) Belgium (−0.6850 ***) Bulgaria (−1.1135 ***) Bosnia and Herzegovina (−0.3911 ***) Croatia (−0.4024 ***) Cyprus (−0.4714 ***) Denmark (−0.8906 ***) Estonia (−2.5935 **) Finland (−6750 ***) France (−0.8296 ***) Germany (−0.8524 ***) Greece (−0.7889 ***) Hungary (−1.0287 ***) Ireland (−0.4113 ***) Italy (−0.9941 ***) Latvia (−2.6530 ***) Lithuania (−1.9727 ***) Luxembourg (−0.2095 **) Malta (−0.1906 ***) Montenegro (−0.3924 ***) Netherlands (−0.7989 ***) North Macedonia (−0.8944 ***) Norway (−0.6379 ***) Poland (−0.7666 ***) Portugal (−0.3138 ***) Romania (−0.5063 ***) Russia (−0.9728 ***) Serbia (−0.5766 ***) Slovenia (−0.2483 ***) Spain (−0.9438 ***) Sweden (−0.8761 ***) Switzerland (−0.4903 ***) Turkey (−0.2812 ***) United Kingdom (−0.9471 ***)	Cape Verde (0.1149) Czech (−0.1615) Iceland (0.1237) Moldova (1.8505 ***) Slovakia (−0.1639 **) Ukraine (0.1406)

Table 6. *Cont.*

Continent	Support to EKC Hypothesis	Reject the EKC Hypothesis
Africa		
	Algeria (−1.5759 ***)	Angola (2.1134 ***)
	Botswana (−0.7280 ***)	Burkina Faso (−7.0044)
	Burundi (−10.1060 **)	Chad (1.9051 ***)
	Cameroon (−5.7137 ***)	Comoros (1.3505 **)
	Cent. African Rep. (−2.9990 ***)	Congo (0.0227)
	Dem. Rep. of Congo (−1.8716 ***)	Cote d'Ivoire (−3.9265)
	Djibouti (−2.1016 ***)	Equatorial Guinea (0.2423 ***)
	Egypt (−0.4208 *)	Ethiopia (0.9081)
	Eswatini (−1.0469 ***)	Gambia (0.7366)
	Gabon (−3.1903 ***)	Ghana (4.6146 ***)
	Guinea (−1.5205 ***)	Guinea-Bissau (0.8004)
	Kenya (−0.9679 ***)	Liberia (0.8134 ***)
	Lesotho (−6.6436 ***)	Malawi (0.7052 **)
	Libya (−0.3754 ***)	Mali (5.7105 ***)
	Madagascar (−6.3631 **)	Mauritius (0.1226)
	Mauritania (−3.8924 ***)	Mozambique (2.9358 ***)
	Morocco (−1.3541 ***)	Namibia (−0.4725)
	Niger (−6.2876 ***)	Rwanda (10.9701 ***)
	Nigeria (−2.5193 ***)	Senegal (31.5548 *)
	Seychelles (−1.3043 ***)	Sierra Leone (1.8441 **)
	South Africa (1.7201 ***)	São Tomé and Príncipe (−0.2383)
	Tanzania (−1.5524 ***)	Uganda (5.8374 ***)
	Togo (−14.5573 ***)	Zambia (0.495)
	Tunisia (−0.4595 ***)	
	Zimbabwe (−1.7046 *)	
North America		
	Canada (−1.1960 ***)	Barbados (0.9096 ***)
	Costa Rica (−0.4993 ***)	Haiti (−13.2546)
	Cuba (−7.0740 ***)	Jamaica (−0.1269)
	Dominica (−0.3737 ***)	Trinidad and Tobago (0.2723)
	Dominican Republic (−1.2384 ***)	
	El Salvador (−1.8960 ***)	
	Guatemala (−4.2802 ***)	
	Honduras (−1.3672 ***)	
	Mexico (−0.9063 ***)	
	Nicaragua (−6.8917 ***)	
	Panama (−0.6966 ***)	
	Saint Lucia (−0.6775 ***)	
	United States (−1.5400 **)	
South America		
	Argentina (−1.6496 ***)	
	Bolivia (−4.1208 ***)	
	Brazil (−0.1704 ***)	
	Chile (−0.8802 ***)	
	Colombia (−2.2712 ***)	
	Ecuador (−0.5463 **)	
	Paraguay (−1.0384 ***)	
	Peru (−0.8833 ***)	
	Venezuela (−1.5521 ***)	

Table 6. *Cont.*

Continent	Support to EKC Hypothesis	Reject the EKC Hypothesis
Asia		
	Azerbaijan (−0.4356 ***) Bahrain (−0.8480 ***) Bangladesh (−1.7524 ***) China (−0.8283 ***) Hong Kong ((0.3074 ***) India (−2.4608 ***) Indonesia (−2.2076 ***) Iran (−0.6990 ***) Japan (−0.7631 ***) Jordan (−1.7637 ***) Malaysia (−0.6270 ***) Mongolia (−0.6003 ***) Myanmar (−0.6113 ***) Nepal (−4.4781 ***) North Korea (−9.0973 ***) Oman (−0.7282 ***) Pakistan (−0.3542 ***) Palestine (−9.4365 *) Philippines (−2.1951 ***) Saudi Arabia (−1.1383 ***) Singapore (−0.4399 ***) South Korea −0.7387 ***) Taiwan (−0.5805 ***) Thailand (−0.7234 ***) Vietnam (−0.6115 *)	Afghanistan (3.1452 ***) Armenia (0.5998) Benin (5.5487 ***) Cambodia (−0.5440) Georgia (0.8713 **) Iraq (0.8325 **) Israel (0.0405) Kazakhstan (−0.2475) Kuwait (0.7893 **) Kyrgyzstan (1.6259 ***) Laos (0.3338 *) Lebanon (1.0449 ***) Qatar (1.6803 ***) Sri Lanka (0.0145) Syria (3.0551 **) Tajikistan (0.8836 ***) Turkmenistan (0.2105 ***) Yemen (−1.5609) Uzbekistan (0.4061) United Arab Emirates (8.9096 ***)
Oceania		
	Australia (−1.4977 ***) New Zealand (−0.5440 ***)	

Note: The estimates of $b_{n,2}$ in equation (is reported in the parentheses. In addition, *, **, and *** stands for the level of significance is 10%, 5%, and 1%, respective.

As shown in Table 6, it can be seen that most of countries in Europe, North America, South America, and Oceania, support to the EKC hypothesis, however, there are almost half of countries in Asia and Africa which are not supported to the EKC hypothesis. On the other hand, some countries either in Europe or in Asia which support to the EKC hypothesis, however, the estimates of quadratic term are insignificant.

4.3. *Computation of Optimal Allocation of CO_2 Emission Quota*

The first step is to calculate the optimal allocation with economic growth, W^* by using the Equation (12). Second, in accordance to the Equation (24), estimate the regression coefficients of b's for each country. Third, the diagonal matrix, K, was formed, and then the optimal allocation of a CO_2 emissions quota was determined by W_E^*, given in Equation (19). Such that, the optimal CO_2 emission quota considering the economic growth can be found by Equation (22).

4.3.1. Continental Economics and CO_2 Emissions

For each continent, countries' CO_2 emission and GDP per capita have been collected from the Our World in Data website for the last 20 years. The efficiency frontier curve of the optimal allocation of CO_2 emissions in countries with a minimum risk of economic growth uncertainty are shown in Figures 5–9.

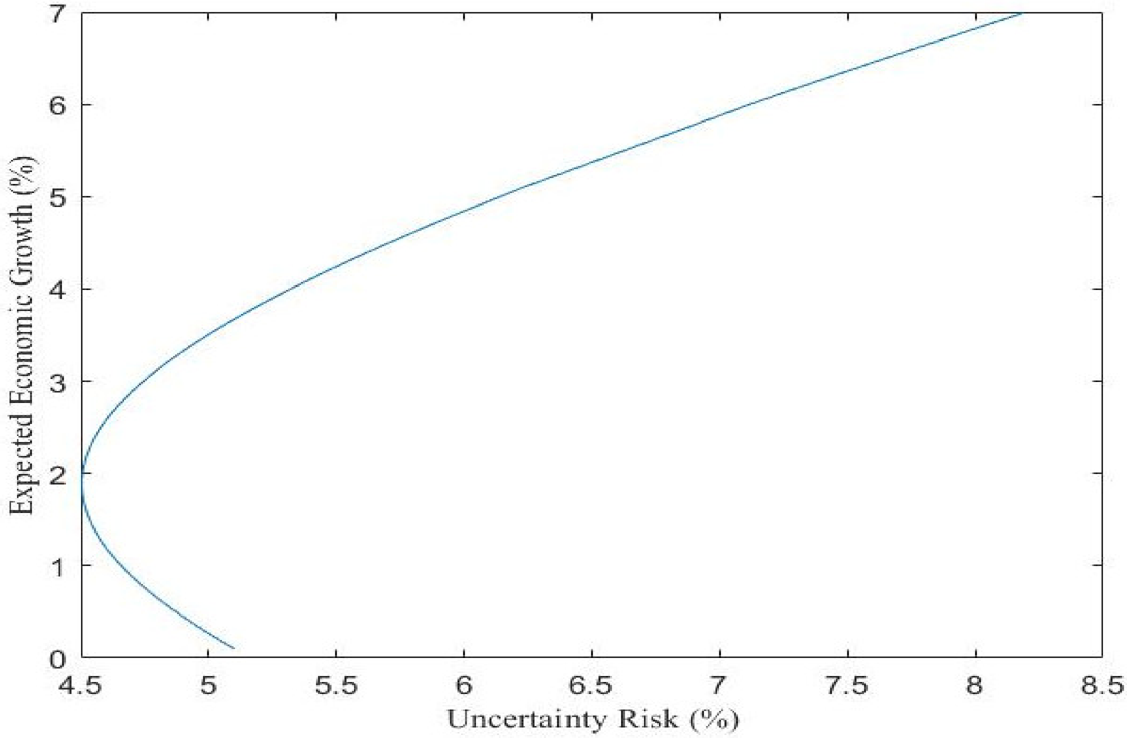

Figure 5. The efficient frontier of CO_2 emission quota for European countries.

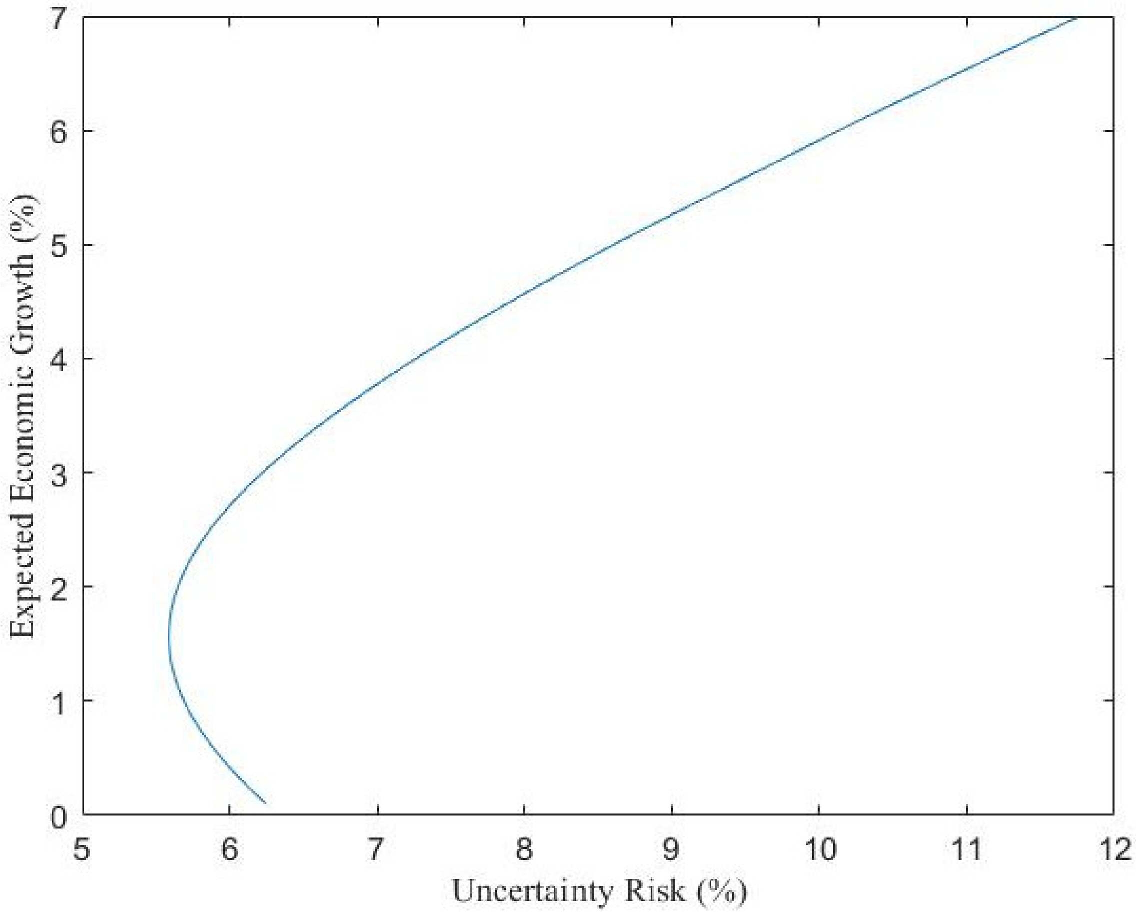

Figure 6. The efficient frontier of CO_2 emission quota for North American countries.

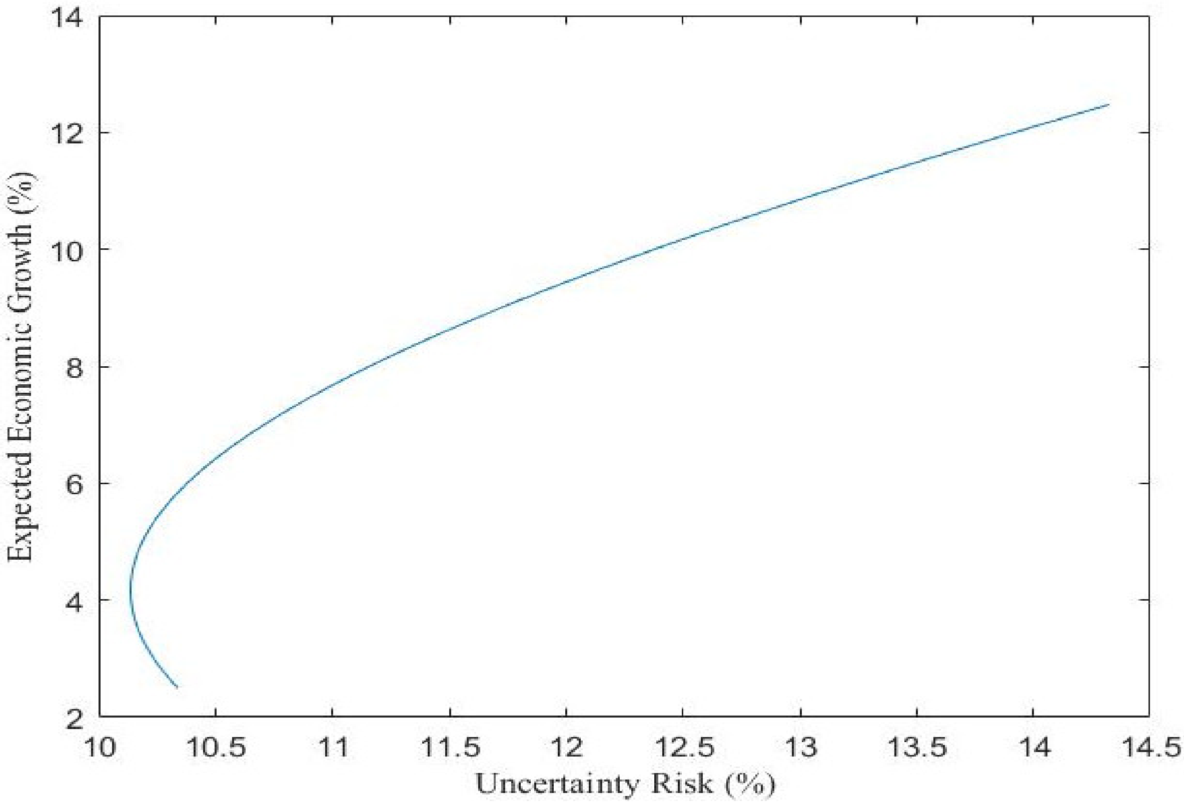

Figure 7. The efficient frontier of CO_2 emission quota for South American and Oceania countries.

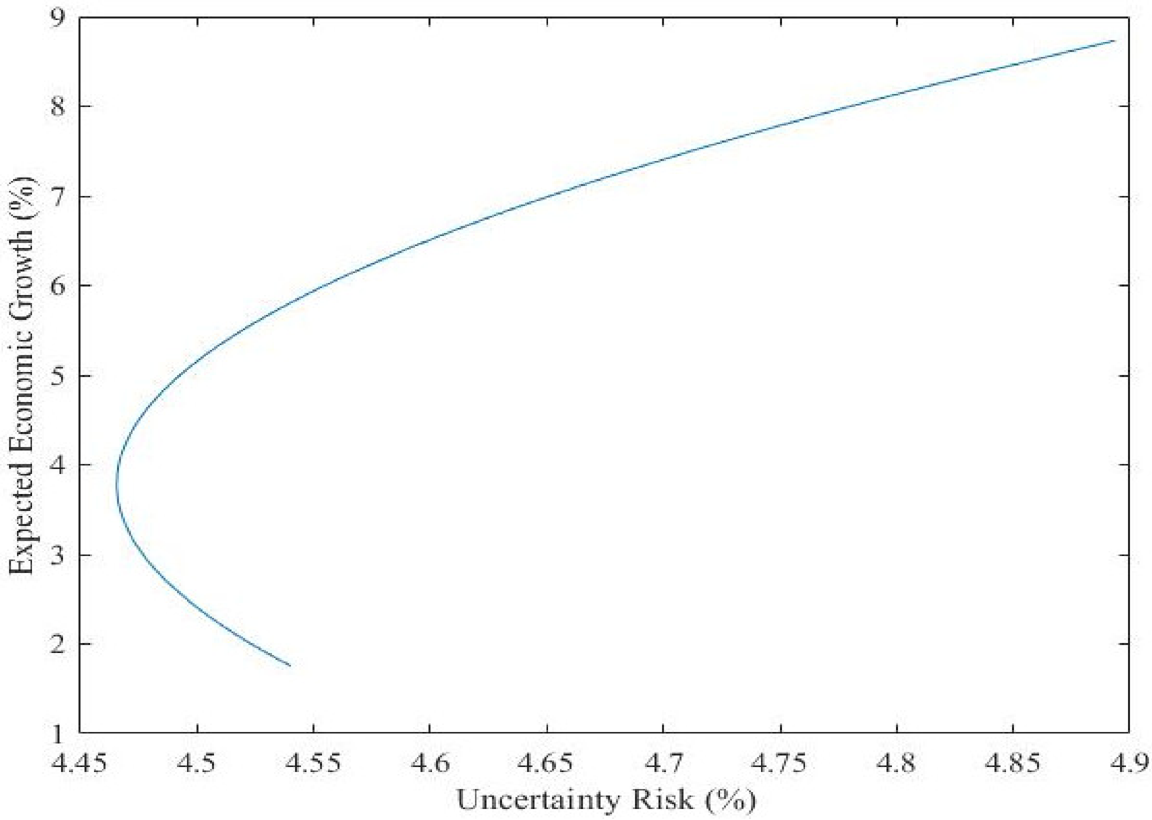

Figure 8. The efficient frontier of CO_2 emission quota for Asian countries.

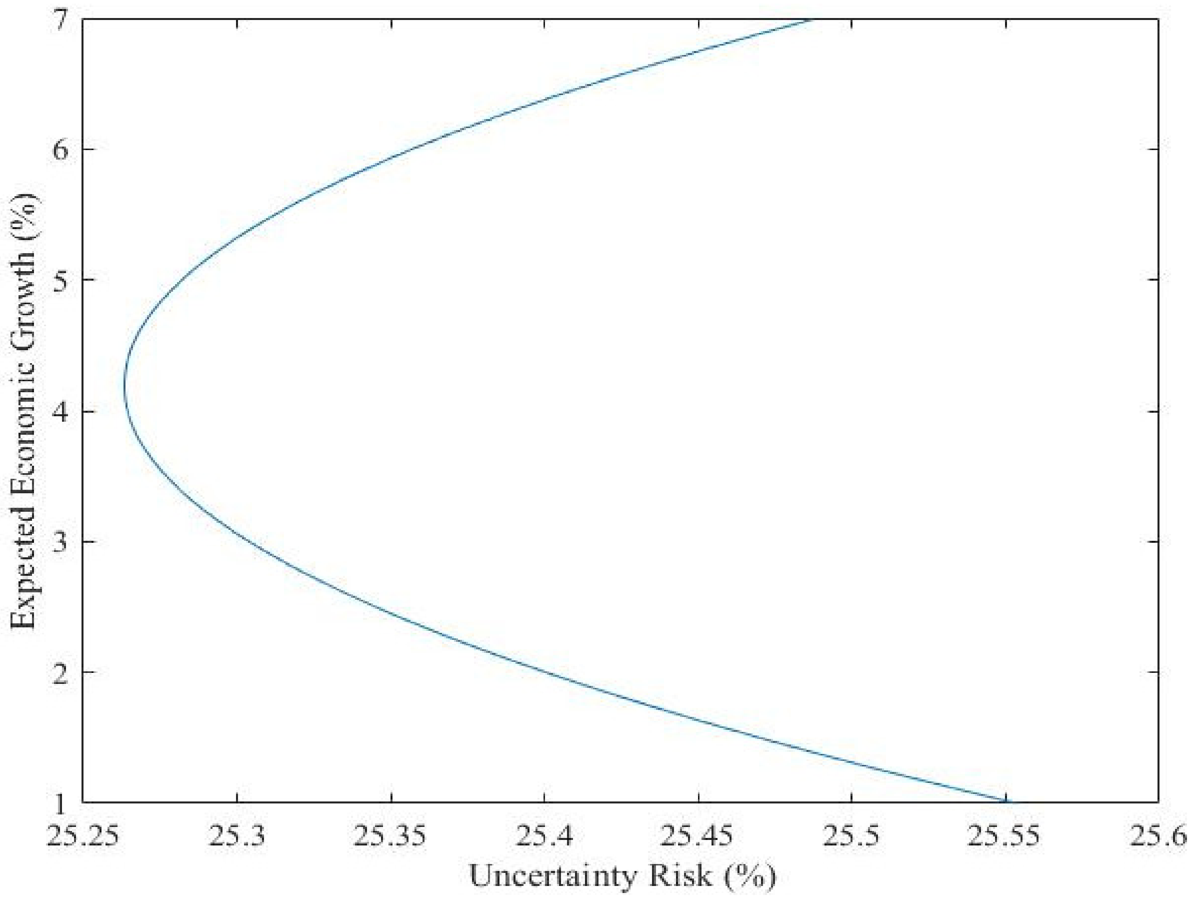

Figure 9. The efficient frontier of CO_2 emission quota for African countries.

As shown in the Figures 5–9, the higher the expected economic growth rate, the higher the uncertainty risk. The Asian regional economic growth is the less volatile than other continents, however the African regional economic growth has the highest volatility. It may be contributed to the larger difference of economic condition between the African countries than that in the other continents.

4.3.2. Global Economics and CO_2 Emissions

As for the global economic, data on a total of 162 countries were collected from the Our World in Data website for the last 20 years. The efficiency front curve of the optimal allocation of CO_2 emissions in countries with the minimum risk of global economic growth uncertainty (see Figure 10). As shown in the Figure 10, the higher the expected economic growth rate, the higher the uncertainty risk. For instance, if the global expected economic growth rate of 6%, then the uncertainty risk was approximately 12.52%; however, if the global expected economic growth rate was of 12%, then the uncertainty risk was approximately 20.63%. Therefore, under this situation, the amount of CO_2 emissions of global countries are shown in the following table.

Since this study uses the emissions of the previous year as the benchmark when estimating GHG emissions in the following year, according to the proportion of global economic growth that countries should bear, since 2020 onwards, due to the closure of borders and the reduction of economic activities due to the COVID-19 lockdown, the economies of various countries have come to a standstill (Le Quéré et al., 2020 [3]; Hsiao, 2022 [4]); thus, their GHG emissions have also greatly reduced. Therefore, the GHG emission amounts of each country in the following year will be lower than those before 2020.

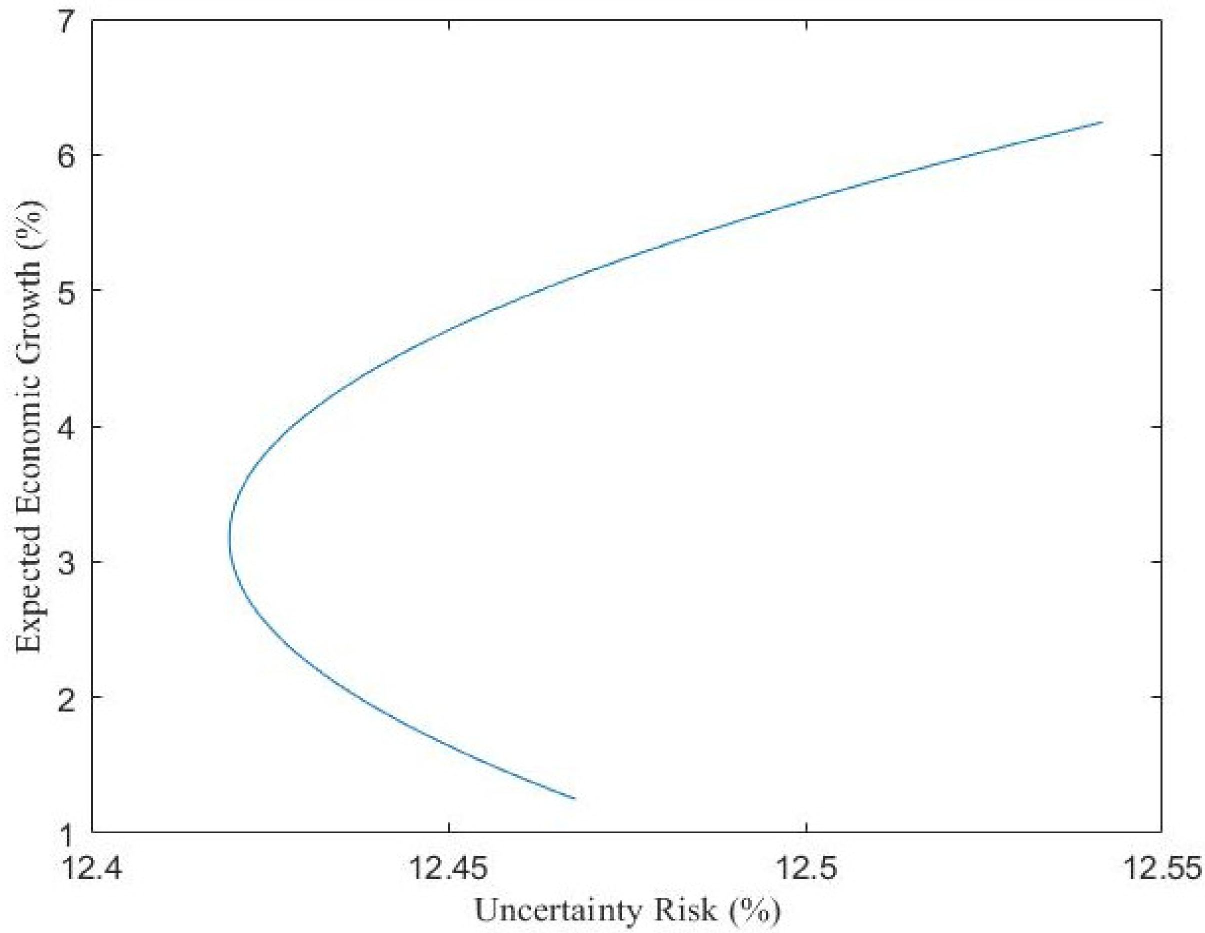

Figure 10. Efficient frontier of CO_2 emission quota for all countries.

The results in Table 7 show that the optimal quota of CO_2 emissions may decrease compared to the amount in the previous year, considering the uncertainty risk of global economic growth (volatility) for some countries, especially for larger economies in Europe or North America and smaller economies in Africa. However, there are some countries that may increase their amount of CO_2 emissions when considering global economic growth such as the larger economies in Asia or Africa.

Table 7. Optimal CO_2 emissions quota of all countries in 2021.

ISO Code of Country	CO_2 Emission Amount in 2020 (MtonCO_2e)	Optimal CO_2 Emission Quota in 2021 (MtonCO_2e)	
European region			
ALB	4.535	4.6028	4.6040
AUT	60.635	60.3689	60.3706
BEL	83.749	85.0776	85.2190
BGR	37.444	37.3882	37.3870
BIH	21.418	21.7649	21.7655
BLR	57.445	57.7561	57.7597
CHE	32.298	31.9855	31.9809

Table 7. *Cont.*

ISO Code of Country	CO_2 Emission Amount in 2020 (MtonCO_2e)	Optimal CO_2 Emission Quota in 2021 (MtonCO_2e)	
CYP	6.496	6.5266	6.5277
CZE	87.975	87.1473	87.1308
ESP	208.915	207.2991	207.2809
EST	10.452	10.1161	10.1168
DEU	644.310	636.1301	635.5406
DNK	26.195	26.4995	26.5038
FIN	39.288	38.6103	38.5824
FRA	276.634	271.7850	271.7766
GBR	329.579	321.5172	321.4169
GRC	52.235	51.2032	51.2315
HRV	16.982	16.9874	16.9874
HUN	48.275	47.7420	47.7310
IRL	33.349	32.9119	32.8919
ISL	2.936	2.9774	2.9775
ITA	303.815	302.8852	302.8285
LTU	13.799	13.8752	13.8767
LUX	8.175	8.3003	8.2983
LVA	6.773	6.7923	6.7926
MDA	5.147	5.2084	5.2104
MKD	7.147	6.9914	6.9862
MLT	1.595	1.5459	1.5427
MNE	2.310	2.3417	2.3423
NLD	138.100	137.3132	137.3003
NOR	41.283	41.3566	41.3579
POL	299.593	299.7536	299.7566
PRT	40.388	39.9484	39.9286
ROU	71.475	70.9922	71.0044
RUS	1577.136	1583.6777	1583.8182
SRB	43.135	43.1096	43.1091
SVK	30.730	30.4346	30.4296
SVN	12.563	12.5463	12.5464
SWE	38.635	38.0208	37.9904
TUR	392.794	402.0143	403.1277
American region			
BRB	1.087	1.0663	1.0641
CAN	535.823	536.1096	536.1150
CRI	7.907	8.0591	8.0617
CUB	20.152	20.2224	20.2237

Table 7. *Cont.*

ISO Code of Country	CO_2 Emission Amount in 2020 (MtonCO_2e)	Optimal CO_2 Emission Quota in 2021 (MtonCO_2e)	
DMA	0.139	0.1456	0.1459
DOM	27.769	27.2944	27.2812
GTM	18.938	18.3199	18.3242
HND	9.660	9.7481	9.7499
HTI	2.920	1.8081	2.0370
JAM	7.429	7.1724	7.1643
LCA	0.440	0.4351	0.4350
MEX	356.968	245.7812	278.0396
NIC	5.074	5.2303	5.2322
PAN	10.780	11.3302	11.3460
SLV	6.124	6.1866	6.1878
TTO	35.509	36.5395	36.5436
USA	4712.771	4672.3139	4605.9988
ARG	156.978	161.3801	161.6716
BOL	20.700	21.2198	21.2328
BRA	467.384	446.0132	446.3326
CHL	81.171	84.8071	85.0436
COL	89.105	90.4693	90.4865
ECU	30.932	32.1550	32.3221
PER	44.706	46.9450	47.0297
PRY	7.570	7.7630	7.7586
VEN	84.609	84.7788	85.0845
Oceania region			
AUS	391.892	524.8084	514.2120
NZL	33.475	33.4566	33.4560
Asian region			
AFG	12.160	13.5445	13.4615
ARE	150.268	167.9964	165.1578
ARM	5.890	6.7770	5.8318
AZE	37.720	34.8413	36.4820
BGD	92.842	93.8462	93.9066
BHR	34.960	35.4795	35.4792
CHN	10,667.890	11,197.6191	11,186.7793
HKG	31.239	33.2620	33.1307
GEO	9.968	10.0162	10.0168
IDN	589.500	598.9654	590.7691
IND	2441.792	2517.2714	2517.6586
IRN	745.035	776.3739	776.3946

Table 7. *Cont.*

ISO Code of Country	CO_2 Emission Amount in 2020 ($MtonCO_2e$)	Optimal CO_2 Emission Quota in 2021 ($MtonCO_2e$)	
IRQ	210.829	219.2870	219.0662
ISR	56.351	54.8225	54.7648
JOR	25.487	25.5863	25.5871
JPN	1030.775	1235.4181	1119.6552
KAZ	291.336	301.7645	301.7991
KGZ	11.508	10.7879	10.9950
KHM	15.326	15.5454	15.5486
KOR	597.605	621.4273	621.6629
KWT	88.935	102.5310	100.3587
LAO	33.847	36.3780	36.2851
LBN	25.969	26.5192	26.5393
LKA	21.106	31.5918	30.3117
MMR	36.326	39.0713	39.1506
MNG	88.442	90.3368	90.3564
MYS	272.607	310.8236	305.0755
NPL	16.958	18.1257	18.2163
OMN	62.163	68.3546	68.2415
PAK	234.755	330.8475	325.9357
PHL	136.018	205.5030	188.4140
PRK	29.311	31.5005	31.3831
PSE	2.899	3.0471	3.0436
QAT	106.655	109.6790	107.7144
SAU	625.508	591.3475	609.5351
SGP	45.504	42.4464	42.3837
SYR	30.532	29.5040	29.5009
THA	257.766	282.5505	279.5172
TJK	9.448	9.5537	9.5556
TKM	75.338	81.2938	81.1456
TWN	273.175	377.0800	364.9841
UZB	112.784	116.2030	116.2643
VNM	254.303	271.4037	269.7127
YEM	9.768	9.6506	9.6480
African region			
AGO	22.198	23.5458	23.5008
BDI	0.602	0.5950	0.5956
BEN	6.703	6.8931	6.8956
BFA	3.970	2.5417	2.8197
BWA	6.519	7.6059	7.1416

Table 7. *Cont.*

ISO Code of Country	CO_2 Emission Amount in 2020 ($MtonCO_2e$)	Optimal CO_2 Emission Quota in 2021 ($MtonCO_2e$)	
CAF	0.188	0.4832	0.3830
CIV	10.071	8.8744	8.8847
CMR	6.889	7.0045	6.9824
COD	2.477	2.4377	2.4357
COG	3.117	2.8289	2.7698
COM	0.258	0.1409	0.1268
CPV	0.550	0.5931	0.5928
DJI	0.351	0.6326	0.5532
DZA	154.995	159.9009	160.0371
EGY	213.457	198.6484	189.8422
ETH	14.665	14.2352	14.2277
GAB	4.298	4.5479	4.5413
GHA	16.001	17.1114	17.0921
GIN	3.394	3.0935	3.0804
GMB	0.500	0.5124	0.5128
GNB	0.287	0.3220	0.3230
GNQ	10.265	7.0718	7.2478
KEN	16.146	14.1335	13.2895
LBR	1.009	1.3220	1.1334
LBY	50.721	56.3641	55.9407
LSO	2.183	2.0025	2.0365
MAR	64.536	62.3316	62.4447
MDG	3.680	3.8624	3.7593
MLI	3.390	3.5199	3.5217
MOZ	6.571	3.1883	3.7665
MRT	3.377	3.5663	3.6931
MUS	3.979	4.5680	4.7017
MWI	1.395	1.5412	1.3862
NAM	3.877	4.8387	4.7688
NER	1.690	2.6664	2.4049
NGA	125.463	131.0488	131.0921
RWA	1.033	0.4226	0.5468
SEN	10.451	10.8063	10.8091
SLE	0.877	1.0778	1.0768
STP	0.113	0.1346	0.1085
SWZ	0.956	1.0630	1.0634
SYC	0.491	0.4718	0.4700
TCD	0.912	0.9072	0.9071
TGO	2.192	2.2348	2.2345

Table 7. *Cont.*

ISO Code of Country	CO_2 Emission Amount in 2020 (MtonCO_2e)	Optimal CO_2 Emission Quota in 2021 (MtonCO_2e)	
TUN	28.127	24.6207	24.2436
TZA	10.939	13.0518	11.1844
UGA	4.892	4.7703	4.7672
ZAF	451.957	465.5652	465.6443
ZMB	6.753	8.1071	7.8863
ZWE	10.531	10.9705	10.9860
Expected growth rate of CO_2 emission (%)		6.0	4.0
Volatility of expected growth rate of CO_2 emission (%)		12.5208	8.9529

Table 7 also reveals that not all countries should take carbon reduction actions immediately. Under the consideration of global economic growth, countries have their own economic growth needs and carry out appropriate economic activities. When the EKC hypothesis holds, economic activities may degrade the environmental index; however, they may also improve the quality of the environment such as the improvement in production technology, the development of environmental protection equipment, the increase in green financial investment, and technological innovation of carbon sequestration or carbon capture. As a result, some over-emitting countries should formulate policies to reduce emissions and achieve their commitments to COP26. According to US EPA research, there are many ways that governments can promote carbon reduction programs such as improving energy efficiency, increasing energy conservation subsidies, replacing fossil energy with renewable energy, promoting carbon sequestration or carbon capture technology research and development, and changing land use and management. Furthermore, under-emitting countries may take appropriate economic activities to improve their economic growth level, which will help world economic growth, although it will increase GHG emissions. In addition, part of their carbon rights can be traded with other countries that emit excess emissions through the international carbon rights trading platforms.

5. Concluding Remarks

In this study, the linkage between CO_2 emission equivalents and GDP per capita is an inverted U-shaped function for most countries that support the EKC hypothesis. Under the EKC hypothesis, this study proposed a framework to determine an optimal allocation of CO_2 emissions for each country considering global economic growth and uncertainty risk. Based on this allocation, government policymakers may implement policies to reduce extra emissions such as energy efficiency and energy conservation enhancement, fuel switching, carbon capture and sequestration, and land management practices.

Furthermore, the framework proposed in this study can be applied to industry-level data and even company-level data in addition to national-level data. It is said that under the premise of considering the national economic growth, the optimum GHG emissions/sinks of each industry or company should be calculated to minimize the uncertainty risk, first, and then policies should be formulated to improve GHG emissions/sinks of each industry or company.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The author declares no conflict of interest.

References

1. Guggenheim, P.D.; Al Gore, A.A. *An Inconvenient Truth*; Paramount Pictures Corporation: Los Angeles, CA, USA, 2006.
2. TVBS Sisy's World News Group. *±2 °C—The Truth That Taiwan Must Face*; Taiwan, 2010. Available online: https://movie.douban.com/subject/4312211/ (accessed on 16 May 2022).
3. Le Quéré, C.; Jackson, R.B.; Jones, M.W.; Smith, A.J.; Abernethy, S.; Andrew, R.M.; De-Gol, A.J.; Willis, D.R.; Shan, Y.L.; Canadell, J.G.; et al. Temporary Reduction in Daily Global CO_2 Emissions during the COVID-19 Forced Confinement. *Nat. Clim. Change* **2020**, *10*, 647–653. [CrossRef]
4. Hsiao, C.M. Effects on Second Waves of COVID-19 Epidemics: Social Stringency, Economic Forces, and Public Health. *Theor. Econ. Lett.* **2022**, *12*, 278–320. [CrossRef]
5. Abbass, K.; Qasim, M.Z.; Song, H.M.; Murshed, M.; Mahmood, H.; Younis, I. A Review of the Global Climate Change Impacts, Adaptation, and Sustainable Mitigation Measures. *Environ. Sci. Pollut. Res.* **2022**, *29*, 42539–42559. [CrossRef] [PubMed]
6. Forster, P.; Storelymo, T.; Armour, K.; Collins, W.; Dufresne, J.; Frame, D.; Lunt, D.; Mauritsen, T.; Palmer, M.; Watanabe, M.; et al. Chapter 7: The Earth's Energy Budget, Climate Feedbacks, and Climate Sensitivity. In *Climate Change 2021: The Physical Science Basis*; Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change; IPCC: Geneva, Switzerland, 2021. Available online: https://www.ipcc.ch/report/ar6/wg1/downloads/report/IPCC_AR6_WGI_FOD_Chapter07.pdf (accessed on 16 May 2022).
7. Myhre, G.; Shindell, D.; Bréon, F.M.; Collins, W.; Fuglestvedt, J.; Huang, J.; Koch, D.; Lamarque, J.-F.; Lee, D.; Mendoza, B.; et al. Chapter 8: Anthropogenic and Natural Radiative Forcing. In *Climate Change 2013: The Physical Science Basis*; Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change; IPCC: Geneva, Switzerland, 2013; pp. 659–740. Available online: https://archive.ipcc.ch/pdf/assessment-report/ar5/wg1/WG1AR5_Chapter08_FINAL.pdf (accessed on 16 May 2022).
8. Golombek, R.; Kittelsen, S.A.C.; Rosendahl, K.E. Price and Welfare Effects of Emission Quota Allocation. *Energy Econ.* **2013**, *36*, 568–580. [CrossRef]
9. Zhou, P.; Zhang, L.; Zhou, D.Q.; Xia, W.J. Modeling Economic Performance of Interprovincial CO_2 Emission Reduction Quota Trading in China. *Appl. Energy* **2013**, *112*, 1518–1528. [CrossRef]
10. Wei, Y.M.; Wang, L.; Liao, H.; Wang, K.; Murty, T.; Yan, J.Y. Responsibility Accounting in Carbon Allocation: A Global Perspective. *Appl. Energy* **2014**, *130*, 122–133. [CrossRef]
11. Pan, X.Z.; Teng, F.; Wang, G.H. A Comparison of Carbon Allocation Schemes: On the Equity-Efficiency Tradeoff. *Energy* **2014**, *74*, 222–229. [CrossRef]
12. Pan, X.Z.; Teng, F.; Wang, G.H. Sharing Emission Space at an Equitable Basis: Allocation Scheme based on the Equal Cumulative Emission per Capita Principle. *Appl. Energy* **2014**, *113*, 1810–1818. [CrossRef]
13. Zhang, Y.J.; Wang, A.D.; Da, Y.B. Regional Allocation of Carbon Emission Quotas in China: Evidence from the Shapley Value Method. *Energy Policy* **2014**, *74*, 454–464. [CrossRef]
14. Hao, Y.; Liao, H.; Wei, Y.M. Is China's Carbon Reduction Target Allocation Reasonable? An Analysis based on Carbon Intensity Convergence. *Appl. Energy* **2015**, *142*, 229–239. [CrossRef]
15. Pang, R.Z.; Deng, Z.Q.; Chiu, Y.H. Pareto Improvement through a Reallocation of Carbon Emission Quotas. *Renew. Sustain. Energy Rev.* **2015**, *50*, 419–430. [CrossRef]
16. Carretero, A.L.; de la Rosa, J.; Sanchez-Rodas, D. Applying Statistical Tools Systematically to Determine Industrial Emission Levels associated with the best Available Techniques. *J. Clean. Prod.* **2016**, *112*, 4226–4236. [CrossRef]
17. Miao, Z.A.; Geng, Y.; Sheng, J.C. Efficient Allocation of CO_2 Emissions in China: A Zero Sum Gains Data Envelopment Model. *J. Clean. Prod.* **2016**, *112*, 4144–4150. [CrossRef]
18. Han, R.; Tang, B.J.; Fan, J.L.; Liu, L.C.; Wei, Y.M. Integrated Weighting Approach to Carbon Emission Quotas: An Application Case of Beijing-Tianjin-Hebei Region. *J. Clean. Prod.* **2016**, *131*, 448–459. [CrossRef]
19. Chang, K.; Zhang, C.; Chang, H. Emissions Reduction Allocation and Economic Welfare Estimation through Interregional Emissions Trading in China: Evidence from Efficiency and Equity. *Energy* **2016**, *113*, 1125–1135. [CrossRef]
20. An, Q.X.; Wen, Y.; Xiong, B.B.; Yang, M.; Chen, X.H. Allocation of Carbon Dioxide Emission Permits with the Minimum Cost for Chinese Provinces in Big Data Environment. *J. Clean. Prod.* **2017**, *142*, 886–893. [CrossRef]
21. Zhou, Z.B.; Liu, C.J.; Zeng, X.M.; Jiang, Y.J.; Liu, W.B. Carbon Emission Performance Evaluation and Allocation in Chinese Cities. *J. Clean. Prod.* **2018**, *172*, 1254–1272. [CrossRef]
22. Crémieux, L. What Is at Stake in the "Yellow Jacket" Mobilization. *International Viewpoint*. 2018. Available online: https://internationalviewpoint.org/IMG/pdf/what-is-at-stake-in-the-yellow-jacket-mobilization_a5802.pdf (accessed on 27 November 2018).
23. Markowitz, H. Portfolio Selection. *J. Financ.* **1952**, *7*, 77–91.
24. Chen, M.H.; Jang, S.C.; Peng, Y.J. Discovering Optimal Tourist Market Mixes. *J. Travel Res.* **2010**, *50*, 602–614. [CrossRef]
25. Hsiao, C.M. Enterprise Risk Management with Foreign Exchange Exposures: Evidence from Taiwan Tourism Industry. *Asian Econ. Financ. Rev.* **2017**, *7*, 882–906.
26. Bashir, M.F.; Ma, B.J.; Shahbaz, M.; Jiao, Z.L. The Nexus between Environmental Tax and Carbon Emissions with the Roles of Environmental Technology and Financial Development. *PLoS ONE* **2020**, *15*, e0242412. [CrossRef]

27. World Bank. *State and Trends of Carbon Pricing 2021*; World Bank: Washington, DC, USA, 2021; p. 10. [CrossRef]
28. Grossman, G.M.; Krueger, A.B. Environmental Impacts of a North American Free Trade Agreement. In *National Bureau of Economic Research Working Paper, No. 3914*; National Bureau of Economic Research: Cambridge, MA, USA, 1991.
29. Selden, T.M.; Song, D. Environmental Quality and Development: Is there a Kuznets curve for Air Pollution Emissions? *J. Environ. Econ. Manag.* **1994**, *27*, 147–162. [CrossRef]
30. Kuznets, S. Economic Growth and Income Inequality. *Am. Econ. Rev.* **1955**, *45*, 1–28.
31. Stern, D.I.; Common, M.S.; Barbier, E.B. Economic Growth and Environmental Degradation: The Environmental Kuznets Curve and Sustainable Development. *World Dev.* **1996**, *24*, 1151–1160. [CrossRef]
32. Shahbaz, M.; Mutascu, M.; Azim, P. Environmental Kuznets Curve in Romania and the Role of Energy Consumption. *Renew. Sustain. Energy Rev.* **2013**, *18*, 165–173. [CrossRef]
33. Sun, Y.; Li, M.X.; Zhang, M.J.; Khan, H.S.U.; Li, J.Q.; Li, Z.Y.; Sun, H.Z.; Zhu, Y.; Anaba, O.A. A Study on China's Economic Growth, Green Energy Technology, and Carbon Emissions based on the Kuznets curve (EKC). *Environ. Sci. Pollut. Res.* **2021**, *28*, 7200–7211. [CrossRef]
34. Ahmad, N.; Du, L.S.; Lu, J.Y.; Wang, J.L.; Li, H.Z.; Hashmi, M.Z. Modelling the CO_2 Emissions and Economic Growth in Croatia: Is there any Environmental Kuznets Curve? *Energy* **2017**, *123*, 164–172. [CrossRef]
35. Balsalobre-Lorente, D.; Leitão, N.C. The Role of Tourism, Trade, Renewable Energy Use and Carbon Dioxide Emissions on Economic Growth: Evidence of Tourism-led Growth Hypothesis in EU-28. *Environ. Sci. Pollut. Res.* **2020**, *27*, 45883–45896. [CrossRef]
36. Uzar, U.; Eyuboglu, K. The Nexus between Income Inequality and CO_2 Emissions in Turkey. *J. Clean. Prod.* **2019**, *227*, 149–157. [CrossRef]
37. Koc, S.; Bulus, G.C. Testing Validity of the EKC Hypothesis in South Korea: Role of Renewable Energy and Trade Openness. *Environ. Sci. Pollut. Res.* **2020**, *27*, 29043–29054. [CrossRef]
38. Salahuddin, M.; Gow, J. Economic Growth, Energy Consumption and CO_2 Emissions in Gulf Cooperation Council Countries. *Energy* **2014**, *73*, 44–58. [CrossRef]
39. Lin, B.Q.; Omoju, O.E.; Nwakeze, N.M.; Okonkwo, J.U.; Megbowon, E.T. Is the Environmental Kuznets Curve Hypothesis a Sound Basis for Environmental Policy in Africa? *J. Clean. Prod.* **2016**, *133*, 712–724. [CrossRef]
40. Lu, W.C. Greenhouse Gas Emissions, Energy Consumption and Economic Growth: A Panel Cointegration Analysis for 16 Asian Countries. *Int. J. Environ. Res. Public Health* **2017**, *14*, 1436. [CrossRef]
41. Mensah, I.A.; Sun, M.; Gao, C.X.; Omari-Sasu, A.Y.; Zhu, D.B.; Ampimah, B.C.; Quarcoo, A. Analysis on the Nexus of Economic Growth, Fossil Fuel Energy Consumption, CO_2 Emissions and Oil Price in Africa based on a PMG Panel ARDL Approach. *J. Clean. Prod.* **2019**, *228*, 161–174. [CrossRef]
42. Aslan, A.; Altinoz, B.; Özsolak, B. The Nexus between Economic Growth, Tourism Development, Energy Consumption, and CO_2 Emissions in Mediterranean Countries. *Environ. Sci. Pollut. Res.* **2021**, *28*, 3243–3252. [CrossRef] [PubMed]
43. Azam, M.; Khan, A.Q.; Abdullah, H.B.; Qureshi, M.E. The Impact of CO_2 Emissions on Economic Growth: Evidence from Selected Higher CO_2 Emissions Economies. *Environ. Sci. Polluti. Res.* **2016**, *23*, 6376–6389. [CrossRef] [PubMed]
44. Dogru, T.; Bulut, U.; Kocak, E.; Isik, C.; Suess, C.; Sirakaya-Turk, E. The Nexus between Tourism, Economic Growth, Renewable Energy Consumption, and Carbon Dioxide Emissions: Contemporary Evidence from OECD Countries. *Environ. Sci. Pollut. Res.* **2020**, *27*, 40930–40948. [CrossRef]
45. Kongkuah, M.; Yao, H.X.; Fongjong, B.B.; Agyemang, A.O. The Role of CO_2 Emissions and Economic Growth in Energy Consumption: Empirical Evidence from Belt and Road and OECD Countries. *Environ. Sci. Pollut. Res.* **2021**, *28*, 22488–22509. [CrossRef]
46. Bekhet, H.A.; Othman, N.S. The Role of Renewable Energy to Validate Dynamic Interaction between CO_2 Emissions and GDP toward Sustainable Development in Malaysia. *Energy Econ.* **2018**, *72*, 47–61. [CrossRef]
47. Merton, R. An Analytic Derivation of the Efficient Portfolio Frontier. *J. Financ. Quant. Anal.* **1972**, *7*, 1851–1872. [CrossRef]
48. Jang, S.C.; Chen, M.H. Financial Portfolio Approach to Optimal Tourist Market Mixes. *Tour. Manag.* **2008**, *29*, 761–770. [CrossRef] [PubMed]