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Greenhouse gas emission accounting for EU member states from 1991 to 2012

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HIGHLIGHTS

- GHG emissions for the EU28 during 1991–2012 are accounted.
- The EU28 are classified into four groups based on GHG emission structure.
- It can facilitate classified management of GHG emissions.
- The EU case shows the common but differentiated principle in emission reduction.

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ABSTRACT

Collectively, the EU is among the world's largest greenhouse gas (GHG) emitters, though remarkable decreases in GHG emissions have been observed in recent years. In this work the GHG emissions for the 28 EU member states between 1991 and 2012 are accounted for and compared according to the inventory method of the Intergovernmental Panel on Climate Change (IPCC). The structure of GHG emissions at a national level, their distribution between countries, and trends across the period are then analyzed. National emission sources and sinks are decomposed for each country to elucidate the contribution of each sector (energy, industrial processes, solvents and other product use, agriculture, land use/land-use change and forestry, and waste) to the national totals. Germany was the largest emitter, with net emissions totaling 939 Tg CO_2 equivalent in 2012, 60% more than the UK and 89% more than France, the second and third biggest emitters, respectively. The energy sector and agriculture were found to be the largest sources of emissions in most countries. Four quadrants were established to compare countries' performance in emission intensity, carbon removal rate, and net reduction rate of GHG emissions. Slovenia, Portugal, Sweden, and Finland were located in Quadrant II as they displayed relatively low emission intensities and high carbon removal rates. Conversely, Hungary, Greece, Cyprus, the Czech Republic, and Poland were located in Quadrant IV because of their relatively high emission intensities and low carbon removal rates. Some suggestions for integrating the annual results and the trends both within and among countries into national and regional emissions reduction strategies are also included. The unified accounting framework and analysis of the structure of GHG emissions may also be useful for other countries and regions.

1. Introduction

The European Union (EU) is a pioneer in mitigating climate change. In 1996, the European Commission recommended that the rise in global temperature should be limited to 2 °C above pre-industrial levels [1]. In March 2007, EU Prime Ministers agreed upon a post-Kyoto target, committing to a unilateral greenhouse gas (GHG) emission reduction target of 20% by 2020 compared with 1990 levels, and agreeing to a reduction of 30%, provided that other major emitters agreed to take on their fair share in a global effort to decrease emissions [1–4]. For the second commitment period of the Kyoto Protocol (2013–2020), which was established in Doha in 2012, the Member States of the EU (EU28) and Iceland also agreed to a 20% reduction compared to the base year [2].

Various policies, projects, and mechanisms have been proposed to decrease EU GHG emissions. One key climate policy instrument

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is the emissions trading system (ETS). Launched in 2005, this is regarded as the world's largest multi-country, multi-sector GHG ETS, covering more than 12,000 installations and airlines across the EU28, Iceland, Norway and Liechtenstein [5,6]. In total, the EU ETS covers around 45% of EU GHG emissions [6,7]. Another relevant policy, which has been in force since January 2013, is the European Industrial Emissions Directive. This requires industrial installations to be equipped with best available technologies (BAT) and sets new limits on emissions from, for example, large combustion plants [8]. Waste management has also been a focus of EU environmental policy since the early 1970s with targets and objectives being increased year-on-year. For example, the Low Cost-Zero Waste Municipality project (ZERO WASTE), which began in 2009, aims to develop an integrated zero waste management system for municipalities based on reducing, reusing, and recycling waste that would otherwise be sent to landfill sites [4]. In addition, the EU has a strong record of developing renewable energy sources [9]. For instance, the region produced almost 65% of the world's biodiesel in 2008 [10,11].

Remarkable decreases in emissions have been observed in the EU following the implementation of these policies and mechanisms. Indeed, GHG emissions for the EU28 plus Iceland, fell by 4.1% between 2013 and 2014 (by 185.4 million tonnes to 4301 Tg CO_2 equivalent) to almost a quarter less than 1990 levels [2]. Most of this decrease is attributed to a decrease in energy intensity and an increase in the use of zero-carbon energy sources [12]. In 2013, the mean per capita emissions of CO_2 in the EU was 7.3 tonnes, a little less than that of China (7.4 tonnes) and less than half the level in the USA (16.6 tonnes). In terms of emissions per unit of GDP, emissions intensity in the EU (0.22 kg CO_2/USD) was a third lower than in the US (0.33 kg CO_2/USD) and nearly two-thirds lower than that in China (0.65 kg CO_2/USD) [13]. Nonetheless, the EU remains one of the world's largest GHG emitters [14], even if its proportion of global CO_2 emissions decreased from 16% in 2004 [1] to 11% in 2013 [13] and to 10% in 2014 [15].

Various EU departments and institutions have published reports that specifically address GHG emissions. These include reports that cover a range of subjects including previous emissions [3,5,16], different accounting perspectives [17], trends in the EU ETS [18], future predictions [12,18], and reports covering subregions [19,20], collections of member states [21–29], and cities [30].

Research has also been published that focuses on sector-specific emissions, including emissions from agriculture [31–34], livestock [35], transportation [36–38], retail [39], paper production [40], and waste recycling and management [4,41,42]. Within the different sectors, the main contributors to GHG emissions in the EU include fuel combustion by energy industries, transport, manufacturing and construction, and agriculture [2]. Because of energy production's leading contribution, special attention has been paid to renewable energy and the ETS. While the promotion of renewable energy resources has significantly decreased GHG emissions in the EU [43–45], GHG emissions from installations included in the ETS decreased by 24% between 2005 and 2014. This falling trend is set to continue with ETS emissions in 2020 and 2030 at least 26% and 31% below 2005 levels, respectively [18].

Further studies focusing on GHG emissions in the EU also exist. These include investigating the relationship between emissions and air pollution [46,47], estimating the potential for decreasing emissions [48], and analyzing the underlying reasons behind changes in GHG emissions [43,49–51]. An increase in GHG emissions in the EU in 2010 spurred many researchers to investigate the impact of various aspects on total emissions (including the contribution of different member states, sectors and types of GHG) [3,52]. A number of studies also applied decomposition analysis to interrogate the impact on GHG emissions of economic development, population growth, the energy mix, energy efficiency, and emission intensity [1,53–55].

Despite this body of work, two issues remain unclear: (1) how to establish a common platform to comprehensively compare the performance of different member states in terms of GHG emissions; and (2) how to implement differentiated GHG management strategies in the different member states based on their GHG emissions performance to date. Correspondingly, the aim of this paper is twofold. First, a generalized concept of emission structure is applied to summarize and analyze the EU GHG emission characteristics from different spatial and temporal scales. Second, the EU member states are grouped based on their emission characteristics to aid with the design of differentiated management strategies.

2. Methodology

2.1. Procedure of GHG emission accounting

The basic procedure of GHG emission accounting generally includes five steps:

(1) Identifying the spatial and temporal boundary of GHG emissions. Specifically, the GHG emissions of the EU28 from 1991 to 2012 were used in this case study. The EU28 were chosen because of their leading stance on decreasing emissions and the political and economic similarities between the nations.
(2) Establishing a unified accounting framework for GHG emissions to facilitate comparisons among different nations. This involves considering the accounting framework (top-down or bottom-up); the methodology (inventory, input–output, or other models); and how to assess variation between sectors and GHG gases. In this study a bottom-up framework was adopted using the inventory method of the Intergovernmental Panel on Climate Change (IPCC) to also include the contribution to total emissions of different sectors.
(3) Creating the emissions inventory. This is where the sectors, the processes within those sectors, and the emissions factors of each GHG are detailed. In this work, the emission inventory included six types of GHG (CO_2, CH_4, N_2O, hydrofluorocarbons, perfluorocarbons, and SF_6), emitted by six sectors (energy, industrial processes (IP), solvents and other product use (SOPU), agriculture, land use/land-use change and forestry (LULUCF), and waste), in accordance with the 2006 IPCC guidelines for national GHG inventories [56].
(4) Compiling and assimilating data. Data in this study was sourced from the national inventory report and common reporting format 1990–2012, submitted in April 2014 under the United Nations Framework Convention on Climate Change (UNFCCC) and the Kyoto Protocol [57]. Over 70 tables were drawn from this resource to provide detailed data on GHG emissions and removals across the studied period.
(5) Analyzing the annual characteristics of GHG emissions and their trends over time. The composition of GHG emissions represented by sector contributions for each EU member state at a specific time was used as a proxy for the static emission characteristics. Changes in the relative performance of different states in terms of GHG emissions during 1991–2012 were used as proxies for the dynamic emission characteristics.

2.2. Calculation of GHG emissions

2.2.1. Absolute emission quantity

First, the GHG emissions of each sector (or gas) in a specific country were calculated by summing the emissions of different gases (or sectors) from different activities, as shown in Eqs. (1)–(3):

$$E_{ijp} = \sum_{k=1}^{n} A_{ijk} \times F_{ijpk}, \quad (1)$$

$$E_{ij} = \sum_{p=1}^{m} E_{ijp} \times GWP_p, \quad (2)$$

$$E_{ip} = GWP_p \times \sum_{j=1}^{q} E_{ijp}, \quad (3)$$

where E is the emission amount; A is the activity data (such as the amount of fuel consumed or produced, the quantity of industrial products produced or consumed, the livestock population, or the area of land use change); and F is the emission factor. GWP_p is the global warming potential of gas p compared with an equivalent mass of CO_2. The concrete values for different gases can be referred to IPCC's guideline [58,59]. n is the total number of activities (k) in each sector (j); m is the total number of types of gas, and q is the total number of sectors in each country (i).

The GHG emissions of each country were then obtained by summing the emissions of the different sectors, as shown in Eq. (4):

$$E_i = \sum_{j=1}^{q} E_{ij} = \sum_{p=1}^{m} E_{ip}, \quad (4)$$

2.2.2. Relative emission quantity

The contributions of different sectors or gases to total GHG emissions were obtained by calculating their relative proportions, as shown in Eqs. (5) and (6):

$$C_{ij} = \frac{E_{ij}}{E_i} \times 100\%, \quad (5)$$

$$C_{ip} = \frac{E_{ip}}{E_i} \times 100\%, \quad (6)$$

where C_{ij} is the contribution of sector j to the total GHG emissions in country i and C_{ip} is the contribution of gas p to the total GHG emissions in country i.

Besides the purely emission side, other factors closely related to GHG emissions were also considered to reflect the emission characteristics. For instance, the emission intensities for each country were calculated by Eq. (7) to reflect the ratio of GHG emissions to the country's gross domestic product (GDP):

$$I_i = \frac{E_i}{\mathrm{GDP}_i}, \quad (7)$$

where I_i is the emission intensity of country i.

2.2.3. Trends in GHG emissions

The calculations above obtained GHG emissions for a specific year but a wider dataset allowed the change in GHG emissions to be further investigated to elucidate trends over time. For example, Eq. (8) shows how the annual net reduction in GHG emissions was calculated:

$$R_{i,t} = \frac{E_{i,t-1} - E_{i,t}}{E_{i,t-1}} \times 100\%, \quad (8)$$

where $R_{i,t}$ is the annual net reduction of GHG emissions in country i in year t. Here net emissions means that both GHG emissions (source) and removals (sink) were considered. Values $R_{i,t}$ of were then averaged over several multi-year periods to investigate longer term trends.

2.3. Analysis of GHG emissions

GHG emission structure is proposed to analyze the characteristics of GHG emissions, which is defined in this paper as the composition and configuration of GHG emissions within a certain temporal and spatial scope. As a concept with both specialized and generalized meanings, it involves the features of both static status and dynamics of GHG emissions. Furthermore, both the internal composition of GHG emissions for a specific study unit (specified as an EU member state herein), and the distribution of GHG emissions among different study units need to be considered.

2.3.1. Annual GHG emissions

The amount of GHG emissions from each sector and the proportional contribution to total GHG emissions were used to analyze annual GHG emissions for the EU28. Because LULUCF mostly acts as a GHG sink in the EU28 [49], it was assessed individually to more clearly identify the amount of GHGs removed and the carbon removal rate, which is the amount of GHG removal by LULUCF divided by the total GHG emissions excluding LULUCF. The decomposition of source and sink also gives a profile analysis of GHG emission structure.

2.3.2. Trends in GHG emissions

Three indicators were chosen to reflect trends in GHG emissions between countries: the carbon emission intensity (expressing the emission source, and the relative quantity of emissions to the economic factors); the carbon removal rate (expressing the sink, and the relative quantity of carbon removals to emissions); and the net reduction rate of GHG emissions (expressing the net emissions integrating source and sink, and the trends in emission reduction). Averaging the indicators over several years helped to minimize the impact of outlying events. The 1991–2012 period was therefore divided into four smaller intervals (1991–1996, 1997–2002, 2003–2008, and 2009–2012).

Using the method of four quadrants, the EU28 were then classified into different groups based on their emission intensity (horizontal axis) and their carbon removal rate (vertical axis). Annual net reduction in GHG emissions was then represented by the size and color of the bubbles. The center point of the four quadrants was where the average values of the first two indicators met.

2.4. Study area

All the 28 EU member states (at July 2013) are considered; these were Austria, Belgium, Bulgaria, Croatia, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, Netherlands, Poland, Portugal, Romania, Slovakia, Slovenia, Spain, Sweden, and United Kingdom. The similarity of political environment and economic condition as well as the smooth communication among the EU member states makes the comparisons of their GHG emissions more feasible and effective.

3. Results

3.1. GHG emissions in the EU28 in 2012

3.1.1. GHG emission source

The contribution of each sector to the total GHG emissions for EU member states, including absolute emission quantities and relative proportions, is shown in Fig. 1 for 2012. Germany emitted more GHGs than other state in 2012; 60% more than the UK and 89% more than France, the second and third biggest emitters, respectively. Germany's emissions were also 299 greater than those of Malta and 101 times greater than those of Cyprus, the two smallest emitters. Similar relationships were also observed at a sectoral level: for example, Germany's energy sector produced more emissions than any other.

Disaggregating by source, emissions were generally produced according to the following order: energy, agriculture, IP, waste, and SOPU. In some nations the order of agriculture, IP, and waste varied but the energy sector was always the dominant emissions producer while SOPU was always the smallest contributor, in agreement with previous studies [2,3]. In fact, SOPU's emissions were too small to be included in Fig. 1.

3.1.2. GHG sink

Fig. 2 shows GHG removal by LULUCF in 2012 both in terms of the absolute quantity of GHGs removed and the carbon removal rate.

In terms of the absolute quantity of GHG removed, the LULUCF contributed the largest amount in France in 2012; removing as much as 25% and 32% more than in the second and third ranked countries, Sweden and Spain, and as much as 6131 and 2300 times that in the last first and last second ranked countries showing the removal effect, Malta and Cyprus. In the Netherlands, LULUCF acted as a carbon emitter, producing 3.54 Tg CO_2 equivalent. With respect to the relationship of the carbon removal rate of LULUCF to GHG emissions, Latvia ranked first, with a removal rate of 112%, Sweden and Finland followed with a removal rate of 61% and 42% respectively. The carbon removal rate was less than 0.4% in Cyprus, Malta, and Germany.

3.1.3. Net GHG emissions

Combining GHG sources and sinks, Fig. 3 shows the net GHG emissions for the EU28 in 2012. The relatively small contribution from GHG sinks means that the trend in Fig. 3 was similar to that in Fig. 1 with the eight largest emitters remaining the same. Toward the right hand side of the figure, Croatia, Estonia, Slovenia, Lithuania, Luxembourg, Cyprus, and Malta continued to be the smallest GHG emitters on a net basis. Latvia was the only nation in the EU28 to report net GHG removal in 2012.

3.2. Trends in GHG emissions

Fig. 4 shows the averaged trend indicators for the 1991–1996 and 2009–2012 periods. Although the trends for some nations varied, collectively, the majority of nations remained in Quadrant III (see Table 1 and below for quadrant characteristics).

Table 1 summarizes the distribution of nations across the quadrants for each of the four periods. Choosing the situation in 2009–2012 as an example, Slovakia, Romania, Croatia, Lithuania, Latvia, Bulgaria, and Estonia were located in Quadrant I, which features relatively high emission intensities and relatively high carbon removal rates. Slovenia, Portugal, Sweden, and Finland were located in Quadrant II (relatively low emission intensities and relatively high carbon removal rates). Hungary, Greece, Cyprus, Czech Republic, and Poland were located in Quadrant IV (relatively high emission intensities and relatively low carbon removal rates). The other 12 countries were located in Quadrant III (relatively low emission intensities and relatively low carbon removal rates).

Unlike in 1991–1996 (see Fig. 2(a)), most countries decreased net GHG emissions between 2009 and 2012 (Fig. 2(b)) with Latvia, Slovakia, Denmark, Hungary, Greece, Spain, and Croatia reporting the fastest decreases in net GHG emissions. Malta, and particularly, Estonia and Finland saw net emissions grow over the period.

3.3. Trends in GHG emissions 1991–2012

Fig. 5 shows the location of each nation between and within the quadrants across the four periods and also offers a way of interpreting the position of each nation compared with other nations. Taking the situation during 2009–2012 (purple arrows) as an example, QII contained Sweden, Portugal, Finland, and Slovenia, which were the best performing nations of the EU28. Within this group, Sweden reported the lowest emission intensity, while Slovenia reported the highest emission intensity. Finland was the only one of these nations to report an increase in net GHG emissions over this period.

Moreover, Fig. 5 also displays trends across the entire period for each country. Most countries remained in the same quadrant throughout. This suggested that the position of each nation relative

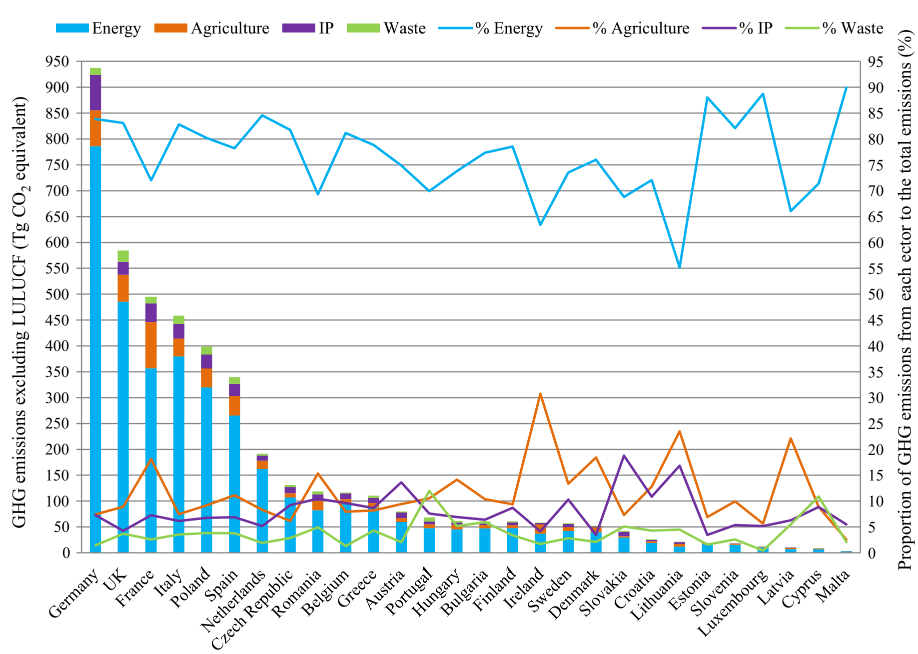

Fig. 1. The contribution of different sectors to GHG emissions in the EU28 in 2012.

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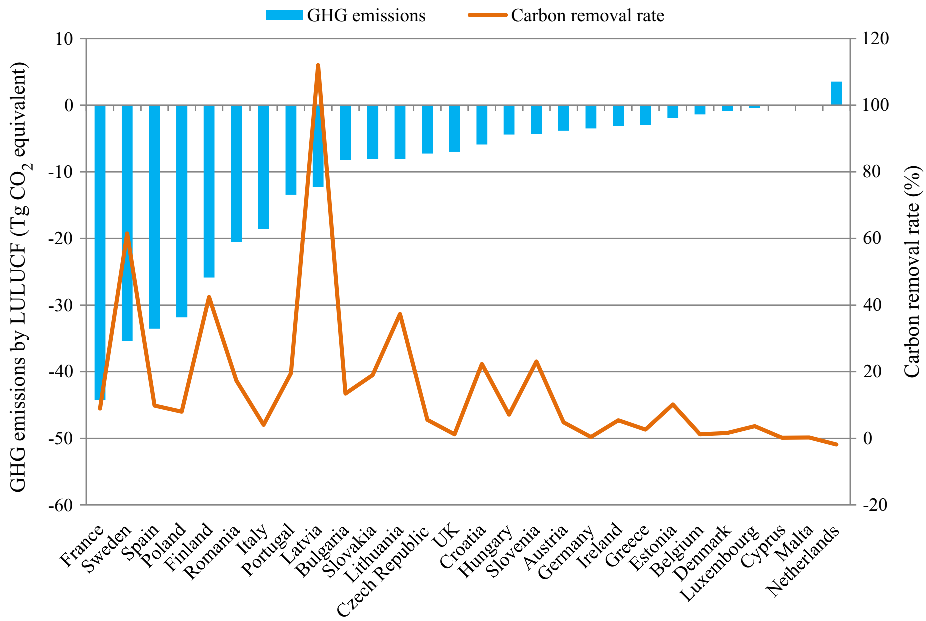

Fig. 2. The amount of GHG emissions by LULUCF and the related carbon removal rate in the EU28 in 2012. Here, negative values for GHG emissions by LULUCF reflect net GHG removal by the sector. The carbon removal rate is expressed by dividing the amount of GHG removal by LULUCF by the amount of GHG emissions excluding LULUCF.

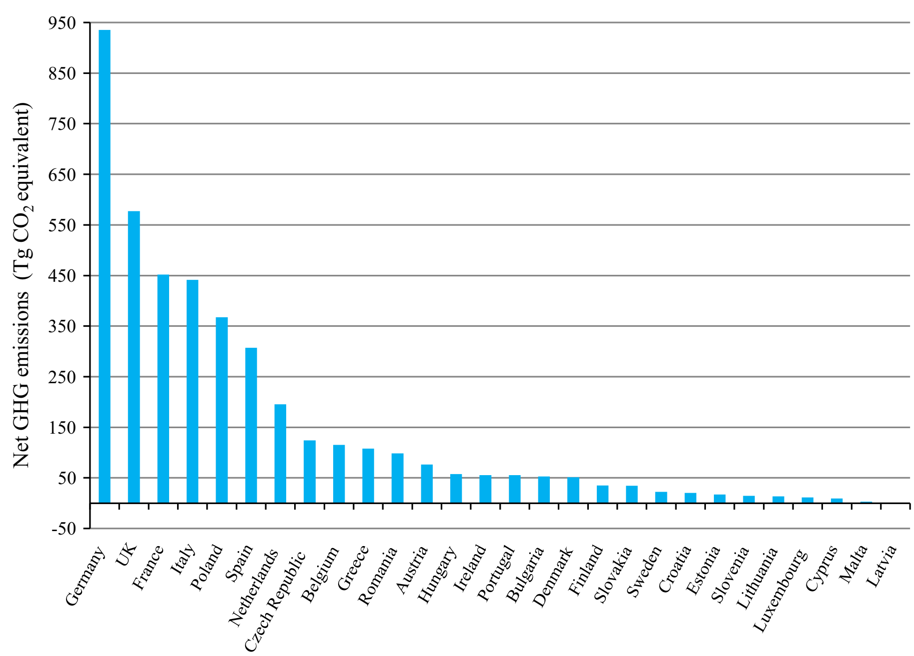

Fig. 3. The amount of net GHG emissions in the 28 EU member states in 2012.

to the EU28 average was largely unchanged and is likely attributed to the fact that emissions are tied to relatively stable factors such as population, economic growth, economic structure, and domestic consumption patterns. Nonetheless, Austria's position fell from Q II to Q III when the carbon removal rate declined during 2003–2008 just after Slovenia's position had risen in the previous period for the opposite reasons. Even though Croatia's emission intensity fell during the 1999–2002 period, its position fell from Q II to Q I. Similarly, although the carbon intensity of Cyprus and Greece fell from QIII to QIV in 2009–2012, both countries saw their positions in the quadrant fall. In these cases, other countries also made efforts to reduce their emission intensity and caused the average value to decrease faster than the values in Croatia, Cyprus and Greece. Fluctuations in its carbon removal rate saw Estonia first fall from Q I to Q IV during 1997–2002 before rising back to Q I during 2003–2008, while Poland experienced the opposite trajectory during 2003–2008 and 2009–2012.

Despite being some of the largest net emitters in absolute terms, Germany, UK, France, Italy, and Spain were located in Q III because of their relatively low emission intensity. However, Poland, which was also a large net emitter, was located in Q IV because of its relatively high emission intensity. Emitting relatively small amounts of GHGs during the study period, Slovenia, Cyprus, Malta, and Luxembourg were located in Q III because of their relatively low emission intensities. Conversely, Latvia and Estonia were located in Q I because of their relatively high emission intensities.

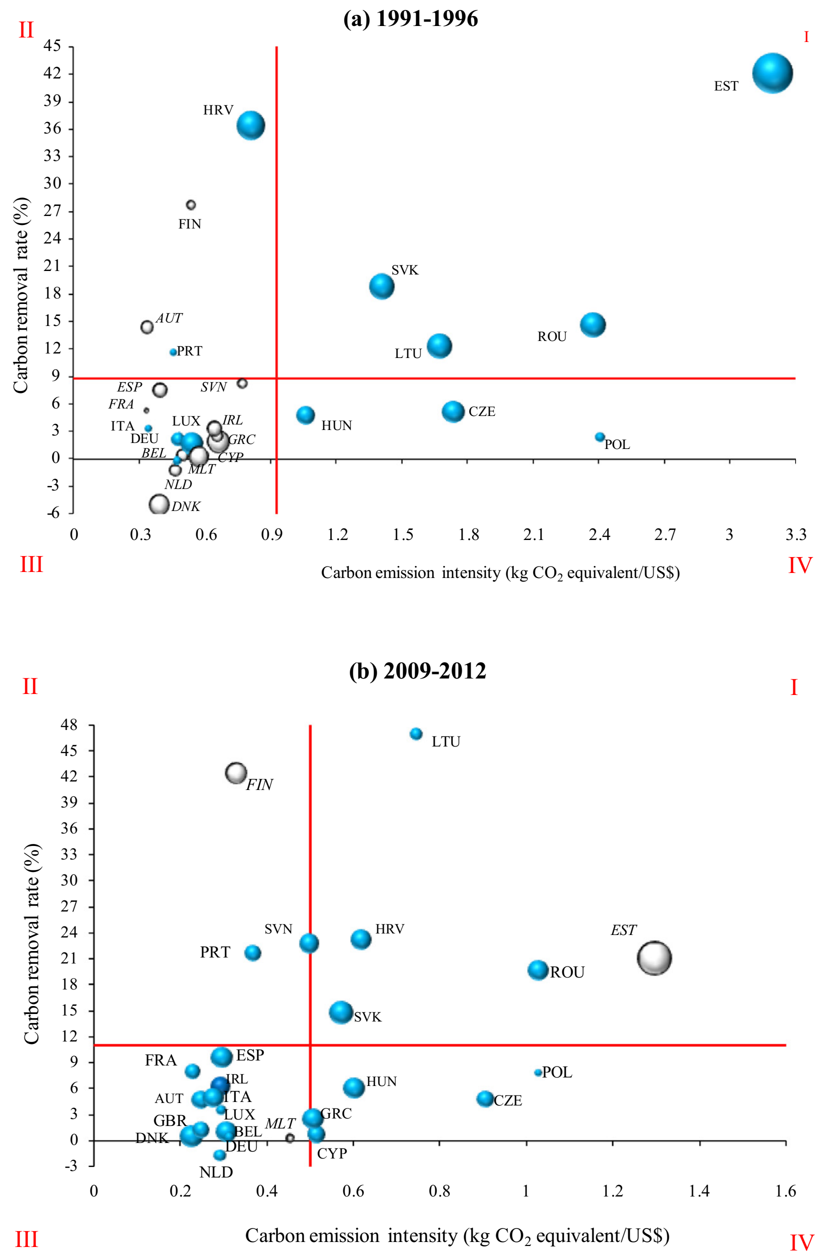

Fig. 4. The grouping results for the EU28 based on GHG emissions during (a) 1991–1996 and (b) 2009–2012. A larger bubble indicates a higher average net reduction rate in GHG emissions during the period. Blue indicates a positive net reduction rate; and grey indicates a negative net reduction rate (the corresponding names are written in italics). Note that for clarity, outlying results for Bulgaria (QI), Latvia (QI), and Sweden (QII) were not displayed. AUT: Austria, BEL: Belgium, HRV: Croatia, CYP: Cyprus, CZE: Czech Republic, DNK: Denmark, EST: Estonia, FIN: Finland, FRA: France, DEU: Germany, GRC: Greece, HUN: Hungary, IRL: Ireland, ITA: Italy, LTU: Lithuania, LUX: Luxembourg, MLT: Malta, NLD: Netherlands, POL: Poland, PRT: Portugal, ROU: Romania, SVK: Slovakia, SVN: Slovenia, ESP: Spain, GBR: United Kingdom. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Aside from Malta, all countries reduced emissions for at least one of the four periods and in 2009–2012, 25 countries reported decreases in net GHG emissions. Even Latvia, the country with the smallest net emissions, reduced net emissions in three of the four periods. Three countries (Germany, UK, and Hungary) effected net emission decreases over the whole period providing confidence for future emission-reduction pathways (especially in Germany and the UK).

4. Discussion

4.1. The importance of a comprehensive analysis of GHG emissions

The analysis in this work included annual GHG emissions and changing trends over time. Moreover, it revealed the structure of GHG emissions within a country, highlighted how emissions compared between countries, and established the relationship between emission sources and sinks. This finer detail that marries in-country emissions with changes observed at a regional level is useful for decision-making within countries and for negotiation between them, and would not be possible if only single-country or regional analyses were performed. For instance, if only the internal GHG emission structure was considered, Latvia would have appeared to have performed well by maintaining low GHG emissions and a high carbon removal rate. However, its unchanged location in Q I reminds us of Latvia's urgent need to reduce its emission intensity. Conversely, continual decrease in net GHG emissions only available from the national data offers hope in the case of Hungary, which was located in Q IV throughout the

Table 1
Characteristics of quadrants and their population by EU28 nations.

Qua.	Feature	1991–1996		1997–2002	
		Net reduction	Net growth	Net reduction	Net growth
I	Relatively high emission intensity and high carbon removal rate	EST, SVK, LTU, ROU, BGR, LVA		ROU, SVK, LTU, BGR, LVA	HRV
II	Relatively low emission intensity and high carbon removal rate	HRV, PRT	AUT, FIN, SWE	SVN, SWE	PRT, AUT, FIN
III	Relatively low emission intensity and low carbon removal rate	LUX, DEU, ITA, GBR	DNK, MLT, CYP, ESP, GRC, IRL, SVN, NLD, BEL, FRA	DNK, GBR, DEU, NLD, BEL, FRA	ESP, CYP, GRC, IRL, ITA, MLT, LUX
IV	Relatively high emission intensity and low carbon removal rate	CZE, HUN, POL		POL, CZE, HUN	EST
		2003–2008		2009–2012	
		Net reduction	Net growth	Net reduction	Net growth
I	Relatively high emission intensity and high carbon removal rate	EST	LTU, HRV, SVK, POL, ROU, LVA, BGR	SVK, ROU, HRV, LTU, LVA, BGR	EST
II	Relatively low emission intensity and high carbon removal rate	FIN, PRT, SWE	SVN	SVN, PRT, SWE	FIN
III	Relatively low emission intensity and low carbon removal rate	DNK, DEU, NLD, GBR, BEL, ITA, FRA, IRL	LUX, AUT, MLT, GRC, CYP, ESP	ESP, DNK, NLD, DEU, GBR, LUX, ITA, IRL, BEL, AUT, FRA	MLT
IV	Relatively high emission intensity and low carbon removal rate	HUN	CZE	HUN, GRC, CYP, CZE, POL	

Qua.: Quadrant, AUT: Austria, BEL: Belgium, BGR: Bulgaria, HRV: Croatia, CYP: Cyprus, CZE: Czech Republic, DNK: Denmark, EST: Estonia, FIN: Finland, FRA: France, DEU: Germany, GRC: Greece, HUN: Hungary, IRL: Ireland, ITA: Italy, LVA: Latvia, LTU: Lithuania, LUX: Luxembourg, MLT: Malta, NLD: Netherlands, POL: Poland, PRT: Portugal, ROU: Romania, SVK: Slovakia, SVN: Slovenia, ESP: Spain, SWE: Sweden, GBR: United Kingdom.

study period. Furthermore, the continuous change in both internal composition of GHG emissions and quadrant location compared to other nations implies the importance of dynamic analyses rather than just focusing on static annual results.

4.2. Preliminary suggestions for emissions-reduction strategies

Based on this analysis, specific measures should be implemented to reduce GHG emissions in different countries. Such measures should take into account annual emissions at a sectoral, national, and regional level and how trends in these values change over time. The most urgent area to focus effort is in those countries in Q IV that currently show relatively high emission intensities and relatively low carbon removal rates. This is especially important for Poland, the trend for which appears to be moving in the opposite direction. Analyzing emissions by sector suggests that it is more urgent to decrease absolute GHG emissions in (and thereby the emission intensity of) Poland and Czech Republic than to increase their rate of carbon removal. In both countries, achieving this could target the energy sector by changing the energy mix, improving energy efficiency and decoupling energy consumption from economic growth [15]. Individually, an analysis of each country's sectoral emissions suggests that Poland could decrease overall emissions by targeting its agricultural sector, but it would be more prudent to target industrial processes in the Czech Republic. Conversely, in Estonia, a better strategy than decreasing absolute GHG emissions would be to improve the rate of carbon removal through afforestation, reforestation, carbon sequestration and substitution of biological products for fossil fuels or energy-intensive products [60].

Countries located in Q I should adopt measures to decrease their emission intensities while countries in Q III should aim to improve their rate of carbon removal. Countries located in Q II should act to maintain their competitiveness noting that the changes in other nations could alter their positions, as the analysis showed for Austria and Croatia.

With regard to effecting decreases in GHG emissions across the EU, it is suggested that decision-makers consider the following: (1) Understand a nation's relative performance based on the distribution of GHG emissions between different countries before analyzing a country's sectoral GHG emissions. (2) Investigate the overall trends in GHG emissions before analyzing current, static emissions data. Together, these suggestions mean decision-makers should strive to incorporate a historical and comparative understanding into any feasible strategy to reduce emissions nationally and regionally.

Although the EU continues to make good progress toward its short-term climate and energy goals, achieving longer-term objectives—such as an 80% decrease in emissions compared with 1990 levels by 2050—will require a considerable increase in effort [12]. Achieving such objectives is likely to require limiting energy-intensive activities in power generation, manufacturing and road transport; improving energy efficiency through innovation and the adoption of more efficient techniques; shifting the energy mix further toward a greater reliance on low-carbon and renewable resources; and cultivating behavioral changes that promote energy saving in industry and households [15,34,61–63]. The potential side effects of these changes (both positive and negative, for example on social welfare [60]) should also be analyzed to understand policy tradeoffs.

4.3. Suggestions for further work

Although the comprehensive analysis of GHG emissions conducted here has revealed the current status and trends of emissions between and among sectors, nations and regions, further studies are necessary to guide policy development. For example, although the relationship between GDP and GHG emissions was addressed in this study (because economic development is often regarded as the main driver for changes in GHG emissions [55,64,65]), the influence of other socioeconomic factors that may influence GHG emissions (including population, industrial structure, and consumption patterns) should be investigated [34]. Alternatively, it may be useful to investigate changes in GHG emissions through a lens of technological development or macroeconomic development that may also allow future projections to be drawn.

Finally, integrating more comprehensive emissions data (for example using data that better accounts for indirect emissions or characterizes emissions factors to account for regional differences)

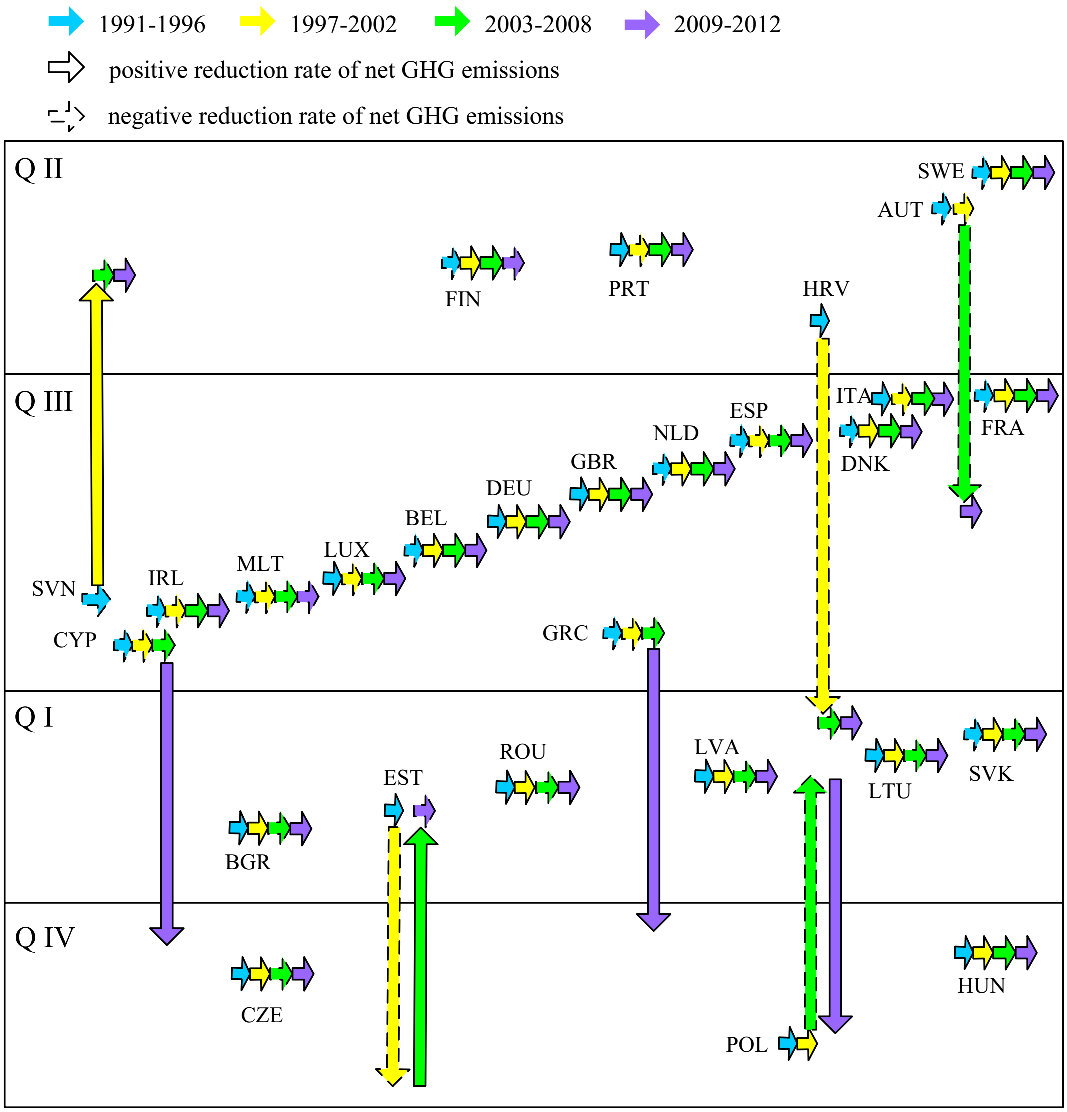

Fig. 5. The changes in GHG emission structure for the EU28 during 1991–2012. Those countries located in higher position perform better in GHG emissions, i.e., the ranking order from the best to the worst is countries in Q II, Q III, Q I, Q IV. Concretely speaking, countries located in Q II have relatively low emission intensity and high carbon removal rate, countries located in Q III have relatively low emission intensity and low carbon removal rate, countries located in Q I have relatively high emission intensity and high carbon removal rate, and countries located in Q IV have relatively high emission intensity and low carbon removal rate. Within the same quadrant, those countries with a higher position generally have recorded a better performance, which is expressed by lower emission intensity. AUT: Austria, BEL: Belgium, BGR: Bulgaria, HRV: Croatia, CYP: Cyprus, CZE: Czech Republic, DNK: Denmark, EST: Estonia, FIN: Finland, FRA: France, DEU: Germany, GRC: Greece, HUN: Hungary, IRL: Ireland, ITA: Italy, LTU: Lithuania, LUX: Luxembourg, MLT: Malta, NLD: Netherlands, POL: Poland, PRT: Portugal, LVA: Latvia, ROU: Romania, SVK: Slovakia, SVN: Slovenia, ESP: Spain, SWE: Sweden, GBR: United Kingdom.

will increase the usefulness of analyses like the one presented here [66,67].

5. Conclusions

Although part of a common community, each member state in the EU has a unique set of characteristics; this is important when analyzing national and regional GHG emissions. Therefore, this work proposed a method of analyzing national GHG emissions on a common and comparable platform. The analysis that followed considered both the emission sources and sinks in absolute and relative terms on an annual basis and by considering trends over multi-year periods. Furthermore, the analysis revealed the sectoral structure of GHG emissions within nations as well as the distribution of GHG emissions between them.

The EU's performance overall improved over the study period even though the 28 countries were individually classified into four quadrants depending on their performance in GHG emissions. This improvement was shown by the decrease in average emission intensity, the increase in the rate of carbon removal, and by an increasing number of countries showing net decreases in GHG emissions year-on-year.

The analysis used in this paper could be extended to better understand the principle of common but differentiated responsibilities between other countries and regions in addressing climate change. The comparison of national emissions using a common platform combined with the subsequent classification of nations into similar groups allows strategies that apply to individual nations and to similar groups to be devised. Further refinement of methods for accounting for and evaluating GHG emissions could enhance the usefulness of this method.

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