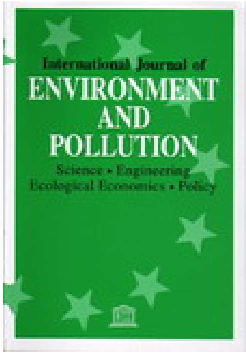

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Decarbonisation drivers and climate change concerns of developed economies

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Abstract The research is built on the World Bank, OECD, and the Heritage Foundation datasets for OECD economies. It investigates the main drivers of decarbonisation and climate change in these countries, analysing three CO_2 indicators: total and per capita CO_2 emissions as well as carbon efficiency. The results have confirmed that the growth of nations' welfare increases economies' carbonisation levels while creating prerequisites for improving states' carbon efficiency. It proves the positive influence of energy efficiency progress on OECD countries' decarbonisation. In contrast, green energy development has no significant effect on the reduction of total CO_2 emissions but positively influences increasing carbon efficiency and reducing per capita carbon dioxide emissions. Oil prices and most institutional factors like EU membership and Heritage Foundation indicators have no noticeable influence on CO_2 indicators. The paper provides policy recommendations and points to future research based on the research results.

Keywords: decarbonisation; climate change; CO_2 emissions; carbon efficiency; economic growth; energy efficiency; renewable energy; institutional factors; OECD countries.

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1 Introduction

Every year brings more and more questions that arise related to the global climate problems. The attention of many researchers is devoted to developing effective adaptation and mitigation measures to reduce the scale and minimise the negative feedback of climate change (CC). Global CC is revealed not only through increased air temperature but also related to more incidents of natural disasters (earthquakes, hurricanes, droughts, tsunami, etc.). Many factors cause this problem, but the anthropogenic effect has the most significant impact due to the increased carbon dioxide and other greenhouse gas (GHG) emissions. Following the data from the International Energy Agency (IEA) experts, 65% of total global GHG emissions by the gas type are carbon dioxide (CO_2). In terms of CO_2 emissions by sector, about 20% is accounted for by road transport. Concerning the BP Statistical Review of World Energy (2019), the OECD countries are still the largest energy-consuming economies with 40.9% of global energy consumption. Respectively, the OECD economies have the largest share in GHG emissions and urgent need for decarbonisation since most consumed energy is produced from conventional non-renewable resources.

This paper discusses the factors that cause CO_2 emissions in developed economies within the context of their decarbonisation and climate change concerns. We focus on the economies of the OECD from 2001 to 2014 since they are the biggest contributors to global GHG emissions.

The main hypotheses of research are as follows:

- CO_2 emissions in OECD economies are directly related to the economic achievements, and it is expected that improved economic indicators are linked with higher per capita levels of GHG emissions.
- Energy efficiency measured as the gross domestic product (GDP) per kilogram of oil equivalent should positively influence the GDP per unit of CO_2 as well as reduce the total CO_2 emissions and its per capita emissions.
- Investments in gross fixed capital should increase the levels of GHG emissions.
- Value added, manufacture (% of GDP) has unknown influence since it is needed to know which manufacturing equipment is created. Suppose the equipment is for the renewable energy sector. In that case, the value-added manufacture should increase the GDP per unit of CO_2 and reduce the overall carbon dioxide emissions and its emissions per capita. Otherwise, value-added services (annual % growth) should have the same impact on CO_2 indicators.
- Patents applications by country (residential) have an unknown influence since it is needed to know which direction they are applied to. In general, we expect that patents applications should increase carbon efficiency as well as reduce the total carbon dioxide emissions and its per capita emissions.
- High technology export (percentage of GDP) means a more developed economic structure and should impact CO_2 indicators. Thus, the export of high-technological products is expected to reduce per capita GHG emissions.
- Average crude oil prices (USD, in constant prices) should directly correlate with carbon indicators, and higher average crude oil prices should reduce total and per capita emissions and improve the relative economic efficiency of CO_2.
- It is expected that electricity generation from renewables reduces the GHG emissions in OECD countries.
- Institutional changes such as EU membership may reduce per capita levels of CO_2 emissions.
- Institutional changes such as property rights values and other Heritage foundation indicators should improve the GDP per unit of CO_2 and reduce overall and per capita carbon dioxide emissions.

The paper has such structure. Section 2 presents a review of the revealed drivers for CO_2 emissions and decarbonisation as well as relationships between GHG and economic growth. Section 3 covers methodical approaches used in the study as well as the description of the model and initial data for obtaining empirical results. Section 4 provides the empirical results. The conclusions section contains conclusions and policy recommendations based on the conducted study.

2 Literature review

According to Saboori et al. (2014), using the OECD data from 1960 to 2008, positive long-term interaction between GHG and GDP growth was revealed. Similar positive long-run relationships were found between energy usage and economic development. Shahbaz et al. (2018) proved the positive influence of economic development on energy consumption for the group of the largest energy-consuming economies. Mokiy et al. (2020, 2021) and Ilyash et al. (2021) emphasise emergencies where new external factors affect the development of the energy-saving construction sector and regional economic development and form dependencies between industrial development and energy consumption efficiency. Camara (2020) has proved that during 1990–2012, some OECD countries do not have a very strong decoupling between GDP per capita and CO_2 emissions in terms of consumption-based emissions. According to Karaca et al. (2019), in half of the respondents in Nursultan (Kazakhstan), motor vehicles are considered the main cause of environmental pollution. According to the Global Carbon Project (2018), carbon dioxide emissions have reached top record levels recently. China has the highest value in terms of CO_2 emissions and growth rates (an increase of 4.8% compared with the previous year). Such emissions in the Chinese economy are caused by a governmental policy aimed at stimulating economic expansion (mainly construction, heavy industry, coal, and steel industries). The second-largest CO_2 emissions are attributed to the USA, which started to reduce territorial CO_2 emissions starting 2015 (Global Carbon Project, 2018). Transport is the main source of CO_2 emissions in the EU, and the volume of fossil fuels used by airplanes and road transport increased by 4% in 2017. In this regard, the EU has introduced mandatory standards for CO_2 efficiency by trucks and buses, and during the next 10 years (2020–2030) the carbon dioxide emissions from cargo vehicles should be reduced by 15% and by 20% till 2030 (Global Carbon Project, 2018).

The rapid increase in global CO_2 emissions (by almost 2.7% in 2018, which is 1.6% higher than in the previous year) is associated with the fast-growing global car market. The global car production was more than 70 million cars in 2016 compared to around 40 million vehicles in 1999 (OICA, 2018),

González et al. (2019) state that road transport is responsible for 92% of CO_2 emissions from all vehicles. For the dataset of 13 EU economies throughout 1990 and 2015, they proved that carbon emissions depended on technological progress and improvements in fuel usage. Furthermore, the increased economic activity positively influenced increasing carbon emissions from cars. According to Saboori et al. (2014), and Shkarupa et al. (2017), most CO_2 emissions in the transportation sector come from energy consumption, which promotes the necessity of shifting to biofuel and other renewable energy sources. The usage of bioethanol may reduce CO_2 emissions and promote a green economy in general (Klymchuk et al., 2020; Burlakova et al., 2017).

Many scientists have investigated the relationship between consumption of energy resources and economic growth (see, e.g., Arouri et al., 2012, Abaas et al., 2018; Belke et al., 2011; Bella et al., 2014; Chontanawat et al., 2008; Coers and Sanders, 2013; Dedeoglu and Kaya, 2013; Heidari et al., 2015; Hens et al., 2018; Sineviciene et al., 2018; Sineviciene et al., 2017; Sotnyk and Kulyk, 2014; Sotnyk et al., 2015). Polishchuk et al. (2019) revealed that innovative SMEs use Smart-contracts for decarbonisation more often than others companies. Benetyte et al. (2021) and Melnyk (2021) proved that innovations contribute both to the company's economic potential and the sustainability of the whole economy. Educational achievements are considered to be a factor that promotes climate change mitigation, while the accessive shadow economy sector promotes negative environmental externalities (Pereira et al., 2020; Lyulyov et al., 2021). According to Shafiei and Salim (2014), who have used research programs in structural human ecology STIRPAT to figure out the dynamic links between human and the ecological systems in 1980–2011 for OECD countries, there is a direct influence of conventional energy consumption growth on the increase in CO_2 emissions. Besides, it was found that renewable energy consumption by OECD countries is promoted by the energy efficiency of GDP (Melnyk et al., 2020). According to Kahouli (2019), who has studied the interaction between the level of economic growth and energy usage for 34 OECD economies during 1990–2015, there is a bidirectional relationship between these variables. Moreover, they made a hypothesis that energy consumption decrease may slow down economic growth. Destek (2016) has estimated a causality relation between natural gas usage and GDP growth using the data from 26 OECD economies for 1991–2013. The study's findings were that natural gas usage and annual growth rates of GDP are cointegrated, having endogeneity in structural breaks. Furthermore, the vector ECM proved a hypothesis that natural gas usage determined an increase in GDP in the short-term period.

Using the OECD and non-OECD data for the period 2010-2014 and based on the meta-frontier dynamic DEA model, Li et al. (2019) found that economic and environmental efficiency in OECD economies is higher compared to the non-OECD states. Using panel data from 15 OECD member states in 1980–2012, Ozcana and Ari (2015) found no significant relations between atomic energy production/usage and economic achievements. For the selected OECD states, nuclear energy consumption refers to a relatively low fraction of the overall energy mix. For that reason, it does not have any relationship to economic prosperity.

Reducing CO_2 and economies' decarbonisation became urgent issues for OECD countries, which have the largest pollution statistics. In this regard, empirical estimation of key drivers that influence CO_2 emissions is a priority of economic development. There are many research papers devoted to the decarbonisation of developed economies. However, their results are quite contradictory, and this research intends to add to the literature in the field.

3 Research methodology

The research deals with determinants of CO_2 emissions in enhancing decarbonisation and reducing environmental concerns for the panel for 36 countries of OECD during 2001–2014.

Using the World Bank, International Energy Agency, the Heritage Foundation, and OECD data (OECD, 2019; IEA, 2018, The Heritage Foundation, 2019) on economic, energy, and institutional performance, we estimate the following regression model:

$$CO_{2t} = F\,(y_t, ee_t, gfcf_t, mva_t, sva_t, pa_t, hte_t, reo_t, opt_t, pr_t, tb_t, bf_t, mf, tf_t, if_t, eu_t, t_t, \varepsilon), \quad (1)$$

where:

The dependent variable is CO_{2t} (carbon dioxide indicator), which is measured as:

1 CO_2 emissions per capita (metric tons)

2 total CO_2 emissions (metric tons per 2010 USD of GDP)

3 GDP per unit of CO_2 emissions (USD GDP per CO_2 emissions metric tons) or carbon efficiency.

Explanatory variables are:

y_t – is GDP per capita (in constant prices)

ee_t – is energy efficiency (measured as GDP per kilogram of oil equivalent)

$gfcf_t$ – is gross fixed capital formation (in fixed prices)

mva_t – is value-added, manufacture (% of GDP)

sva_t – is value-added, services (annual % growth)

pa_t – is the number of patents applications by country (residential)

hte_t – is high technology export (percentage of GDP)

reo_t – is renewable electricity output (% of total electricity output)

opt_t – is average crude oil prices (USD, in constant prices)

pr_t – is property rights values (as measured by Heritage foundation)

tb_t – is the tax burden values (as measured by Heritage foundation)

bf_t – is the business freedom values (as measured by Heritage foundation)

mf_t – is the monetary freedom values (as measured by Heritage foundation)

tf_t – is the trade freedom values (as measured by Heritage foundation)

if_t – is the investment freedom values (as measured by Heritage foundation)

eu_t – is the EU institutional dummy (1 for countries subjected to EU, 0 – otherwise)

t_t – is the annual dummy (2001–2014)

ε – is the error term.

The following section presents the empirical estimations of economic, social, and institutional factors impact on carbon indicators in OECD countries in 2001–2014.

4 Results and discussion

The linear specification of the model is the most widely used in econometric modelling of CO_2 emissions in metric tons per capita. Thus, linear models are used by Li et al. (2020), Sineviciene et al. (2017), Kubatko and Kubatko (2019).The random-effect generalised least squares estimators are used for panel variables. To figure out key drivers that should be added to the econometric model, we used the research results described in the literature review.

The empirical estimations of economic, social performance impact on carbon intensity (calculated as CO_2 emissions, metric tons per capita) in OECD countries in 2001-2014 are shown in Table 1.

Table 1 The estimations of per capita CO_2 emissions drivers for OECD economies in 2001–2014

```
Random-effects (RE) GLS regr.        Numb. of observations     =        488
                                     Numb.of groups  =         36
R-squared:                           Observ. per group:
     within  = 0.5843                minimum =           7
     between = 0.5240                averg =        13.6
     total = 0.5249                maximum =         14
                                     Wald chi2(28)     =     625.57
Correlat.(u_i, X)= 0 (assumed)       Probab. > chi^2   =     0.0000
```

CO2 per capita	Coefic.	Stand.Er.	z(st)	P>|z|	95%Confidence	Inter.]
yt	.0001276	.0000147	8.66	0.000	.0000988	.0001565
eet	-.4554082	.0531161	-8.57	0.000	-.559514	-.3513025
gfcft	.0614995	.0155249	3.96	0.000	.0310713	.0919277
mvat	.184235	.0269574	6.83	0.000	.1313995	.2370705
svat	-.0119792	.0161294	-0.74	0.458	-.0435923	.0196339
pat	-4.33e-06	2.69e-06	-1.61	0.107	-9.61e-06	9.43e-07
htet	.0168121	.0077549	2.17	0.030	.0016128	.0320115
reot	-.0335283	.0065261	-5.14	0.000	-.0463192	-.0207374
optt	.0068881	.0031059	2.22	0.027	.0008007	.0129755
prt	.0364959	.0086239	4.23	0.000	.0195933	.0533984
tbt	-.0081798	.008383	-0.98	0.329	-.0246103	.0082507
bft	-.0062447	.0058113	-1.07	0.283	-.0176347	.0051452
mft	.0186266	.0079826	2.33	0.020	.0029811	.0342722
tft	-.0014757	.0125874	-0.12	0.907	-.0261467	.0231952
ift	.0072678	.0056826	1.28	0.201	-.0038699	.0184055
eu	-.794228	.7638097	-1.04	0.298	-2.291268	.7028115
y2002	.1979563	.1538597	1.29	0.198	-.1036032	.4995159
y2003	.4225344	.152705	2.77	0.006	.1232381	.7218307
y2004	.4052369	.1480748	2.74	0.006	.1150156	.6954581
y2005	.2076642	.1421263	1.46	0.144	-.0708983	.4862267
y2006	.1948178	.1436996	1.36	0.175	-.0868283	.4764639
y2007	.2043862	.1494563	1.37	0.171	-.0885428	.4973153
y2008	.0686707	.1568701	0.44	0.662	-.238789	.3761303
y2009	.2451691	.1694241	1.45	0.148	-.0868961	.5772343
y2010	.4423262	.1448409	3.05	0.002	.1584432	.7262092
y2011	.0241828	.1514318	0.16	0.873	-.2726181	.3209836
y2012	-.0901509	.1509495	-0.60	0.550	-.3860064	.2057046
y2014	-.080748	.1490234	-0.54	0.588	-.3728285	.2113325
_cons	1.15619	1.80453	0.64	0.522	-2.380624	4.693004

Authors estimations with Stata 14.0.

Table 1 proves that gross domestic product per capita has a positive impact on carbon dioxide emissions per capita. A rise in GDP per capita by 10 thousand US dollars contributes on average to 1.3 metric tons of dioxide emissions per capita increase for the selected OECD economies. That is, the richer the national economies, the more carbon dioxide per capita emissions are produced. This result states that richer societies are consuming more energy and producing more CO_2 emissions.

A rise in energy efficiency reduces CO_2 emissions per capita. In contrast, a rise in GDP per unit of energy by 10 US dollars contributes on average to 4.5 metric tons decrease of CO_2 emissions per capita for 36 OECD countries. It implies that there is a relationship between energy efficiency and climate friendliness.

The variable of gross fixed capital formation (GFCF) has a positive correlation with carbon dioxide emissions per capita. Thus, an increase in GFCF by 10 points leads to an increase in CO_2 per capita emissions by 0.6 metric tons. The last could be explained by GFCF being related to climate unfriendly activities (machinery, equipment purchases/ construction, construction activities of roads, railways, schools/kindergartens, etc.). All the above-mentioned activities are hardly called climate-friendly ones. The expansion of production capacity and increased fixed capital in the economy contribute to the continuous operation of production facilities. The OECD counties are pursuing a policy aimed at stimulating real investment and increasing the efficiency of production processes, which leads to a rise in CO_2 per capita.

According to the results of our study (Table 1), it can be seen that the factor of renewable electricity production is statistically significant and contributes to the reduction of CO_2 emissions per capita. With an increase in the usage of green energy by 10%, there is a decrease in CO_2 emissions by 0.3 metric tons per capita. To further reduce CO_2 emissions, the development and mass introduction of environmentally friendly technologies have to be applied, namely, electric vehicles that use electrical energy for their operation. In addition, investment in renewable energy sources is expected to reduce CO_2 emissions into the atmosphere. This statement is supported by modern literature. For example, discovering the dynamics of per capita carbon emissions, Cheng et al. (2019) proved the existence of a bell-shaped (Environmental Kuznets Curve) trend at different quintile levels between green energy and CO_2 emissions. The latter means that at the beginning of renewable energy development, the carbon emissions per capita may grow, but later on, starting some critical points the carbon emission per capita should decline. According to Chen et al. (2019), for Chinese provinces over the period 1995–2012, traditional energy usage positively influenced carbon dioxide emissions per capita. In addition, it was found that renewable energy consumption decreases the level of CO_2 emissions per capita in the eastern and western regions of China. The structure of the economy is considered to be the relevant factor for energy efficiency and origination of damage from ecosystem services deterioration (Karintseva et al., 2021; Veklych et al., 2020; Melnyk et al., 2013).

The export of high technology products appeared to be a statistically significant factor for increasing carbon dioxide emissions per capita. It was expected that introducing new technologies and scientific developments in the energy field would promote renewable energy sources use, reducing the degree of adverse effects on the environmental quality (Polyakova and Tsurik, 2019). According to our results, with an increase in the use of high technology by 10%, CO_2 emissions are increased by 0.2 metric tons per capita.

Improvements in value-added services, a patent application by residents, and an EU institutional dummy are statistically insignificant factors. Our results are in contrast to Kahouli (2019), who has stated that OECD EU countries promote the boost of the EU economy through the Energy Union. Improvements in Heritage foundation indicators such as tax burden, business, trade, and investments freedoms are also not statistically related to CO_2 emissions per capita.

Having discussed the significant drivers that determine per capita carbon dioxide emissions for OECD economies, we would continue the analysis of the determinants for total CO_2 emissions (Table 2).

Table 2 The empirical results of total CO_2 emissions drivers for OECD economies in 2001–2014

```
Random-effects (RE) GLS regr.       Numb. of observations     =       488
                                    Numb.of groups  =         36
R-squared:                          Observ. per group:
     within  = 0.2443               minimum =         7
     between = 0.0197               average =      13.6
     total = 0.0194                 maximum =        14
                                                Wald chi2(28)     =    132.26
Correlat.(u_i, X)= 0 (assumed)        Prob > chi2       =    0.0000
```

CO2 emissions (kt)	Coefic.	Stand.Er.	z(st)	P>|z|	95%Confidence	Inter.]
yt	5.374315	1.776377	3.03	0.002	1.89268	8.855951
eet	-11739.74	4103.555	-2.86	0.004	-19782.56	-3696.925
gfcft	1571.206	1132.067	1.39	0.165	-647.6038	3790.017
mvat	4691.551	1987.179	2.36	0.018	796.7519	8586.351
svat	-2327.408	1124.518	-2.07	0.038	-4531.422	-123.3936
pat	-1.22021	.2076531	-5.88	0.000	-1.627202	-.8132172
htet	807.3076	540.5492	1.49	0.135	-252.1494	1866.765
reot	-70.85152	521.4493	-0.14	0.892	-1092.873	951.1703
optt	-33.66021	238.7776	-0.14	0.888	-501.6557	434.3353
prt	24.24594	623.2202	0.04	0.969	-1197.243	1245.735
tbt	627.8012	600.639	1.05	0.296	-549.4296	1805.032
bft	388.6299	404.7857	0.96	0.337	-404.7354	1181.995
mft	2236.652	566.8223	3.95	0.000	1125.701	3347.604
tft	-84.48188	873.3533	-0.10	0.923	-1796.223	1627.259
ift	725.8858	397.4222	1.83	0.068	-53.04741	1504.819
eu	-575977.5	275795.9	-2.09	0.037	-1116528	-35427.46
y2002	4957.064	10661.17	0.46	0.642	-15938.45	25852.58
y2003	8409.05	10623.09	0.79	0.429	-12411.82	29229.92
y2004	10652.26	10367.15	1.03	0.304	-9666.979	30971.49
y2005	8410.69	9876.82	0.85	0.394	-10947.52	27768.9
y2006	103.6989	10017.5	0.01	0.992	-19530.24	19737.64
y2007	11682.57	10491.81	1.11	0.265	-8880.995	32246.13
y2008	2966.602	10838.36	0.27	0.784	-18276.19	24209.39
y2009	-12764.33	12039.29	-1.06	0.289	-36360.9	10832.24
y2010	9705.132	10058.95	0.96	0.335	-10010.05	29420.31
y2011	2500.132	10479.04	0.24	0.811	-18038.4	23038.67
y2012	-3824.156	10415.77	-0.37	0.714	-24238.7	16590.38
y2014	-1912.301	10408.62	-0.18	0.854	-22312.83	18488.23
_cons	249359.4	253550.6	0.98	0.325	-247590.7	746309.5

Source: Authors estimations with Stata 14.0.

It is seen from Table 2 that using carbon dioxide emissions in thousands of metric tons as a response variable, a positive impact of GDP per capita on CO_2 emissions is observed. A rise in GDP per capita by 1000 USD increases carbon dioxide emissions on average to 5374 thousand metric tons of CO_2 in selected OECD economies. The richer the national economics the more absolute amounts of carbon dioxide emissions are produced.

The indicator of energy efficiency (GDP per kilogram of oil equivalent) reduces CO_2 emissions. A rise in GDP per unit of energy by one USD contributes on average in 36 OECD countries to 11,739 thousand metric tons decrease in CO_2 emissions. This implies a positive relationship between energy efficiency and climate friendliness. Another explanation of the above-mentioned result is that energy-efficient societies are also wealthy states with a predominant service economy and digital economy sector. The bulk of GDP in such states is produced in the fossil-fuel-free sector, which is supported by the econometric results. Thus, the relative variable of value-added, services (annual % growth) is negatively correlated with carbon dioxide emissions, and the growth of value-added, services by one percent leads to a decrease in carbon dioxide emissions by 2327 thousand metric tons. It means that the service-based economy provides less CO_2 emissions.

An increase in the number of patent applications by residents by one unit reduces carbon dioxide emissions by 1.22 thousand metric tons. The last is in accordance with Hashmi and Alam (2019), who used a GMM Estimations with the Driscoll–Kraay correction for the robustness of standard errors for the panel of OECD countries during the period 1999–2014, found that 1% rise in eco-friendly patent applications decreases CO_2 emissions by 0.017%, and 1% rise in ecological taxes decreases these emissions by 0.03%.

In addition, the export of high technology products appeared to be a statistically significant factor for increasing carbon dioxide emissions. It was expected that the introduction of new technologies and scientific developments in the energy field would promote renewables, reducing the degree of adverse effects on the environmental quality. Thus, with an increase in the use of high technology by 10%, total CO_2 emissions increase by 807 thousand metric tons.

Improvements in gross fixed capital formation, export of high technology products, electricity production from renewable energy sources, oil prices are statistically insignificant factors. The data does not allow us to see exactly the gross fixed capital formed to relate it with CO_2 production. The same is true with the export of high technology products. The other situation is with the electricity production from renewable energy sources when limitations in time period do not allow to see the exact effect of the variable. As for the oil prices, we may assume that OECD economies are not oil-vulnerable economies, and fluctuations in oil prices do not influence energy consumption.

Changes in Heritage Foundation fiscal burden, business, trade, investing freedom, and property rights are also not statistically related to all CO_2 emissions.

Having discussed the significant drivers determining the total amounts of CO_2 emissions in OECD economies, we would continue analysis using the relative indicator of carbon efficiency measured as GDP per carbon dioxide (Table 3).

With regard to Table 3, a rise in GDP per capita by 10 thousand US dollars contributes on average to 0.45 USD of GDP per metric ton of CO_2 emissions increase in selected OECD economies. That is, the richer the national economies, the higher relative carbon dioxide efficiency it achieves. However, there is a rebound effect since higher carbon dioxide efficiency leads to higher total carbon dioxide emissions.

Progress in the energy efficiency of GDP positively influences carbon dioxide efficiency. A rise in GDP per unit of energy by 10 USD contributes on average to an increase of 3.3 USD of GDP per metric ton of CO_2 emissions for 36 OECD countries, which indicates that energy effective states have a relatively higher level of climate friendliness. These results are in accordance with Mozayeni et al. (2019), who have found for a case study of 4 OECD countries that the demand for solar panels per capita income is the main driver of solar energy production in France, Germany, Italy, and the USA. Among the other explanatory factors, the price of solar equipment, inflation (borrowing) rate, and pricing of non-renewable energy are also appeared to be statistically significant, with theoretically expected explanatory power. Similar findings were received by Xu et al. (2019) for the panel of 35 European countries, who proved that the GDP growth indicators are positively related to the renewable energy sector, which means that increased living standards do promote environmental awareness and renewable energy development.

Table 3 The empirical results of a relative indicator of carbon efficiency for OECD economies during 2001–2014

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Random-effect (RE) GLS regr.        Numb. of observations      =        488
                                     Numb.of groups  =         36
R-squared:                           Observ. per group:
     within  = 0.6666                  minimum =          7
     between = 0.6202                  average =       13.6
     total = 0.6243                    maximum =         14
                                       Wald chi^2(28)      =     901.47
Correlation(u_i, X)=  0  (assumed)          Probab.  >  chi^2      =        0.0000
```

GDP_per_ CO2	Coefic.	Stand.Er.	z(st)	P>|z|	95%Confidence Inter.]	
yt	.0000451	.00001	4.50	0.000	.0000255	.0000647
eet	.3315813	.0350394	9.46	0.000	.2629053	.4002573
fcft	-.0389513	.0101557	-3.84	0.000	-.058856	-.0190465
mvat	-.0414803	.0176804	-2.35	0.019	-.0761332	-.0068273
svat	.0210639	.0105144	2.00	0.045	.0004561	.0416718
pat	-4.63e-07	1.78e-06	-0.26	0.795	-3.95e-06	3.02e-06
htet	.0064309	.0050579	1.27	0.204	-.0034825	.0163443
reot	.0163361	.0043159	3.79	0.000	.0078772	.0247951
optt	.0006317	.0020368	0.31	0.756	-.0033604	.0046238
prt	-.0040042	.0056487	-0.71	0.478	-.0150755	.0070672
tbt	-.0147629	.005484	-2.69	0.007	-.0255114	-.0040145
bft	.0127493	.0037896	3.36	0.001	.0053219	.0201767
mft	-.0105848	.0052096	-2.03	0.042	-.0207953	-.0003742
tft	.0064971	.0082036	0.79	0.428	-.0095816	.0225758
ift	-.0016112	.0037058	-0.43	0.664	-.0088744	.005652
eu	-.1935764	.5318819	-0.36	0.716	-1.236046	.8488929
2002	-.0284653	.1002529	-0.28	0.776	-.2249574	.1680268
2003	-.0617587	.0995327	-0.62	0.535	-.2568392	.1333219
2004	-.0495117	.0965382	-0.51	0.608	-.2387232	.1396998
2005	.0009377	.0926197	0.01	0.992	-.1805937	.182469
2006	-.0936868	.0936581	-1.00	0.317	-.2772533	.0898796
2007	-.0927785	.0974534	-0.95	0.341	-.2837837	.0982267
2008	-.0726301	.1022051	-0.71	0.477	-.2729485	.1276882
2009	.0148115	.1105682	0.13	0.893	-.2018982	.2315211
2010	-.1993129	.0943885	-2.11	0.035	-.384311	-.0143148
2011	-.0444366	.0986516	-0.45	0.652	-.2377902	.148917
2012	.0624517	.0983153	0.64	0.525	-.1302426	.2551461
2014	.1400308	.0971422	1.44	0.149	-.0503643	.330426
cons	1.399087	1.190626	1.18	0.240	-.9344972	3.73267

Source: Authors estimations with Stata 14.0.

However, our results are in contrast to Antonakakis et al. (2017), who have used a panel of more than 100 countries clustered by income groups. They found that there was no significant influence of renewable energy on GDP growth. It was found that there is no bell-shaped (Environmental Kuznets Curve) dependence between economic prosperity and carbon dioxide emissions, which means that there is no evidence that developed countries reduce GHG emissions through the increase in economic performance. The above-mentioned authors moved further and put a hypothesis that questions the impact of renewables on sustainable growth, stating that only zero economic growth is achievable under the environmental sustainability condition. Their results were achieved through the panel vector autoregression. To our mind, the analysed period taken by them was not suitable to see the positive influence of the renewable energy sector on economic growth. Our results prove that renewable energy development promotes GDP per CO_2 improvements with more recent data.

COVID-19 pandemic crisis affected environmental sustainability (Lentner and Hegedűs, 2021).

Moreover, using a panel of 28 OECD over the 1971–2015 period, Demir and Cergibozan (2020) have obtained a statistically significant convergence involving alternative energy usage.

The relative variable of GFCF is negatively correlated with GDP per unit of CO_2. Thus, an increase in GFCF by 10 points leads to a decrease in GDP per unit of CO_2 emissions by 0.4 USD per metric ton. As in Table 1, the last could be explained by the fact that GFCF is related to unfriendly climate activities, often consuming more energy and emitting more GHG. Similar results are achieved for the value-added manufacture (measured as a percentage of GDP). Thus, an increase in value-added manufacture by 10 percentage points leads to a decrease in GDP per unit of CO_2 emissions by 0.4 USD per metric ton. The opposite situation is observed when we analyse the value-added services (measured as annual % growth). Thus, an increase in value-added services by 10 percentage points leads to a rise in GDP per CO_2 emissions by 0.2 USD per metric ton. According to the results of our study, it is seen that the factor of renewable electricity production is statistically significant and contributes to the increase of GDP per unit of carbon dioxide emissions.

Koçak and Ulucak (2019) proved that for the panel of 19 high-income OECD states, the R&D spending for energy efficiency of the conventional energy sector has a growing influence on emissions of carbon dioxide. While R&D spending for energy efficiency of the green energy sector does not affect CO_2 emissions. We do not agree with these results since the renewable energy sector is still comparatively small to significantly influence the reduction of carbon dioxide emissions. In addition, the positive correlation between R&D expenditures and energy efficiency of the non-renewable energy sector does not necessarily mean causality. Our empirical results prove that a rise in the use of energy from renewable resources by 10% provides a rise in GDP per unit of CO_2 emissions by 0.16 USD per metric ton. Melnyk et al. (2020) received similar results, and the renewable electricity output improves both relative carbon dioxide indicators.

Improvements in a patent application by residents, export of high technology products, and oil price are statistically insignificant factors for GDP per unit of CO_2 emissions change. The country's membership in the European Union does not influence CO_2 emissions volumes. That is the policy of the European Union, which supports all international agreements and programs in the field of renewable energy and CC is in line with the similar policies of OECD economies and therefore does not demonstrate positive influence. Other institutional indicators of the Heritage Foundation, such as property rights, trade, investment, monetary freedom, and fiscal burden, are also not statistically related to GDP per unit of CO_2 emissions. The improvements in business freedom indicators are positively correlated with carbon efficiency improvements.

There is no problem in sharing the best OECD experience of reducing carbon efficiency since, according to Zofío and Prieto (2001), new technologies and innovations are available to all economies due to the openness and access to specialised journals, technological fairs, etc. Similar to that, Lau et al. (2019) using the panel of 18 OECD economics for the period 1995–2015, proved that electricity generated by nuclear power plants leads to lower carbon emissions without slowdown the long-run economic growth. However, even if long-term economic growth is not endangered with regard to structural factors, emergency risk factors could be questioned due to the specifics of nuclear energy (Sushchenko et al., 2020). For that reason, renewable energy is the most evident path for the long-run sustainable economic developments of any national economy.

5 Conclusions

The results of our research have confirmed that the growth of the welfare of nations leads to an increase in the carbonisation level of their economies. At the same time, per capita GDP growth in the OECD countries creates prerequisites for improving their carbon efficiency. Taking into account this result, the policies of the national governments should be aimed at maintaining sustainable economic growth with an emphasis on the implication of low carbon technologies for the purpose of breaking the negative link "increasing welfare – increasing CO_2 emissions".

The hypothesis concerning the positive impact of energy efficiency improvement on the OECD economies' decarbonisation has been confirmed since more efficient energy use contributes to reducing CO_2 emissions and preventing climate change.

Given the small part of green energy resources in the total energy consumption of many OECD member states, currently, green energy development does not significantly affect overall CO_2 emissions but positively influences the reducing per capita CO_2 emissions and increasing carbon efficiency. In general energy efficiency increases in terms of investment in green energy (Astanakulov et al., 2021).

Therefore, it is expedient to further expand the renewable energy sector so that it could become a solid decarbonising driver. The hypothesis about the positive influence of investments in gross fixed capital formation on the growth of GHG gases emissions has been only partially confirmed. This factor raises per capita CO_2 emissions and accordingly worsens carbon efficiency but does not affect the fluctuations in total CO_2 emissions. Therefore, it is necessary to change the state investment priorities and enhance the processes of investments greening to transfer the carbonisation factor into a powerful ecologisation driver for the OECD economies.

The results of our study have disproved the hypothesis about reducing per capita CO_2 emissions due to the growth of high technology export. Instead, this factor increases both per capita and total CO_2 emissions. In addition, it does not have a noticeable effect on the change in the carbon efficiency of OECD countries. Therefore, it is expedient for the national governments to revise the priorities in this field and stimulate the development of green high technology export.

In general, the hypothesis regarding the influence of value-added, manufacture, and value-added, services on the dynamics of the CO_2 indicators can be considered as confirmed. While these factors do not significantly influence CO_2 emissions per capita, the development of services in national economies reduces total CO_2 emissions and increases carbon efficiency. The increment in value-added, manufacture causes deterioration of the carbon efficiency indicator. From these perspectives, expanding the services sector and reducing the material production share in national economies are promising directions for decarbonising and improving environmental quality in OECD countries and preventing climate change.

The impact of patents applications by country (residential) has been confirmed only for the total CO_2 emissions indicator. That is the factor increase that promotes to fall of CO_2 emissions in national economies. Nonetheless, this driver does not significantly affect other CO_2 indicators: CO_2 emissions per capita and carbon efficiency. Thus, it indicates the contradictory nature of the obtained results and therefore requires further research.

Factors like oil prices, EU membership, and Heritage Foundation indicators are statistically insignificant for CO_2 indicators changes, except for business freedom, which positively affects carbon efficiency growth. This indicates that price and institutional factors have an insufficient influence on economies' decarbonising. Therefore, the environmental and decarbonisation policy of the governments of the OECD countries should be revised to increase its effectiveness with the help of improved price instruments and institutional changes.

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