

Article

Relationship between CO₂ Emissions from Concrete Production and Economic Growth in 20 OECD Countries

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Abstract: Many production activities contribute to environmental degradation by emitting greenhouse gases. The construction sector, one of the main sectors contributing to a country's economic growth, also contributes to greenhouse gas emissions (especially CO₂). Concrete, one of the most commonly used materials in this sector, is a source of CO₂ emissions due to its cement content. The purpose of this article is to examine the decoupling status between environmental degradation caused by CO₂ emissions from ready-mixed concrete production and the economic growth of 20 OECD (Organisation for Economic Co-operation and Development) countries. This study consists of four stages and three periods. In the first stage, the variables are selected; in the second stage, the data are created; and in the third stage, data analysis is performed. In the final stage, the type of decoupling between economic growth and environmental degradation is separately determined for 20 OECD countries. These stages were completed for the pre-commitment period (2000–2007) of the Kyoto Protocol, the first commitment period (2008–2012), and the second commitment period (2013–2019). According to our findings, during the second commitment period of the Kyoto Protocol, only Switzerland and Belgium achieved absolute decoupling between the environmental degradation caused by CO₂ emissions from concrete production and economic growth.

Keywords: construction sector; sustainability; concrete; CO₂ emissions; decoupling; OECD countries



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1. Introduction

In the past thousands of years, the Earth has experienced four glacial periods separated by four warm periods. During this time, the expansion and subsequent melting of glaciers caused fluctuations in sea levels. Although this process led to significant geographical changes, the accumulation rate of carbon dioxide (CO₂) in the atmosphere remained below 300 particles per million. However, it was determined that in 2007 that the accumulation rate of CO₂ in the atmosphere exceeded 380 particles per million [1,2]. The Intergovernmental Panel on Climate Change (IPCC) reports published in 2007 and 2013 stated that the most significant environmental issue is “global warming” [1,3]. The observed increase in greenhouse gas emissions, especially carbon dioxide (CO₂) emissions worldwide, supports this report [4,5]. According to climate scientists, rapid emission reduction is necessary, and the goal should be to achieve net zero emissions by 2050 [6]. The IPCC's Special Report published in 2018 emphasizes the need to limit global warming to 1.5 °C and achieve global carbon neutrality by 2050 [7].

In the IPCC's 2007 report, it was stated that the annual cost of effective and permanent measures to reduce carbon emissions and mitigate climate change would be only 0.1% of the world's GDP value in 2006 [1]. Additionally, Stern (2006) determined in his study that the cost required to reduce CO₂ emissions is only 1% of the world's annual GDP [8]. According to Stern (2006), if no action is taken to combat climate change, there will be a decline of 5% to 20% in global economic production within this century. Furthermore, different weather events that caused the deaths of 35,000 people and USD 15 billion in damages in Europe in 2003 will continue to increase in the next decade [2,8].

According to an article published by the Project Management Institute (PMI), 20% of the world's largest companies have set a net zero target against the increase in greenhouse gas concentrations. To reduce greenhouse gas emissions, many individuals need to implement net zero targets, and governments, academia, and other organizations need to collaborate as well [9]. However, only 33% of projects completed so far have provided improvements for the environment [9]. According to a report published by IPCC in 2022, net human-caused greenhouse gas emissions have increased globally across all major sectors from 2010 to the present. The report also determined that global greenhouse gas emissions from buildings were 12 GtCO₂-eq in 2019, accounting for 21% of global greenhouse gas emissions. The report also stated that 18% (2.2 GtCO₂-eq) of these emissions are from the production of cement and steel used in building construction [10]. According to Favier et al. (2018), the concrete and cement sector plays a significant role in achieving the goals of the Paris Agreement, which aims to keep global warming below 1.5–2 °C.

A significant portion of the energy produced worldwide is used for cement production, and in this production process, 0.55 tons of CO₂ are emitted for each ton of cement produced. Accordingly, every 1 euro of cement sales results in 9 kg of CO₂ emissions [11]. Cement is traditionally a material used in concrete production. Concrete is the most commonly used industrial and structural material in the world [12,13]. According to Orhon (2012), concrete is the “most produced man-made material” [14]. According to the European Ready Mixed Concrete Association (ERMCO) report, the total production of ready-mixed concrete in EU member states was 272.5 million cubic meters in 2021 [15]. The per capita annual consumption of concrete is approximately 0.6 m³ in EU member countries and over 1 m³ worldwide [14,16]. It is expected that annual production of 18 billion tons of concrete will be reached by 2050 globally [13,17]. According to a report published by IPCC in 2022, the majority of emissions in the construction sector are CO₂ gas emissions [10]. Buildings and infrastructure account for approximately 40% of the world's annual CO₂ emissions. Concrete ranks first in CO₂ emissions related to buildings and materials, accounting for 30% [18]. According to a report prepared by the Global Cement and Concrete Association (GCCA) in 2021, if no measures are taken by 2050, the global demand for concrete could result in 3.8 Gt of CO₂ emissions, with 11% of this coming solely from concrete production [19]. According to Jackson (2005), since 2000, there has been a decrease in resource productivity in the use of structural materials such as iron and cement globally. This means that these resources are being consumed rapidly, especially by emerging economies [20].

When these data are examined, the sustainability of concrete, which has high production, is gaining more and more importance every day [12]. Concrete, which has many advantages such as local production, recyclability, and durability alongside disadvantages like CO₂ formation due to its content of cement, can be made more sustainable than it is in its current state with nature-friendly approaches [14]. Sustainability has become an important concept for industries today. Industries collaborate with many stakeholders to manage their projects and organizations sustainably [21,22]. Analyzing the potential impact of project stakeholders on sustainability, determining their priorities, and redirecting these stakeholders' thinking play an important role in assessing sustainability [23–25]. According to Favier et al. (2018), the support of sustainability efforts by all stakeholders throughout the value chain, rather than just by a single stakeholder, will be an important step towards creating a circular economy in the construction sector, which is considered a fundamental element of a sustainable economy [7].

According to organizations such as the OECD and World Bank, decoupling environmental harms from economic benefits is a gateway to sustainability [26]. When an economy can grow without causing environmental damage, there is a decoupling between economic development and the environment [27]. Without decoupling, an increase in economic growth will also increase environmental pressure. This situation will affect all societies and ecosystems [28,29]. The OECD categorized decoupling into absolute and relative decoupling [30]. Relative decoupling is defined as the marginal decrease in environmental degradation per unit of economic output. In other words, relative decoupling refers to the relative decrease in pressure on resources per unit of economic output compared to a one-unit increase in gross domestic product (GDP). In this type of decoupling, the pressure on resources does not completely disappear [31,32]. With an increase in gross domestic product (GDP), the pressure on resources continues to increase; however, this increase in pressure occurs at a slower rate than the increase in GDP [32].

This study aims to answer the question, “What type of relationship exists between environmental degradation caused by CO₂ emissions from ready-mixed concrete production and economic development during and prior to the Kyoto Protocol commitment periods for 20 OECD countries?” The results obtained from this study illustrate the relationship and decoupling between environmental pollution and the economy for concrete, a material with high embodied CO₂ emissions. In the literature, there are studies addressing this relationship for different areas and materials within the construction sector. However, to the authors’ knowledge, there are no studies on this topic specifically for concrete. The 20 OECD countries included in this study are Austria, Belgium, Czechia, Denmark, Finland, France, Germany, Ireland, Italy, the Netherlands, Poland, Portugal, Slovakia, Spain, Sweden, the United Kingdom, Norway, Switzerland, Turkey, and the United States of America.

The Kyoto Protocol is a protocol that directs industrialized and transitioning economies to reduce and limit greenhouse gas emissions [33]. Among the countries included in this study, the United States did not participate in either period of the Kyoto Protocol, while Turkey only participated in the first period. All the other countries participated in both periods.

The remainder of this paper is structured as follows: Section 2 summarizes the literature related to the topic of this study, Section 3 explains the methodology, Section 4 presents the data analysis and findings, Section 5 discusses the data used, and Section 6 outlines the conclusions.

2. Research Background

Greenhouse gas emissions exceeding critical thresholds are a significant cause of concern in both political and academic circles. The traditional growth model implies a linear relationship between greenhouse gas emissions and economic growth [29,34,35]. In this context, the relationship between environmental degradation and economic growth has become increasingly important, with many researchers exploring this relationship using various methods. One of the most commonly used methods in the literature is the environmental Kuznets curve (EKC) [29,36–43]. According to the environmental Kuznets curve, economic growth in its initial stages leads to high levels of environmental degradation. However, investments in efficiency and technological advancements will reduce the pressure of development on the environment in later stages [28,29]. Another method used in the literature involves the Tapio decoupling model [27,29,43,44].

Many organizations worldwide have published reports on assessing global warming and sustainability in the construction sector [1,3,10,18,19]. The IPCC reports from 2007 and 2013 highlight global warming as the most significant environmental issue [1,3]. In a report published in 2022, it was stated that the majority of emissions in the construction sector are CO₂ gas. According to this report, greenhouse gas emissions from buildings account for 21% of the global greenhouse gas emissions, with 18% of these emissions attributed to cement and steel production used in building construction [10]. According to World Bank reports, carbon dioxide emissions arise from the combustion of fossil fuels and cement

production [45]. In a report published by the European Climate Foundation (ECF), the CO₂ emission values for three different structures were determined, and it was found that positive investments in the concrete sector could reduce these emissions by up to 80% compared to the levels in 1990. According to this report, efforts to reduce emissions should be supported by all stakeholders along the value chain [7]. A report prepared by the GCCA (2021) outlines a roadmap for the cement and concrete sector to achieve carbon neutrality by 2050. Without any interventions, it is expected that 3.8 Gt of CO₂ emissions will be generated by 2050 due to the global concrete demand. Additionally, the report suggests the target of achieving a 25% reduction in CO₂ emissions per cubic meter of concrete by 2030 compared to 2020 levels [19]. According to the WEF (2023), using low-carbon concrete and making necessary improvements by 2030 can reduce a project's total concrete emissions by up to 40%. The report also states that even in the high estimate scenario, using low-carbon concrete increases the cost of a structure by 2–3% [18].

Building materials are selected based on their esthetic properties, cost, and performance. In the construction sector, stakeholders also need to consider the carbon content and insulation properties of materials when selecting these [46,47]. According to many researchers, CO₂ emissions should play a major role in material selection [47–54]. In this context, researchers have conducted studies to determine the CO₂ emissions from buildings and construction materials [47,55–61]. Hugo et al. (2014) stated that carbon dioxide emissions can be decreased by reducing the use of construction materials [55]. According to Dakwale and Ralegaonkar (2012), carbon emissions could be reduced by up to 36% by improving the thermal insulation performance of buildings [46]. Zhang et al. examined the GHG emission values of building materials in Switzerland. As a result, they determined that there will be a 25% reduction in GHG emissions by 2055 compared to 2015, due to the decrease in GHG emissions from concrete and bricks. However, according to Zhang et al., this reduction is much lower than the potential of some construction materials and is far from achieving the net-zero target [62]. Griffiths et al. conducted a systematic review identifying 18 innovations to decarbonize cement and concrete, as well as the challenges associated with implementing these innovations [63]. In 2024, Nehdi et al. conducted a systematic review examining the short- and long-term potentials, benefits, and limitations of emerging cement and concrete carbon-saving technologies. The study's findings indicate that most of these emerging technologies are still in the early stages of development [64]. Su et al. identified the sectors within the Chinese construction industry that impact economic growth and carbon emissions [65].

According to research and reports, the construction sector, considered one of the sectors causing the most environmental pollution, also ranks among the leading sectors contributing to national economies. Therefore, researchers have conducted studies examining the relationship between environmental degradation caused by the construction sector and economic growth. These studies can be divided into two categories based on the methods used: the Kuznets curve and the Tapio. Bao and Lu investigated the applicability of the environmental Kuznets curve to construction waste management. The study utilized data on construction waste generation (in tons) and GDP per capita. As a result, an inverted U-shaped relationship was found between economic development and environmental degradation [43].

Tapio examined the relationship between GDP, traffic volumes, and CO₂ emissions from transportation in 15 EU countries. As a result, between 1970 and 2001, passenger transportation showed a shift from expansive negative decoupling to expansive coupling, while freight transportation shifted from weak decoupling to expansive negative decoupling [27]. Cautisanu and Hatmanu examined the degree of decoupling between economic growth, as measured by GDP, and environmental degradation, as indicated by CO₂ and HFC emissions. As a result, it was determined that the Scandinavian countries have achieved absolute decoupling [29]. Wang et al. used the Tapio model to determine the decoupling relationship between economic growth, based on GDP, and construction waste production for the European Union (EU) and China. Additionally, the study identified the driving

factors of construction waste generation using LMDI (logarithmic mean Divisia index) decomposition and the Kaya formula [66]. In addition to these country-focused studies, state-focused analyses are also present in the literature. Du et al. used the Tapio model to investigate the decoupling relationship between economic growth and carbon emissions in the construction sector across 30 provinces in China. They also incorporated the spatial evolution of carbon emissions and the economy into their study. As a result, differences in the geographic structure of the provinces and regional policies led to variations in economic development and carbon emissions [67]. Li and Li examined the relationship between CO₂ emissions from the construction sector and economic growth within the construction industry across 30 provinces and municipalities in China using the Tapio decoupling model and STIRPAT models. The study includes CO₂ emission values for the construction sector, encompassing both direct and indirect carbon emissions. The results indicate that economic growth still promotes CO₂ emissions and that the relationships are in the rising phase of the Kuznets curve [68]. Wu et al. conducted another study examining the decoupling relationship between economic output and carbon emissions in the construction sector across Chinese provinces using the Tapio model. In this study, the Divisia index (LMDI) was used to understand the driving forces behind the decoupling status [69].

In the literature, there are studies that examine the relationship between environmental pollution and economic development in the construction sector overall and in various stakeholder sectors. However, to the best of the authors' knowledge, there are no studies available that specifically investigate the relationship between concrete production-related environmental degradation and economic development.

This study aims to answer the question, "What type of relationship exists between environmental degradation caused by CO₂ emissions from ready-mixed concrete production and economic development during and prior to the Kyoto Protocol commitment periods for 20 OECD countries?"

3. Research Methodology

In this study, the decoupling status between the environmental degradation caused by CO₂ emissions from ready-mixed concrete production and economic growth is examined for 20 OECD countries before and during the commitment periods of the Kyoto Protocol. The 20 OECD countries included in this study are Austria, Belgium, Czechia, Denmark, Finland, France, Germany, Ireland, Italy, the Netherlands, Poland, Portugal, Slovakia, Spain, Sweden, the United Kingdom, Norway, Switzerland, Turkey, and the United States of America.

The methodology developed to achieve the objectives set in this study is illustrated in Figure 1. According to this methodology, this study consists of four stages. The first stage (Stage I) involves identifying the experimental and statistical data from the literature to create the dataset. The second stage (Stage II) involves the creation of the dataset using the data obtained in the first stage. The third stage (Stage III), which involves the analyses conducted with this dataset, consists of two sections. In the first section, the per capita CCO₂, average CCO₂, and per capita average CCO₂ values are calculated. In the second section, curves are created to determine the divergence between environmental degradation caused by CO₂ emissions from ready-mixed concrete production and economic growth for 20 OECD countries. In the final stage, the results of the analyses conducted in the third stage and the curves created are presented and interpreted. Stages I, II, and III are detailed in the Data Analysis and Findings Section, while Stage IV is described in the Section 5.

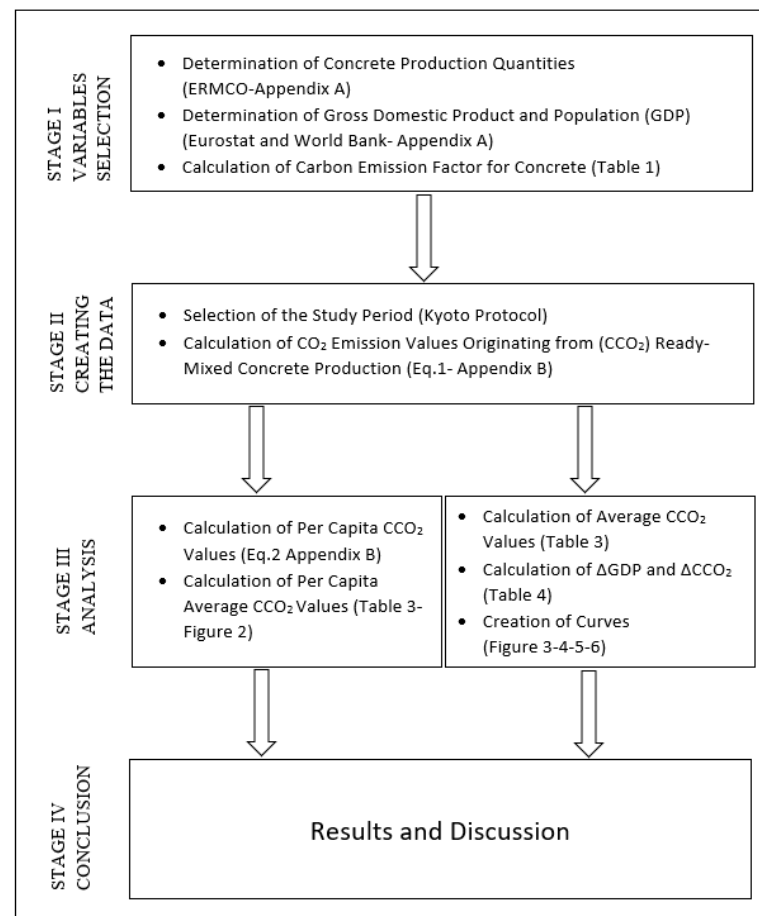


Figure 1. Research methodology.

4. Data Analysis and Findings

This study consists of four stages: Stage I involves identifying the experimental and statistical data from the literature to create the dataset. Data for 20 OECD countries, including RMC production quantities from the European Ready Mixed Concrete Organization (ERMCO) [16], GDP values from the World Bank [45], and population information from Eurostat [70], were obtained. These data are presented in Appendix A.

The carbon emission factor (F_{CM}) value for concrete was determined through a literature review and is shown in Table 1. According to Table 1, the embodied CO₂ emission value for concrete production is determined to be an average of 301.23 kgCO₂/m³.

Table 1. Literature review for embodied CO₂ emissions in concrete.

Literature	CO ₂ Emission Factor		Strength	
Mergos [71]	228.0	kgCO ₂ /m ³	25	MPa
	264.0	kgCO ₂ /m ³	32	MPa
Nielsen [72]	387.0	kgCO ₂ /m ³	35	MPa
Ji et al. [73]	236.8	kgCO ₂ /m ³	24	MPa
	285.7	kgCO ₂ /m ³	30	MPa
	340.0	kgCO ₂ /m ³	40	MPa
de Medeiros and Kripka [74]	224.0	kgCO ₂ /m ³	25	MPa
	265.0	kgCO ₂ /m ³	35	MPa
	255.0	kgCO ₂ /m ³	20	MPa
Yeo and Potra [75]	376.0	kgCO ₂ /m ³	30	MPa
	452.0	kgCO ₂ /m ³	40	MPa

Stage II involves the creation of a dataset using the data obtained in the first stage. In this stage, the CO₂ emission value related to ready-mixed concrete production (CCO₂) is calculated, and the analysis period is selected.

CO₂ emissions from ready-mixed concrete production, not found in the literature or databases for 20 OECD member countries, were calculated using Equation (1).

$$CCO_2 = RMC \times F_{CM} \quad (1)$$

Equation (1), CCO₂ represents the CO₂ emissions from ready-mixed concrete production, F_{cm} represents the carbon emission factor of concrete, and RMC represents the quantity of ready-mixed concrete production. The F_{cm} value was initially taken as 301.23 kgCO₂/m³. The RMC value was obtained from the table in Appendix A. Thus, the CCO₂ values for 20 OECD countries were calculated and are shown in Appendix B. This equation was derived by calculating the ratio of the country's ready-mixed concrete production using the CO₂ emission amount per 1 m³ of concrete, obtained from Table 1.

The analysis period covers the three commitment periods of the Kyoto Protocol, as follows: 2000–2007 for the pre-commitment period, 2008–2012 for the first commitment period, and 2013–2019 for the second commitment period. In this study, the periods are categorized as follows: 2000–2007 as the first period, 2008–2012 as the second period, and 2013–2019 as the third period. According to Jackson (2005), since 2000, there has been a decrease in resource productivity in the use of structural materials such as iron and cement globally. This means that these resources are being consumed rapidly, especially by emerging economies [20]. Therefore, the beginning of the first period in this study is chosen as the year 2000. The second commitment period of the Kyoto Protocol is defined as the years 2013–2020. However, due to the global pandemic and widespread lockdowns in 2020, the last year of the third period in this study is chosen as the year 2019.

In the first section of Stage III, the per capita CO₂ emission values resulting from ready-mixed concrete production (per capita CCO₂) are calculated using Equation (2).

$$\text{per capita } CCO_2 = \frac{CCO_2}{P} \quad (2)$$

Equation (2) represents P as the population values obtained from the World Bank and which are provided in Appendix A, while CCO₂ refers to the CO₂ emissions from ready-mixed concrete production calculated by the authors and shown in Appendix B. In this equation, the total CCO₂ amount for the country is divided by the country's population to calculate the per capita CCO₂ value.

The average values of the CCO₂ emissions (average CCO₂) and the average values of the per capita CCO₂ emissions (average CCO₂ per capita) have been separately calculated for three analysis periods and are shown in Table 2.

According to Table 2, the average CCO₂ values for the 20 OECD countries were determined as 10.68 in the first period, 9.19 in the second period, and 8.74 in the third period. In the first period, the countries with CCO₂ values above 10.68 were the United States of America (96.39), Spain (24.56), Italy (21.86), Turkey (12.65), Germany (12.43), and France (11.47). In the second period, the countries with per capita CCO₂ values above 9.19 were the United States of America (71.33), Turkey (24.02), Italy (16.58), Germany (12.93), Spain (12.62), and France (11.98). In the third period, the countries with per capita CCO₂ values above 8.74 were the United States of America (69.24), Turkey (30.42), Germany (14.89), and France (11.38). This study's findings indicate that the United States of America has the highest CCO₂ values in each period. In the first period, Spain and Italy had CCO₂ values higher than the average of the 20 OECD countries, but they reduced their CCO₂ values in the second period without decreasing below the average. However, in the third period, these two countries were found to have CCO₂ values below the average. This study also revealed that France kept its CCO₂ values constant in all three periods, while Germany and Turkey showed an increase in CCO₂ values in each of the three periods.

Table 2. Average CCO₂ and per capita average CCO₂ values.

Country	Av. CCO ₂ (Million Ton)			Per Capita Av. CCO ₂ (Tons per Capita)		
	1. Period	2. Period	3. Period	1. Period	2. Period	3. Period
Austria (AUS)	2.99	3.20	3.29	0.37	0.38	0.38
Belgium (BEL)	3.38	3.44	3.81	0.32	0.32	0.34
Czechia (CZE)	1.99	2.27	2.04	0.19	0.22	0.19
Denmark (DEN)	0.73	0.62	0.75	0.14	0.11	0.13
Finland (FIN)	0.78	0.79	0.83	0.15	0.15	0.15
France (FRA)	11.47	11.98	11.38	0.18	0.18	0.17
Germany (GER)	12.43	12.93	14.89	0.15	0.16	0.18
Ireland (IRE)	2.39	1.27	1.03	0.59	0.28	0.22
Italy (ITA)	21.86	16.58	8.41	0.38	0.28	0.14
Netherlands (NET)	2.53	2.65	2.07	0.16	0.16	0.12
Poland (POL)	3.32	6.07	6.42	0.09	0.16	0.17
Portugal (POR)	3.29	2.22	1.07	0.31	0.21	0.10
Slovakia (SLO)	0.72	0.78	0.66	0.13	0.14	0.12
Spain (SPA)	24.56	12.62	5.66	0.57	0.27	0.12
Sweden (SWE)	0.80	0.98	1.20	0.09	0.10	0.12
United Kingdom (UK)	7.34	5.35	7.06	0.12	0.09	0.11
Norway (NOR)	0.82	1.01	1.17	0.18	0.21	0.22
Switzerland (SWI)	3.23	3.72	3.49	0.44	0.48	0.42
Turkey (TUR)	12.65	24.02	30.42	0.19	0.33	0.38
United States of America (USA)	96.39	71.33	69.24	0.33	0.23	0.21
Average	10.68	9.19	8.74	0.25	0.22	0.20

The average per capita CCO₂ values for the 20 OECD countries were determined as 0.25 in the first period, 0.22 in the second period, and 0.20 in the third period. In the first period, the countries with per capita CCO₂ values above 0.25 were Ireland (0.59), Spain (0.57), Switzerland (0.44), Italy (0.38), Austria (0.37), the United States of America (0.33), Belgium (0.32), and Portugal (0.31). In the second period, the countries with per capita CCO₂ values above 0.22 were Switzerland (0.48), Austria (0.38), Turkey (0.33), Belgium (0.32), Ireland (0.28), Italy (0.28), Spain (0.27), and the United States of America (0.23). In the third period, the countries with per capita CCO₂ values above 0.20 are Switzerland (0.42), Turkey (0.38), Austria (0.38), Belgium (0.34), Ireland (0.22), and the United States of America (0.21).

Based on this information, and as clearly seen in Table 2, the per capita CCO₂ values of Ireland and Spain decreased in each period. Particularly, it was determined that Spain reduced its per capita CCO₂ values below the average values of the 20 OECD countries in the third period, which corresponds to the second commitment period of the Kyoto Protocol. Portugal, before the commitment periods of the Kyoto Protocol, was found to have per capita CCO₂ values higher than the average of the 20 OECD countries. However, during the two commitment periods, it was observed that these values were below the average. The United States of America is among the countries that have reduced their per capita CCO₂ values above the average in each period. However, this reduction has not brought these values below the average of the OECD countries in any period. The per capita CCO₂ values in Switzerland and Belgium remained constant in all three periods, while there was an increase in Turkey's per capita CCO₂ value in each period. It was determined that in Poland, which reports values below the average of the 20 OECD countries in the three periods, there was also an increase in each period.

In the second section of Stage III, curves were created to determine the relationship between environmental degradation caused by CO₂ emissions from ready-mixed concrete production and economic growth for 20 OECD countries. To create these curves, the Δ GDP and Δ CCO₂ values were first calculated separately for each analysis period using

Equation (3). The results are presented in Table 3. The GDP and CCO₂ values are provided in Appendices A and B, respectively.

$$\Delta V = \left[\frac{V_{n=t}}{V_{n=0}} - 1 \right] \times 100 \quad (3)$$

Table 3. Δ GDP- Δ CCO₂ (%).

	1. Period		2. Period		3. Period	
	Δ GDP	Δ CCO ₂	Δ GDP	Δ CCO ₂	Δ GDP	Δ CCO ₂
AUS	97.27	21.51	−5.24	−7.83	3.35	13.33
BEL	98.88	1.69	−4.09	5.93	2.70	0.00
CZE	207.60	54.55	−11.81	−28.13	19.30	9.23
DEN	94.58	31.82	−7.42	−25.93	0.85	17.39
FIN	103.44	24.00	−9.60	−3.57	−1.05	0.00
FRA	94.82	31.20	−8.42	−11.99	−2.95	4.40
GER	75.85	−29.53	−5.82	12.20	4.16	17.32
IRE	169.52	52.54	−18.27	−79.00	67.54	104.76
ITA	93.00	13.08	−13.36	−45.49	−6.10	−10.41
NET	103.26	4.71	−11.87	−30.48	3.76	18.18
POL	149.11	60.00	−7.19	−8.02	15.57	45.56
POR	102.77	15.00	−17.92	−66.36	5.99	88.89
SLO	196.02	68.42	−6.20	−48.65	6.85	64.71
SPA	146.34	48.91	−18.82	−68.70	2.86	52.15
SWE	86.90	37.50	6.72	−5.71	−9.02	36.36
UK	85.56	11.30	−7.59	−14.15	2.39	27.04
NOR	134.84	65.22	10.29	0.00	−22.29	0.00
SWI	75.76	15.24	21.00	7.44	2.14	−7.50
TUR	148.39	175.56	14.29	33.62	−20.55	−34.31
USA	41.20	0.00	10.05	−16.66	26.94	21.73

Equation (3) represents the V variables, where t denotes the end of the period, and 0 denotes the beginning of the period. This equation has been modified from the source cited in Bodur et al., 2009 [76]; Naqvi and Zwickl, 2017 [44]; and Cautisanu and Hatmanu, 2023 [29]. In the calculation of Equation (3), for the first period, the value of $n = 0$ represents data from the year 2000 (either CO₂ or GDP), and $n = t$ represents data from the year 2007. This equation was calculated separately for each period and each country.

In the literature, various methods and different types of decomposition classes have been used to examine the relationship between environmental degradation and economic growth measured by the GDP. The OECD categorizes the decomposition into absolute and relative decomposition. Tapio [27] conducted a comprehensive study identifying eight types of decomposition. Tapio [27] referred to the decomposition types as “expansive negative decoupling (Δ GDP > 0, Δ VOL > 0, $\% \Delta$ VOL/ $\% \Delta$ GDP > 1.2)”, “expansive coupling (Δ GDP < 0, Δ VOL < 0, $\% \Delta$ VOL/ $\% \Delta$ GDP = 0.8–1.2)”, “recessive coupling (Δ GDP > 0, Δ VOL > 0, $\% \Delta$ VOL/ $\% \Delta$ GDP = 0.8–1.2)”, “strong negative decoupling (Δ GDP < 0, Δ VOL > 0, $\% \Delta$ VOL/ $\% \Delta$ GDP < 0)”, “weak decoupling (Δ GDP > 0, Δ VOL > 0, $\% \Delta$ VOL/ $\% \Delta$ GDP = 0–0.8)”, “strong decoupling (Δ GDP > 0, Δ VOL < 0, $\% \Delta$ VOL/ $\% \Delta$ GDP < 0)”, “recessive decoupling (Δ GDP < 0, Δ VOL < 0, $\% \Delta$ VOL/ $\% \Delta$ GDP > 1.2)”, and “weak negative decoupling (Δ GDP < 0, Δ VOL < 0, $\% \Delta$ VOL/ $\% \Delta$ GDP = 0–0.8)”. Naqvi and Zwickl, 2017 [44], further simplified these eight types determined by Tapio, [27] and reduced them to five types. Tapio [27] and Naqvi and Zwickl [44] illustrated these decomposition types graphically. The horizontal axis of the graph represents the GDP, while the vertical axis represents environmental degradation. Coupling and Relative Decoupling are separated by a dashed line at a 45-degree angle to the horizontal. In this study, the graph and classes presented in Table 4 were also used to determine the degrees of decomposition.

Table 4. Types of decoupling (modified from Tripo, 2005 [27]; Naqvi and Zwickl, 2017 [44]; and Cautisanu and Hatmanu, 2023 [29]).

	1a	Coupling	GDP > 0 Air Emission > 0 GDP < Air Emission	Positive Growth
	1b	Relative Decoupling	GDP > 0 Air Emission > 0 GDP > Air Emission	
	2	Absolute Decoupling	GDP > 0 Air Emission < 0	Negative Growth
	3	Negative Coupling	GDP < 0 Air Emission < 0	
	4	Negative Decoupling	GDP < 0 Air Emission > 0	

Table 4 includes the five types of decoupling simplified by Naqvi and Zwicki. The table is based on the studies by Tripo, 2005 [27]; Naqvi and Zwickl, 2017 [44]; and Cautisanu and Hatmanu, 2023 [29].

According to the results obtained in Table 3, the decoupling statuses of the 20 OECD countries were determined considering the constraints shown in Table 4. The results for the first period covering 2000–2007 are presented in Figure 2, the results for the second period covering 2008–2012 are shown in Figure 3, and the results for the third period covering 2013–2019 are displayed in Figure 4.

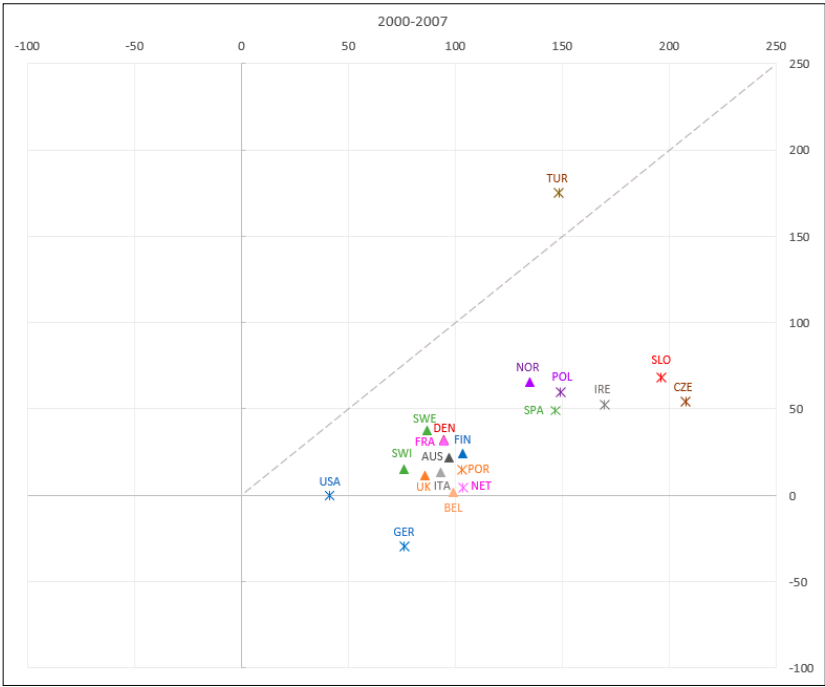


Figure 2. First period (2000–2007) coupling and decoupling results for 20 OECD countries.

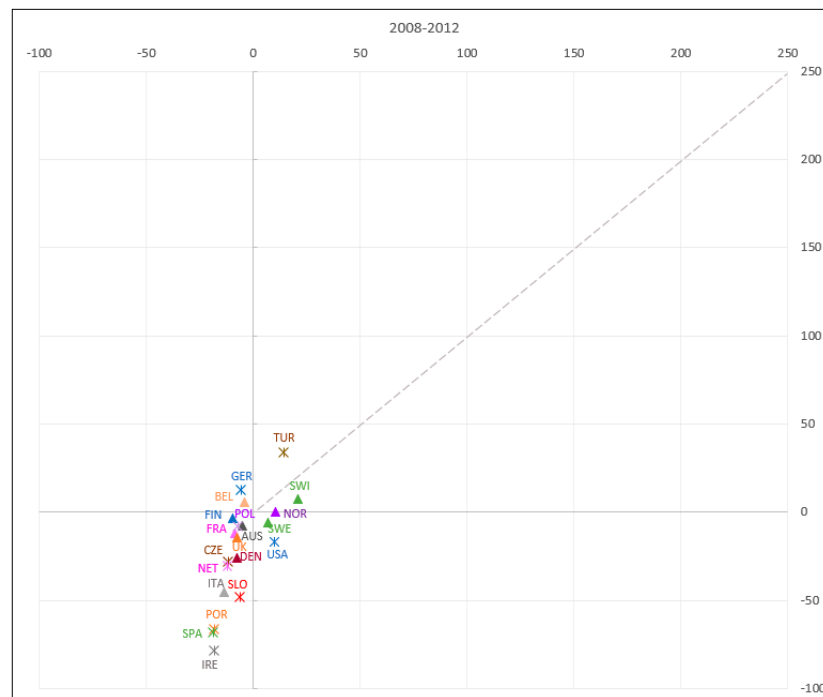


Figure 3. Second period (2008–2012) coupling and decoupling results for 20 OECD countries.

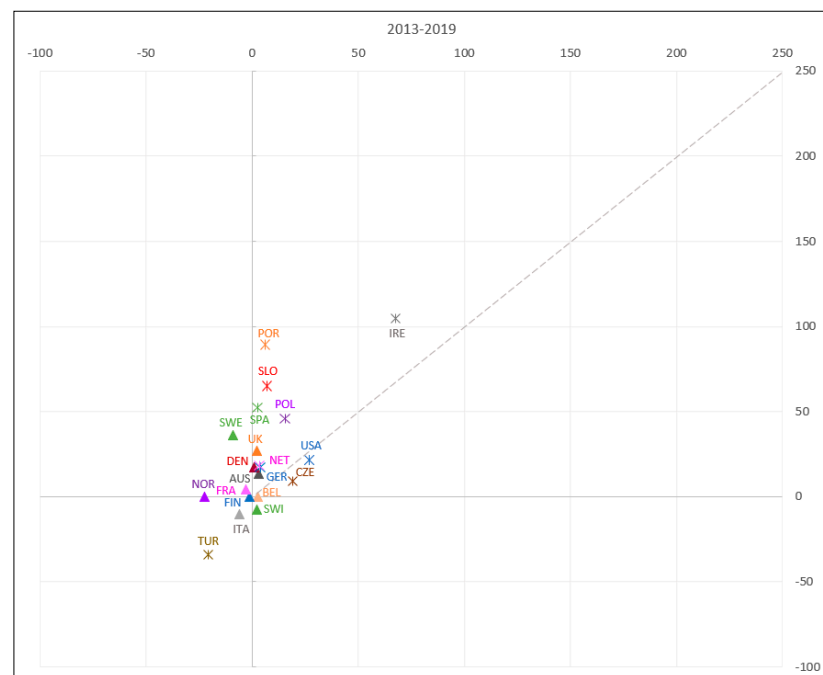


Figure 4. Third period (2013–2019) coupling and decoupling results for 20 OECD countries.

The decoupling types of countries with $\Delta\text{CCO}_2 = 0$ and $\Delta\text{GDP} = 0$ values were determined by the authors considering the other years in the respective period.

5. Discussion

Overall, the results of this paper show that, except for Germany (GER), all the other OECD countries are in the first quadrant during the first period of the Kyoto Protocol. This means that the ΔGDP and ΔCCO_2 values for these 19 countries are greater than zero. In these countries (except Turkey (TUR)), the ΔGDP value is greater than the ΔCCO_2

value. Therefore, in these countries (except Turkey (TUR)), there is a relationship of relative decoupling between the economic growth measured by the GDP and environmental degradation caused by CCO_2 in the first period. In Turkey, however, since the ΔGDP value is smaller than the ΔCCO_2 value, the relationship is observed to display coupling. In Germany, an absolute decoupling relationship is identified. This means that in Germany during the first period, the ΔGDP value is greater than zero, while the ΔCCO_2 values are less than zero. It is also determined that in all 20 OECD countries, the economic growth measured by the GDP is positive in the first period.

According to the decoupling results for the second period, it is determined that 13 countries (Austria (AUS), Czechia (CZE), Denmark (DEN), Finland (FIN), France (FRA), Ireland (IRE), Italy (ITA), the Netherlands (NET), Poland (POL), Portugal (POR), Spain (SPA), Slovakia (SLO), and the United Kingdom (UK)) are in the third quadrant. The decoupling status of these countries is identified as negative coupling. In these countries, both the GDP and CCO_2 values are less than 0. Thirteen countries experienced negative growth during this period. Belgium and Germany are among the countries displaying negative growth as well. The decoupling status for these two countries is determined as negative decoupling. Both countries have GDP values less than 0, and their CCO_2 values are greater than 0. During this period, Turkey (TUR), Switzerland (SWI), Norway (NOR), Sweden (SWE), and the United States of America (USA) exhibited positive growth ($\text{GDP} > 0$). For Turkey (TUR) and Switzerland (SWI), the CCO_2 values are greater than 0. The situation in Turkey (TUR) is defined as displaying coupling ($\text{CCO}_2 > \text{GDP}$), while in Switzerland (SWI), it is identified as relative decoupling ($\text{CCO}_2 < \text{GDP}$). Sweden (SWE), Norway (NOR), and the United States (USA) were determined to be in a state of absolute decoupling due to their CCO_2 values being below 0.

In the third period, Finland (FIN), France (FRA), Norway (NOR), Sweden (SWE), Italy (ITA), and Turkey (TUR) were countries experiencing negative growth. It has been determined that, of these countries, Italy (ITA) and Turkey (TUR) have negative CO_2 emission rates. The decoupling status of these two countries is identified as negative coupling. Finland (FIN), France (FRA), Norway (NOR), and Sweden (SWE), on the other hand, have seen an increase in CCO_2 emission rates. Negative decoupling was identified in these countries. Positive growth was identified in 14 countries, excluding Finland (FIN), France (FRA), Norway (NOR), Sweden (SWE), Italy (ITA), and Turkey (TUR). Within these 14 countries, Switzerland (SWI) and Belgium (BEL) are at the stage of absolute decoupling with negative CCO_2 values. Among the other countries experiencing positive growth, CZE and the USA are at the stage of relative decoupling ($\text{CCO}_2 < \text{GDP}$), while the remaining 10 countries are at the coupling ($\text{CCO}_2 > \text{GDP}$) stage. The coupling and decoupling results of the 20 OECD countries are provided in detail in Figure 5.

In the first period, all countries except Germany (which exhibited absolute decoupling) and Turkey showed relative decoupling. Turkey was determined to display coupling. In Turkey, the share of the construction sector in the gross domestic product (GDP) was 6.3% in 2006 and 6.8% in 2007. The growth rate of the construction sector in Turkey in 2006 was approximately 25.56%, while the GDP growth rate was 7.11%. This indicates a record level of growth for the construction sector. In 2007, the growth rate of the construction sector continued at 10.57%, while the GDP growth rate was 5.03% [77]. Many of the countries identified as experiencing relative decoupling in the first period were found to have experienced negative coupling with negative growth in the second period. The 2008 economic crisis during the second period (2008–2012) may be considered as a contributing factor to this change.



Figure 5. Cont.

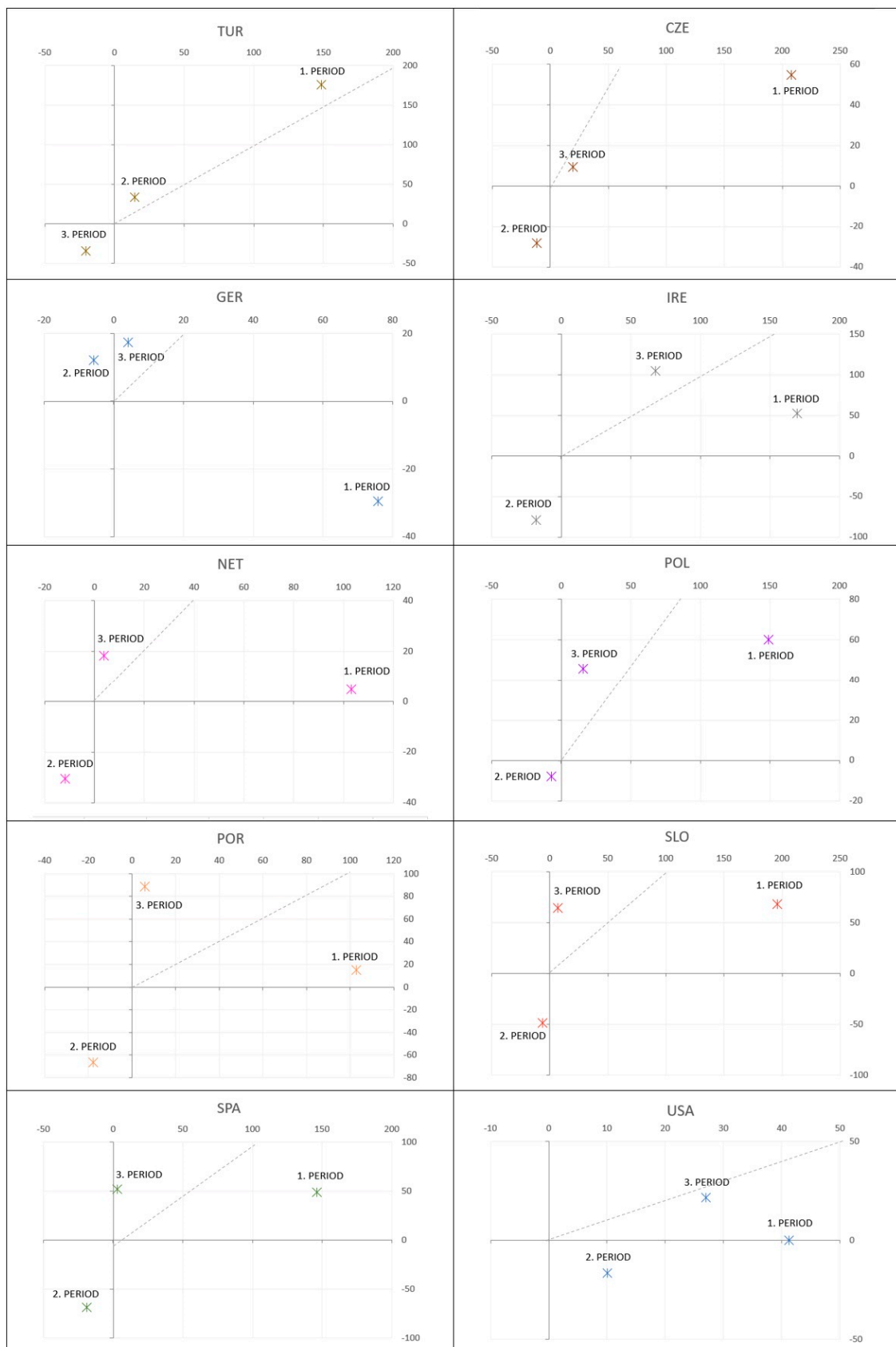


Figure 5. Coupling analysis for each of the 20 OECD countries.

Germany (GER) achieved absolute decoupling during the first period of the Kyoto Protocol, while Sweden (SWE), Norway (NOR), and the United States (USA) achieved it during the second period. However, the lack of observed absolute decoupling in the subsequent periods in these countries suggests that the reduction in CCO₂ levels may be due to factors such as periodic changes in production capacity in the construction sector rather than permanent solutions. In the final period of the protocol, absolute decoupling was observed in Switzerland and Belgium. According to Zhang et al., in 2015, both concrete and insulation materials each contributed to an annual increase of approximately 1.2 MtCO₂ in Switzerland. By 2055, the contribution of concrete is expected to decrease to around 0.4 MtCO₂ per year, while the contribution of insulation materials is expected to increase to approximately 1.6 MtCO₂ annually. This change indicates a focus on renovations rather than new construction in Switzerland [62]. This situation can be seen as the basis for the recent absolute decoupling observed in Switzerland. Although absolute decoupling has been observed in Switzerland recently, an examination of the per capita average CCO₂ results reveals that this country has reported the highest CO₂ emission values among the 20 OECD countries in all three periods. Belgium, another country that achieved absolute decoupling in the most recent period, produced 22.5 million tons of construction and demolition waste in 2018, accounting for more than 82% of the total construction and demolition waste. However, Belgium is considered one of the leading countries in Europe for recycling, as it recycles 90% of its construction and demolition waste [78,79]. Like Switzerland, Belgium achieved absolute decoupling in the most recent period by reducing their CCO₂ value while increasing their GDP. However, despite this, Belgium remains a country where the per capita CCO₂ value during the analysis periods is higher than the average of the 20 OECD countries. The decoupling status of these two countries should be carefully monitored in the future. Due to the global pandemic that began in the final months of 2019 and accelerated in 2020, there were shutdowns and reductions in work in the construction sector, as in many other sectors. Therefore, to monitor decoupling conditions in the future, realistic data obtained after the COVID-19 global pandemic was declared to be over (May 2023 [80]) must be used and a specific analysis period should be completed (at least 5 years for this study).

The limitation of this study is that the produced ready-mixed concrete quantities have not been classified according to grades or other characteristics. Therefore, the calculations were made using the average CO₂ emission values of concrete grades found in the literature.

6. Conclusions

Carbon emissions generated from human activities pose a rapidly escalating global issue that requires urgent attention. Research and reports indicate that the construction sector is contributing to the increase in carbon emissions. In this sector, one of the primary reasons for carbon formation is the use of concrete. Concrete is one of the most commonly used building materials, with an annual production of approximately 200 million cubic meters in EU countries. According to a report prepared by the Global Cement and Concrete Association (GCCA) in 2021, if no measures are taken by 2050, the global demand for concrete could result in 3.8 Gt of CO₂ emissions, with 11% of this coming solely from concrete production [19]. On the other hand, the construction sector is one of great importance in national economies. According to organizations such as the OECD and World Bank, it is necessary to separate environmental damage from economic benefits for sustainability [26]. For sustainable economic growth to be achieved in a country, environmental pollution should decrease despite increasing production. In other words, there should be a decoupling between economic growth and environmental degradation (CO₂ emissions, etc.).

This study was conducted to examine the decoupling status between CO₂ emissions from ready-mixed concrete production and the environmental degradation caused by economic growth for 20 OECD countries. This study was conducted in three separate periods, considering the pre-commitment period (2000–2007) of the Kyoto Protocol, the first commitment period (2008–2012), and the second commitment period (2013–2019). The 20 OECD countries included are Austria, Belgium, Czech Republic, Denmark, Finland, France, Germany, Ireland, Italy, the Netherlands, Poland, Portugal, Slovakia, Spain, Sweden, the United Kingdom, Norway, Switzerland, Turkey, and the United States. The United States did not commit to the Kyoto Protocol in either period. Turkey committed in the first period but did not commit in the second period. The other 18 countries committed to the protocol in both periods.

The annual concrete production quantities, gross domestic product (GDP), and population data for the 20 OECD countries in this study were obtained from the ERMCO, Eurostat, and World Bank databases. The carbon emission factor for concrete was calculated by the authors through a detailed literature review. The analyses were conducted in three stages and three separate periods for each of the 20 OECD countries. In the first stage, the CCO₂ emission values related to ready-mixed concrete production were analyzed. In the second stage, the per capita CCO₂ emission values were calculated. In the final stage, the decoupling status between CCO₂-related environmental degradation and economic growth was determined.

According to the findings of this study, the desired type of decoupling for sustainability, which is absolute decoupling, was identified in six countries. The first of these countries is the United States, and absolute decoupling occurred here in the second period. In the United States, relative decoupling was observed in the first and third periods. According to Jackson (2005), “it’s vital to distinguish between ‘relative’ and ‘absolute’ decoupling” [20]. Among the 20 OECD countries, the transition from relative decoupling to absolute decoupling in the United States, which has the highest CCO₂ emissions, population, and GDP values, is of great importance.

The other countries where absolute decoupling was observed are Sweden and Norway. In these countries, relative decoupling was observed in the first period, while absolute decoupling was identified with improvement in the second period. The CCO₂ and per capita CCO₂ values in Sweden are lower than the average of the 20 OECD countries in all three periods. In Norway, the per capita CCO₂ values are close to the average in the first two periods but above average in the last period. However, for this country, the CCO₂ values are below average in all periods. Nevertheless, the increase in the CCO₂ values and the decrease in the GDP after 2013 resulted in the most undesirable outcome of negative decoupling being identified in both countries in the third period.

This study’s findings indicate that Germany experienced absolute decoupling in the first period, which was before the Kyoto Protocol, and in the second and third periods, it experienced negative decoupling and coupling, respectively. In Germany, the CCO₂ emissions were above the average in each period. In this country, high CCO₂ values were observed in all periods of negative and positive growth.

According to the research, Switzerland experienced relative decoupling in the first two periods, while Belgium experienced relative decoupling in the first period and negative decoupling in the second period. Switzerland and Belgium achieved absolute decoupling in the last period, making them more successful in terms of decoupling compared to the other 18 countries examined. The findings of this study indicate that in these two countries, there was complete decoupling between CCO₂ emission-related environmental degradation and economic growth in the last period.

Turkey experienced coupling in all three stages. However, in the third stage, negative coupling was identified. It was observed that Turkey was the only country that did not experience any type of decoupling in these three periods. This means that in Turkey, there was an increase in the ΔCCO_2 values along with positive economic growth and a decrease in the ΔCCO_2 values along with negative economic growth. Additionally, Turkey was one of the five countries where economic growth was identified in the second period. In the second period, negative economic growth was calculated in all other countries except Sweden, Norway, Switzerland, the USA, and Turkey. However, in Turkey, significant increases were identified in both the average CCO_2 and per capita average CCO_2 emissions in each period.

In Czechia, it was observed that the average CCO_2 emissions and per capita average CCO_2 emissions increased in the second period and decreased in the third period. However, in all three periods, these values did not exceed the average values of the 20 OECD countries. In Czechia, an increase in the ΔCCO_2 value was observed along with positive economic growth, while a decrease in the ΔCCO_2 value was observed along with negative economic growth. The decoupling type for Czechia was identified as relative decoupling in the first and second periods, and negative coupling in the third period.

According to this study, Austria, Denmark, Ireland, the Netherlands, Poland, Portugal, Spain, Slovakia, and the United Kingdom all showed the same type of decoupling in all three periods. For these countries, relative decoupling was observed in the first period, negative coupling in the second period, and relative decoupling again in the third period. The negative growth experienced in the second period can be interpreted as being caused by the global economic crisis lasting from 2008 to 2012. According to this study, in the third period, there was a larger increase in CCO_2 values than in positive growth. In Spain, despite significant decreases in the CCO_2 values in each period, there was no decoupling between environmental degradation and economic growth.

In France, Italy, and Finland, relative decoupling was observed in the first period, while negative coupling was identified in the second period. This negative growth, which began in the second period, continued in the third period as well. With the negative growth in the last period, France and Finland were found to have ΔCCO_2 values below zero, while Italy had ΔCCO_2 values above zero.

According to the research findings, only two countries achieved decoupling between the environmental degradation caused by concrete production-related CO_2 emissions (CCO_2) and economic growth during the second commitment period of the Kyoto Protocol. Additionally, this study highlights that CO_2 emissions (CCO_2) from concrete production are still at high levels today. According to the GCCA (2021), a 25% reduction in the CO_2 per m^3 of concrete should be achieved by 2030 (compared to 2020 levels). As stated in the GCCA (2021) report, specifying CO_2 performance criteria in building and material standards and construction laws in both the public and private sectors will significantly contribute to achieving sustainability. Additionally, the use of low-carbon materials (such as low-carbon concrete) in the construction sector can increase countries' GDP while also achieving the target of absolute decoupling.

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Data Availability Statement: The data that support the findings of this study are available on request from the corresponding author.

Conflicts of Interest: The author declares no competing interests.

Appendix A

Table A1. Ready-mixed concrete production amount (RMC—million m³), gross domestic product (GDP—× 10⁹ USD), and population (P—million).

Country		2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	Av.
AUS	RMC	9.30	7.30	9.60	10.00	9.90	11.00	11.00	11.30	11.50	10.30	10.20	10.50	10.60	10.50	10.00	10.50	10.80	11.00	11.80	11.90	10.45
	GDP	197.29	197.51	214.39	262.27	301.46	316.09	336.28	389.19	432.05	401.76	392.28	431.69	409.40	430.19	442.58	381.97	395.84	417.26	454.99	444.60	362.45
	P	8.01	8.04	8.08	8.12	8.17	8.23	8.27	8.30	8.32	8.34	8.36	8.39	8.43	8.48	8.55	8.64	8.74	8.80	8.84	8.88	8.40
BEL	RMC	11.80	10.90	9.90	10.80	11.20	11.00	12.20	12.00	11.80	10.40	10.80	11.60	12.50	13.00	12.30	12.30	12.50	12.70	12.80	13.00	11.78
	GDP	236.79	236.75	258.38	318.08	369.21	385.71	408.26	470.92	517.33	483.25	481.42	523.33	496.15	521.79	535.39	462.34	476.06	502.76	543.30	535.87	438.16
	P	10.25	10.29	10.33	10.38	10.42	10.48	10.55	10.63	10.71	10.80	10.90	11.04	11.11	11.16	11.21	11.27	11.33	11.38	11.43	11.49	10.86
CZE	RMC	5.50	5.50	5.50	6.00	6.40	7.40	8.00	8.50	9.60	7.30	6.40	7.50	6.90	6.50	6.50	6.50	6.80	6.80	7.10	7.10	6.89
	GDP	61.83	67.81	82.20	100.09	119.81	137.14	156.26	190.18	236.82	207.43	209.07	229.56	208.86	211.69	209.36	188.03	196.27	218.63	249.00	252.55	176.63
	P	10.26	10.22	10.20	10.19	10.20	10.21	10.24	10.30	10.38	10.44	10.47	10.50	10.51	10.51	10.53	10.55	10.57	10.59	10.63	10.67	10.41
DEN	RMC	2.20	2.10	2.30	2.20	2.30	2.60	2.80	2.90	2.70	1.80	1.70	2.10	2.00	2.30	2.30	2.50	2.50	2.60	2.60	2.70	2.36
	GDP	164.16	164.79	178.64	218.10	251.37	264.47	282.88	319.42	353.36	321.24	322.00	344.00	327.15	343.58	352.99	302.67	313.12	332.12	356.84	346.50	292.97
	P	5.34	5.36	5.38	5.39	5.40	5.42	5.44	5.46	5.49	5.52	5.55	5.57	5.59	5.61	5.64	5.68	5.73	5.76	5.79	5.81	5.55
FIN	RMC	2.50	2.60	2.60	2.30	2.40	2.50	2.70	3.10	2.80	2.00	2.60	3.00	2.70	2.70	2.60	2.60	2.90	3.00	2.80	2.70	2.66
	GDP	126.02	129.53	140.40	171.65	197.48	204.89	217.09	256.38	285.72	253.50	249.42	275.60	258.29	271.36	274.86	234.53	240.77	255.65	275.71	268.51	229.37
	P	5.18	5.19	5.20	5.21	5.23	5.25	5.27	5.29	5.31	5.34	5.36	5.39	5.41	5.44	5.46	5.48	5.50	5.51	5.52	5.52	5.35
FRA	RMC	34.30	34.50	34.60	34.80	37.50	40.50	43.40	45.00	44.20	37.00	37.40	41.30	38.90	38.60	36.40	34.80	36.10	38.60	39.70	40.30	38.40
	GDP	1365.64	1377.66	1501.41	1844.54	2119.63	2196.95	2320.54	2660.59	2930.30	2700.89	2645.19	2865.16	2683.67	2811.88	2855.96	2439.19	2472.96	2595.15	2790.96	2728.87	2395.36
	P	60.92	61.37	61.82	62.26	62.72	63.19	63.63	64.02	64.38	64.71	65.03	65.35	65.66	66.00	66.31	66.55	66.72	66.92	67.16	67.39	64.60
GER	RMC	57.90	51.10	46.90	47.20	44.20	18.00	24.00	40.80	41.00	37.70	42.00	48.00	46.00	45.60	46.80	46.00	49.50	52.00	52.70	53.50	44.55
	GDP	1947.98	1945.79	2078.48	2501.64	2814.35	2846.86	2994.70	3425.58	3745.26	3411.26	3399.67	3749.31	3527.14	3733.80	3889.09	3357.59	3469.85	3690.85	3974.44	3889.18	3219.64
	P	82.21	82.35	82.49	82.53	82.52	82.47	82.38	82.27	82.11	81.90	81.78	80.27	80.43	80.65	80.98	81.69	82.35	82.66	82.91	83.09	82.00
IRE	RMC	5.90	6.00	7.50	7.50	8.50	10.00	9.20	9.00	10.00	3.80	2.70	2.40	2.10	2.10	2.40	2.40	4.20	4.30	4.30	4.30	5.43
	GDP	100.21	109.35	128.60	164.67	194.37	211.88	232.18	270.08	275.45	236.44	221.91	239.17	225.12	238.11	259.68	292.36	298.56	337.24	386.69	398.93	241.05
	P	3.81	3.87	3.93	4.00	4.07	4.16	4.27	4.40	4.49	4.54	4.56	4.58	4.60	4.62	4.66	4.70	4.76	4.81	4.87	4.93	4.43
ITA	RMC	66.50	66.80	71.50	72.80	72.80	77.40	77.50	75.20	73.20	56.30	53.20	52.60	39.90	31.70	28.00	25.30	27.40	27.30	27.30	28.40	52.56
	GDP	1146.68	1168.02	1276.77	1577.62	1806.54	1858.22	1949.55	2213.10	2408.66	2199.93	2136.10	2294.99	2086.96	2141.92	2162.01	1836.64	1877.07	1961.80	2091.93	2011.30	1910.29
	P	56.94	56.97	57.06	57.31	57.69	57.97	58.14	58.44	58.83	59.10	59.28	59.38	59.54	60.23	60.79	60.73	60.63	60.54	60.42	59.73	58.99
NET	RMC	8.50	8.50	8.10	8.30	7.80	8.60	8.50	8.90	10.50	9.30	8.10	8.80	7.30	6.60	6.50	6.30	6.50	6.90	7.50	7.80	7.97
	GDP	417.48	431.59	473.86	580.07	658.38	685.35	733.96	848.56	951.87	871.52	847.38	905.27	838.92	877.17	892.17	765.57	784.06	833.87	914.04	910.19	761.06
	P	15.93	16.05	16.15	16.23	16.28	16.32	16.35	16.38	16.45	16.53	16.62	16.69	16.75	16.80	16.87	16.94	17.03	17.13	17.23	17.34	16.60

Table A1. Cont.

Country		2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	Av.
POL	RMC	10.00	9.00	8.70	8.90	10.50	11.00	14.20	16.00	21.20	17.70	18.60	23.70	19.50	18.00	19.20	19.80	20.40	20.40	25.10	26.20	16.91
	GDP	172.22	190.91	199.07	217.83	255.11	306.15	344.63	429.02	533.60	439.73	475.70	524.37	495.23	515.76	539.08	477.11	470.02	524.64	588.78	596.06	414.75
	P	38.26	38.25	38.23	38.20	38.18	38.17	38.14	38.12	38.13	38.15	38.04	38.06	38.06	38.04	38.01	37.99	37.97	37.97	37.97	37.97	38.10
POR	RMC	10.00	11.30	10.50	9.50	11.50	12.00	11.00	11.50	11.00	8.50	7.50	6.10	3.70	2.70	2.80	2.80	3.20	3.70	4.50	5.10	7.45
	GDP	118.61	121.60	134.80	165.23	189.38	197.25	208.76	240.50	263.42	244.67	238.11	245.12	216.22	226.43	229.90	199.39	206.43	221.36	242.31	239.99	207.47
	P	10.29	10.36	10.42	10.46	10.48	10.50	10.52	10.54	10.56	10.57	10.57	10.56	10.51	10.46	10.40	10.36	10.33	10.30	10.28	10.29	10.44
SLO	RMC	1.90	1.90	1.90	2.10	2.40	2.70	2.90	3.20	3.70	2.60	2.40	2.30	1.90	1.70	1.60	1.90	1.90	2.40	3.00	2.80	2.36
	GDP	29.24	30.78	35.30	46.92	57.44	62.81	70.77	86.56	100.88	89.40	91.16	99.92	94.62	98.94	101.44	88.90	89.95	95.65	106.14	105.71	79.13
	P	5.39	5.38	5.38	5.37	5.37	5.37	5.37	5.37	5.38	5.39	5.39	5.40	5.41	5.41	5.42	5.42	5.43	5.44	5.45	5.45	5.40
SPA	RMC	64.00	71.10	73.50	81.00	82.00	87.60	97.80	95.30	69.00	49.00	39.10	30.80	21.60	16.30	15.90	16.30	16.30	19.70	22.20	24.80	49.67
	GDP	598.36	627.83	708.76	907.49	1069.06	1153.72	1260.40	1474.00	1631.86	1491.47	1422.11	1480.71	1324.75	1355.58	1371.82	1196.16	1233.55	1313.25	1421.70	1394.32	1221.85
	P	40.57	40.85	41.43	42.19	42.92	43.65	44.40	45.23	45.95	46.36	46.58	46.74	46.77	46.62	46.48	46.44	46.48	46.59	46.80	47.13	45.01
SWE	RMC	2.40	2.60	2.40	2.40	2.50	2.70	3.00	3.30	3.50	2.80	3.30	3.30	3.30	3.30	3.30	3.30	4.50	4.50	4.50	4.50	3.27
	GDP	262.84	242.40	266.85	334.34	385.12	392.22	423.09	491.25	517.71	436.54	495.81	574.09	552.48	586.84	581.96	505.10	515.65	541.02	555.46	533.88	459.73
	P	8.87	8.90	8.92	8.96	8.99	9.03	9.08	9.15	9.22	9.30	9.38	9.45	9.52	9.60	9.70	9.80	9.92	10.06	10.18	10.28	9.41
UK	RMC	23.00	23.00	23.00	25.00	25.00	25.20	25.10	25.60	20.50	15.80	15.70	19.20	17.60	19.60	22.70	23.70	24.60	22.90	25.70	24.90	22.39
	GDP	1665.53	1649.83	1785.73	2054.42	2421.53	2543.18	2708.44	3090.51	2929.41	2412.84	2485.48	2663.81	2707.09	2784.85	3064.71	2927.91	2689.11	2680.15	2871.34	2851.41	2549.36
	P	58.89	59.12	59.37	59.65	59.99	60.40	60.85	61.32	61.81	62.28	62.77	63.26	63.70	64.13	64.60	65.12	65.61	66.06	66.46	66.84	62.61
NOR	RMC	2.30	2.20	2.20	2.30	2.70	3.10	3.20	3.80	3.70	2.90	3.00	3.50	3.70	3.80	3.80	3.70	4.00	4.10	4.10	3.80	3.30
	GDP	171.46	174.24	195.91	229.39	265.27	309.98	346.92	402.64	464.92	387.98	431.05	501.36	512.78	526.01	501.74	388.16	370.96	401.75	439.79	408.74	371.55
	P	4.49	4.51	4.54	4.56	4.59	4.62	4.66	4.71	4.77	4.83	4.89	4.95	5.02	5.08	5.14	5.19	5.23	5.28	5.31	5.35	4.89
SWI	RMC	10.50	10.90	10.00	9.30	9.80	11.10	12.10	12.10	12.10	12.10	12.10	12.50	13.00	12.00	12.00	12.00	11.50	11.50	10.90	11.10	11.43
	GDP	279.22	286.58	309.30	362.08	403.91	418.28	441.63	490.74	567.27	554.21	598.85	715.89	686.42	706.23	726.54	694.12	687.90	695.20	725.57	721.37	553.57
	P	7.18	7.23	7.28	7.34	7.39	7.44	7.48	7.55	7.65	7.74	7.82	7.91	8.00	8.09	8.19	8.28	8.37	8.45	8.51	8.58	7.83
TUR	RMC	27.00	25.40	26.80	28.20	37.10	46.30	70.70	74.40	69.60	66.40	79.70	90.00	93.00	102.00	107.00	107.00	109.00	115.00	100.00	67.00	72.08
	GDP	274.29	201.75	240.25	314.60	408.87	506.31	557.08	681.32	770.45	649.29	776.97	838.79	880.56	957.80	938.93	864.31	869.68	858.99	778.97	761.01	656.51
	P	64.11	65.07	65.99	66.87	67.79	68.70	69.60	70.16	71.05	72.04	73.14	74.22	75.18	76.15	77.18	78.22	79.28	80.31	81.41	82.58	72.95
USA	RMC	315.00	315.00	300.00	310.00	330.00	345.00	330.00	315.00	270.00	243.00	243.00	203.00	225.00	230.00	230.00	260.00	65.00	270.00	274.00	280.00	267.65
	GDP	10,250.9	10,581.9	10,929.1	11,456.4	12,217.1	13,039.2	13,815.6	14,474.2	14,769.9	14,478.1	15,048.9	15,599.7	16,253.9	16,843.2	17,550.7	18,206.0	18,695.1	19,477.3	20,533.1	21,380.9	15,280.1
	P	282.16	284.97	287.63	290.11	292.81	295.52	298.38	301.23	304.09	306.77	309.33	311.58	313.88	316.06	318.39	320.74	323.07	325.12	326.84	328.33	306.85

Source: ERMCO, Eurostat, and World bank [16,45,70].

Appendix B

Table A2. CO₂ emission from ready-mixed conc. production (CCO₂—million tons) and CO₂ emission per capita from ready-mixed conc. production (CCO₂ per capita—ton/capita).

Country		2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	Av.
AUS	CCO ₂	2.80	2.20	2.89	3.01	2.98	3.31	3.31	3.40	3.46	3.10	3.07	3.16	3.19	3.16	3.01	3.16	3.25	3.31	3.55	3.58	3.15
	CCO ₂ per capita	0.35	0.27	0.36	0.37	0.36	0.40	0.40	0.41	0.42	0.37	0.37	0.38	0.38	0.37	0.35	0.37	0.37	0.38	0.40	0.40	0.37
BEL	CCO ₂	3.55	3.28	2.98	3.25	3.37	3.31	3.68	3.61	3.55	3.13	3.25	3.49	3.77	3.92	3.71	3.71	3.77	3.83	3.86	3.92	3.55
	CCO ₂ per capita	0.35	0.32	0.29	0.31	0.32	0.32	0.35	0.34	0.33	0.29	0.30	0.32	0.34	0.35	0.33	0.33	0.33	0.34	0.34	0.34	0.33
CZE	CCO ₂	1.66	1.66	1.66	1.81	1.93	2.23	2.41	2.56	2.89	2.20	1.93	2.26	2.08	1.96	1.96	1.96	2.05	2.05	2.14	2.14	2.08
	CCO ₂ per capita	0.16	0.16	0.16	0.18	0.19	0.22	0.24	0.25	0.28	0.21	0.18	0.22	0.20	0.19	0.19	0.19	0.19	0.19	0.20	0.20	0.20
DEN	CCO ₂	0.66	0.63	0.69	0.66	0.69	0.78	0.84	0.87	0.81	0.54	0.51	0.63	0.60	0.69	0.69	0.75	0.75	0.78	0.78	0.81	0.71
	CCO ₂ per capita	0.12	0.12	0.13	0.12	0.13	0.14	0.16	0.16	0.15	0.10	0.09	0.11	0.11	0.12	0.12	0.13	0.13	0.14	0.14	0.14	0.13
FIN	CCO ₂	0.75	0.78	0.78	0.69	0.72	0.75	0.81	0.93	0.84	0.60	0.78	0.90	0.81	0.81	0.78	0.78	0.87	0.90	0.84	0.81	0.80
	CCO ₂ per capita	0.15	0.15	0.15	0.13	0.14	0.14	0.15	0.18	0.16	0.11	0.15	0.17	0.15	0.15	0.14	0.14	0.16	0.16	0.15	0.15	0.15
FRA	CCO ₂	10.33	10.39	10.42	10.48	11.30	12.20	13.07	13.56	13.31	11.15	11.27	12.44	11.72	11.63	10.96	10.48	10.87	11.63	11.96	12.14	11.57
	CCO ₂ per capita	0.17	0.17	0.17	0.17	0.18	0.19	0.21	0.21	0.21	0.17	0.17	0.19	0.18	0.18	0.17	0.16	0.16	0.17	0.18	0.18	0.18
GER	CCO ₂	17.44	15.39	14.13	14.22	13.31	5.42	7.23	12.29	12.35	11.36	12.65	14.46	13.86	13.74	14.10	13.86	14.91	15.66	15.87	16.12	13.42
	CCO ₂ per capita	0.21	0.19	0.17	0.17	0.16	0.07	0.09	0.15	0.15	0.14	0.15	0.18	0.17	0.17	0.17	0.17	0.18	0.19	0.19	0.19	0.16
IRE	CCO ₂	1.78	1.81	2.26	2.26	2.56	3.01	2.77	2.71	3.01	1.14	0.81	0.72	0.63	0.63	0.72	0.72	1.27	1.30	1.30	1.30	1.64
	CCO ₂ per capita	0.47	0.47	0.57	0.57	0.63	0.72	0.65	0.62	0.67	0.25	0.18	0.16	0.14	0.14	0.16	0.15	0.27	0.27	0.27	0.26	0.38
ITA	CCO ₂	20.03	20.12	21.54	21.93	21.93	23.32	23.35	22.65	22.05	16.96	16.03	15.84	12.02	9.55	8.43	7.62	8.25	8.22	8.22	8.55	15.83
	CCO ₂ per capita	0.35	0.35	0.38	0.38	0.38	0.40	0.40	0.39	0.37	0.29	0.27	0.27	0.20	0.16	0.14	0.13	0.14	0.14	0.14	0.14	0.27
NET	CCO ₂	2.56	2.56	2.44	2.50	2.35	2.59	2.56	2.68	3.16	2.80	2.44	2.65	2.20	1.99	1.96	1.90	1.96	2.08	2.26	2.35	2.40
	CCO ₂ per capita	0.16	0.16	0.15	0.15	0.14	0.16	0.16	0.16	0.19	0.17	0.15	0.16	0.13	0.12	0.12	0.11	0.11	0.12	0.13	0.14	0.14
POL	CCO ₂	3.01	2.71	2.62	2.68	3.16	3.31	4.28	4.82	6.39	5.33	5.60	7.14	5.87	5.42	5.78	5.96	6.15	6.15	7.56	7.89	5.09
	CCO ₂ per capita	0.08	0.07	0.07	0.07	0.08	0.09	0.11	0.13	0.17	0.14	0.15	0.19	0.15	0.14	0.15	0.16	0.16	0.16	0.20	0.21	0.13
POR	CCO ₂	3.01	3.40	3.16	2.86	3.46	3.61	3.31	3.46	3.31	2.56	2.26	1.84	1.11	0.81	0.84	0.84	0.96	1.11	1.36	1.54	2.24
	CCO ₂ per capita	0.29	0.33	0.30	0.27	0.33	0.34	0.31	0.33	0.31	0.24	0.21	0.17	0.11	0.08	0.08	0.08	0.09	0.11	0.13	0.15	0.21
SLO	CCO ₂	0.57	0.57	0.57	0.63	0.72	0.81	0.87	0.96	1.11	0.78	0.72	0.69	0.57	0.51	0.48	0.57	0.57	0.72	0.90	0.84	0.71
	CCO ₂ per capita	0.11	0.11	0.11	0.12	0.13	0.15	0.16	0.18	0.21	0.15	0.13	0.13	0.11	0.09	0.09	0.11	0.11	0.13	0.17	0.15	0.13

Table A2. Cont.

Country		2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	Av.
SPA	CCO ₂	19.28	21.42	22.14	24.40	24.70	26.39	29.46	28.71	20.78	14.76	11.78	9.28	6.51	4.91	4.79	4.91	4.91	5.93	6.69	7.47	14.96
	CCO ₂ per capita	0.48	0.52	0.53	0.58	0.58	0.60	0.66	0.63	0.45	0.32	0.25	0.20	0.14	0.11	0.10	0.11	0.11	0.13	0.14	0.16	0.34
SWE	CCO ₂	0.72	0.78	0.72	0.72	0.75	0.81	0.90	0.99	1.05	0.84	0.99	0.99	0.99	0.99	0.99	0.99	1.36	1.36	1.36	1.36	0.99
	CCO ₂ per capita	0.08	0.09	0.08	0.08	0.08	0.09	0.10	0.11	0.11	0.09	0.11	0.11	0.10	0.10	0.10	0.10	0.14	0.13	0.13	0.13	0.10
UK	CCO ₂	6.93	6.93	6.93	7.53	7.53	7.59	7.56	7.71	6.18	4.76	4.73	5.78	5.30	5.90	6.84	7.14	7.41	6.90	7.74	7.50	6.74
	CCO ₂ per capita	0.12	0.12	0.12	0.13	0.13	0.13	0.12	0.13	0.10	0.08	0.08	0.09	0.08	0.09	0.11	0.11	0.11	0.10	0.12	0.11	0.11
NOR	CCO ₂	0.69	0.66	0.66	0.69	0.81	0.93	0.96	1.14	1.11	0.87	0.90	1.05	1.11	1.14	1.14	1.11	1.20	1.24	1.24	1.14	0.99
	CCO ₂ per capita	0.15	0.15	0.15	0.15	0.18	0.20	0.21	0.24	0.23	0.18	0.18	0.21	0.22	0.23	0.22	0.21	0.23	0.23	0.23	0.21	0.20
SWI	CCO ₂	3.16	3.28	3.01	2.80	2.95	3.34	3.64	3.64	3.64	3.64	3.64	3.77	3.92	3.61	3.61	3.61	3.46	3.46	3.28	3.34	3.44
	CCO ₂ per capita	0.44	0.45	0.41	0.38	0.40	0.45	0.49	0.48	0.48	0.47	0.47	0.48	0.49	0.45	0.44	0.44	0.41	0.41	0.39	0.39	0.44
TUR	CCO ₂	8.13	7.65	8.07	8.49	11.18	13.95	21.30	22.41	20.97	20.00	24.01	27.11	28.01	30.73	32.23	32.23	32.83	34.64	30.12	20.18	21.71
	CCO ₂ per capita	0.13	0.12	0.12	0.13	0.16	0.20	0.31	0.32	0.30	0.28	0.33	0.37	0.37	0.40	0.42	0.41	0.41	0.43	0.37	0.24	0.29
USA	CCO ₂	94.89	94.89	90.37	93.38	99.41	103.92	94.89	94.89	81.33	73.20	73.20	61.15	67.78	69.28	69.28	78.32	19.58	81.33	82.54	84.34	80.40
	CCO ₂ per capita	0.34	0.33	0.31	0.32	0.34	0.35	0.33	0.31	0.27	0.24	0.24	0.20	0.22	0.22	0.22	0.24	0.06	0.25	0.25	0.26	0.27

Source: CCO₂ and CCO₂ per capita were calculated by the author.

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