



CO₂ emissions of nuclear power and renewable energies: a statistical analysis of European and global data

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Abstract In this paper, we investigate the CO₂ emissions caused by nuclear and renewable power generation. The knowledge of the share of coal, gas and oil in electricity generation permits the exact calculation of the related CO₂ emissions. In addition, there is a second approach especially within the economic sciences, which applies statistical techniques for the study of the energy-related emissions. The background for these studies is the provision of general political advice and the expectation that political, cultural, or infrastructural considerations guide nations in the preference and choice of specific technologies. In this paper, we are applying both approaches and come to the certain conclusion, that nuclear power is as effective as renewable power in order to reduce the CO₂ emissions. Our results are in complete contradiction to a recent publication (Sovacool et al. in *Nat Energy* 5:928–935, 2020. <https://doi.org/10.1038/s41560-020-00696-3>). The authors of this paper conclude that nuclear power does not reduce the CO₂ emissions, but renewable power efficiently does. In addition, they argue that these two technologies crowd out each other. The possible reason for their claims may result from a specific conditioning of the data. In contrast, our analysis clearly confirms the adequacy of both nuclear and renewable power generation.

1 Introduction

There are not many technical options for a future carbon-free energy supply. Renewable energies in their different forms will contribute a significant share in a future energy portfolio. Fusion might be a possibility once the development is successfully completed [1]. Realistically, this may happen in the second half of this century. Fossil fuels may still be an option but only in combination with CCS technologies (carbon capture and sequestration), which avoid the release of CO₂ into the atmosphere by storing it underground [2]. However, a global implementation has to overcome many local safety concerns. This is also true for fission, which completes the list of potential CO₂-free energies. Since decades, fission contributes about 10% to the world electricity demand—less than hydropower but at present, more than wind and solar power together. One major and highly disputed topic is whether CO₂-free energies—fission together with renewables—can co-exist and jointly form the basis of a future largely carbon-free electricity supply.

Focus Point on The Interplay between Climate and Energy Policies.

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This paper contributes to the debate led mostly within economists (see Sect. 4.1) whether nuclear power reduces CO₂ emission specifically in comparison to renewable technologies. This question has been pursued over years and has been continued by two recent publications. The first one is by B. K. Sovacool et al. [3] coming to the following major conclusions: (1) “One core finding is that countries with nuclear power attachments do not tend to have significantly lower levels of national carbon emissions”. (2) “A second core finding is that lower levels of carbon emissions do associate more strongly with the relative scales of national attachments to renewable energy than with nuclear attachments”. (3) “A third core finding is that the scales of nuclear and renewable attachments tend to vary negatively with each other”—implying that these two technologies “crowd each other out”. The second paper is by Fell et al. [4] observing “that nuclear power and renewable energy are both associated with lower per capita CO₂ emissions with effects of similar magnitude and statistical significance”. The conclusions of Ref. [3] may be surprising at the first glance specifically as the issue is not life-cycle emissions including fuel preparation, construction of power plants, waste management and final waste deposition [5] rather emissions during operation.

This paper is motivated by Ref. [3] because the major results are not in agreement with this author’s findings as published, e.g. in [6–9]. We also adopt the methodology used by most of the authors addressing this issue—nuclear versus renewable energy—by analysing databases by statistical means. We employ three databases, which are all compiled from publicly accessible sources and are introduced in the next section. The results of the statistical analysis will be presented in the first part of this paper. Reference [3] plays a specific role in the second part of this paper where we analyse the data further to identify possible reasons for the obvious discrepancies in the overall findings and their interpretation. We conclude that an in-depth analysis is required before political guidelines can be offered specifically in cases where the scientific advice is formulated without leaving room for alternatives as in case of Ref. [3].

2 Databases

We discriminate between three databases—first, the European database DBeu and the global database DBgl. These databases consider the year 2018 only. The third database, DBw(t), is built from annual data representing world electricity consumption and related CO₂ emission. This database represents a time series covering the period from 1990 to 2018.

2.1 The European databases DBeu and DBeu_n

The European database DBeu of this study covers 26 European countries, 15 of them using additionally nuclear energy. The countries are listed in Appendix A. In 2018, their share on global CO₂ emission by electricity generation, CO₂_el, was 7%. The 15 nuclear countries are singled out in the sub-database DBeu_n with a more balanced representation of both nuclear and renewable energies. European data are available from different sources, which can be compared and average values can be formed. Therefore, DBeu represents a set of fairly complete and carefully scrutinised data (see Appendix B for details).

2.2 The global databases DBgl and DBgl_n

The second database DBgl comprises 62 countries including 31 countries using nuclear power (listed in Appendix A). These countries emit 70% of the world CO₂-el emission.

The nuclear countries are again singled out in the sub-database DBgl. DBgl includes all European countries of DBeu, all nuclear countries outside Europe and has been supplemented by countries listed in the EY *Renewable Energy Country Attractiveness Index* (Recal) from November 2020 [10] and by those with a high human development index (HDI [11]) and a large population. It is expected that the countries selected along these criteria provide data with specific sensitivity to electricity generating technologies and their characteristics. DBgl also includes the large countries China, USA, India, Russia and Japan, which are the major CO₂ emitters. These countries dominate the statistical analysis because in their frame the parameters of the other countries lump together. DBgl may better allow to reveal secondary drivers searched for by [3], which could influence the evolution of electricity generation technologies beyond their technical specifications.

Like DBeu, DBgl contains data only from 2018. In this sense, we limit ourselves to cross-sectional analyses. Emphasis and interest here are to assess the outcome of the historic development in the country-specific mix of electricity technologies up to the year 2018.

2.3 The world database DBw(t)

DBw(t) contains integral world data from the period from 1990 to 2018. The purpose of this database is to carry out a statistical analysis of electricity generation and emission over a longer period of joint evolution.

In the Appendix B, the databases, the data sources, and the data selection procedures are described in detail.

2.4 Variables of the databases

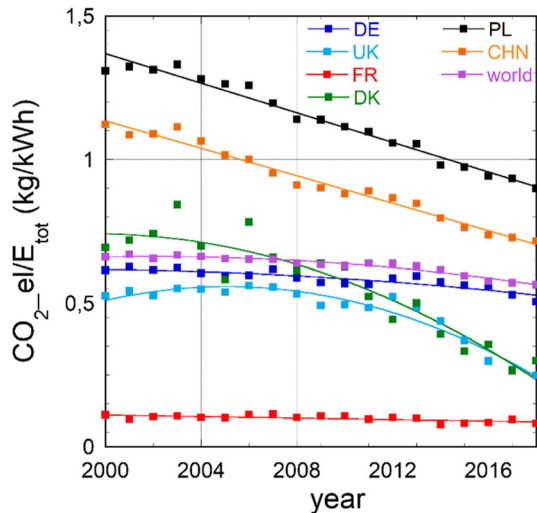
Employing correlation and regression analysis the dependencies of CO₂-emissions on nuclear and renewable power are investigated. In order to avoid a loss of sensitivity regarding renewable versus nuclear electricity generation, we concentrate in this paper on CO₂ emission from electricity production proper. To allow meaningful analysis of widely different countries, CO₂-emission per capita (CO₂pc) is defined as response variable; the explanatory variables are the nuclear- and renewable generation fractions f_{nuc} and f_{res} . They are defined in this paper as the ratio of, e.g. annual nuclear energy $E_{\text{nuc}}/E_{\text{tot}}$, with E_{tot} being the total electricity consumed in a country in a year. In order to assess possible non-technical actors in the evolvement of electricity supply technologies, the gross domestic product per capita, GDP_{pc}, is traditionally used. In this paper, we additionally involve the fossil fuel fraction f_{fos} for some studies, as fossil fuels are the only source for CO₂ emissions during operation. f_{fos} , f_{res} , and f_{nuc} add up to one.

3 Analysis of generation and emission data

3.1 CO₂ emissions of key countries

Figure 1 introduces into the topic of CO₂ emission and avoidance comparing the emission history of different key countries along with the global development. Plotted is the ratio of CO₂-emission by electricity generation CO₂_el and electricity consumption E_{tot} for the period 2000 to 2018. A low value of this ratio (CO₂_el/ E_{tot}) can be seen as a quality factor of the employed technologies and fuels in electricity generation. The following country-specific observations can be made:

Fig. 1 Specific CO₂ emission from electricity generation, CO₂_el, divided by the total electricity consumption E_{tot} [16] for the countries shown in the legend



China: The $\text{CO}_2\text{-el}/E_{\text{tot}}$ values are high because of the predominant use of coal (at present, about 1000 GW coal power stations are in operation). Nevertheless, this quality factor improves roughly linearly within the considered period. The nuclear and renewable electricity generation increase, in this case predominantly hydroelectricity. Also, the efficiency of fossil power stations improves.

Poland: The use of coal dominates electricity production in Poland (see Fig. 5); the technologies for burning fossil fuels improve, however, and, together with a growing share of renewables, reduce emissions in a rate comparable to the one of China.

Denmark: Denmark started with electricity being predominantly generated by coal but has, as is well known, a successful policy to employ more and more wind energy. This is well borne out by the comparatively steep decrease of $\text{CO}_2\text{-el}/E_{\text{tot}}$ during the last decade.

Germany: Here $\text{CO}_2\text{-el}/E_{\text{tot}}$ hardly changed within the 19 years considered in spite of tremendous efforts to expand renewable energies. Indeed, in the period from 2000 to 2018, wind and solar power installations increased from 6 to 104 GW [12]. Unlike the Danish case, this addition of CO₂-free technologies did not pay-off ecologically because in this period, nuclear power, the other CO₂-free supply, has been abolished in Germany in steps from 22.4 to 10 GW. Though the electricity mix in Germany changed strongly by nearly 200 TWh of additional renewable energy generation, about half had to be used to compensate the nuclear energy losses (see Sect. 3.3).

UK: A parabolic fit describes the data. The decrease in recent years has been accomplished by the replacement of coal by gas—a process which started already at the beginning of the 90ies and was accelerated by an early introduction of a CO₂—price system. Now, gas contributes with 40% to UK's electricity generation [13]. The drop of $\text{CO}_2\text{-el}/E_{\text{tot}}$ in recent years is due to the installation of renewables, favourably offshore wind power.

France: Since decades, electricity generation in France excels with very low CO₂ emission factors thanks to the use of nuclear energy and—to a lesser extent—hydropower (see Sect. 3.3).

World: $\text{CO}_2\text{-el}/E_{\text{tot}}$ lies slightly above the German quality factor and is similarly constant over the years. Most of the electricity is generated by fossil fuels. In the last 5 years, the coal fraction drops [14]. The world electricity and emission situation will be discussed in Sect. 3.4.3 in more detail.

Fig. 2 Calculated per capita CO₂ emissions versus tabulated values made available by IEA [15] for the three data basis of this study. The results from the subsets of nuclear countries are also shown. The solid and dashed lines are fits to the data of DBgl and DBeu. Russia is an outlier

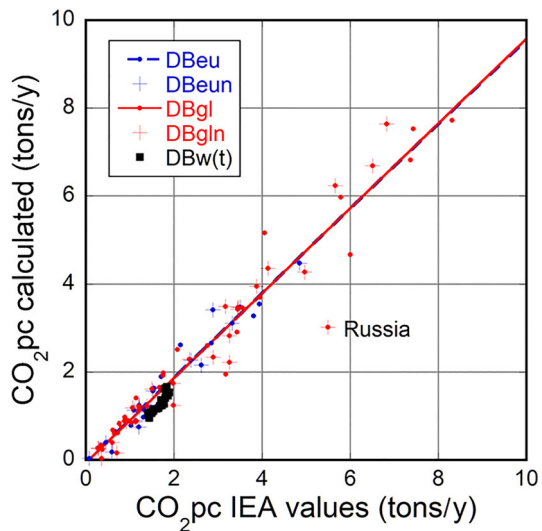


Figure 1 demonstrates the reasons for high CO₂ intensities and which measures allow to reduce them. No statistical analysis is necessary for this realisation. UK (like the USA) shows that the replacement of coal by gas is beneficial for the climate—this is obvious and trivial (as long as methane leakage is not considered). The case of Denmark clearly demonstrates the favourable use of renewable energies and the example of France the advantage of nuclear power. Germany demonstrates indirectly the CO₂ reduction effectiveness of both in a case where renewable energy replaces successively nuclear energy thereby mostly nullifying a distinct impact on CO₂ emissions over many years of the transition period.

3.2 Calculated CO₂ intensities of the countries in the three databases

With the knowledge of lignite, gas, and oil consumption, the CO₂ intensity of electricity generation can be calculated. Figure 2 compares tabulated per capita CO₂ emissions [15] with calculated ones for the countries of the three databases DBeu, DBgl and DBw(t) and the sub-databases DBeuN and DBglN. The calculations are done with fuel-specific CO₂-intensities (Table 7 of the appendix B). The agreement is very good (apart from Russia), which is not surprising but demonstrates the solidity of the used databases. There is a sufficient understanding of CO₂ emission by fossil fuels, which allows valid predictions and there is no need for statistical assessment to identify the primary agents.

3.3 Electricity generation and CO₂-emission history of France and Germany

France and Germany—neighbours with rather similar economic development, which also share the same basic values and cultural attachments—nevertheless selected totally different technologies for electricity generation in the 70ies of last century. Figure 3 compares primary, unprocessed data for both countries over 30 years, starting with 1970. The three major components of annual generation—fossil, nuclear, and renewable power—are plotted. Long before the year 2000, France reduced the fossil share in electricity generation and replaced it by nuclear power; the remarkable increase in demand after 1980 was predominantly met by

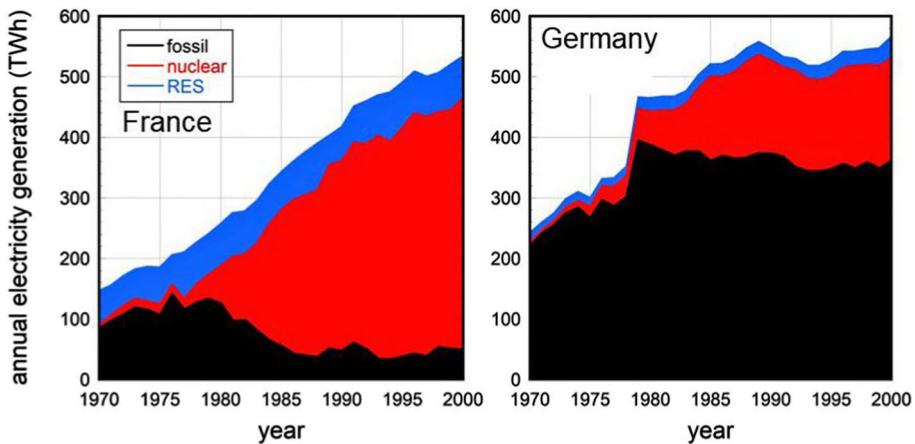


Fig. 3 Development of the electricity mix of France and Germany. The step in the German data at 1979 is an artefact in the sense that from there on—much before German unification—the specifics of electricity generation of the former DDR were included into the public databases

nuclear power. In the period considered here, the renewable energy is mostly hydroelectricity with a substantial contribution in case of France (see also Fig. 5). The hydro-share is rather constant indicating that the national potentials are mostly exploited. In contrary to France, Germany met its electricity consumption growth primarily by fossil fuels, mostly by lignite and hard coal.

After 2000 and under the impression of global warming, Germany started to rapidly increase the use of renewable energies, predominantly wind and PV power. As is well known, it was the Fukushima catastrophe—an exogenic shock, which made Germany to change its energy policy again in 2011 with the goal to step out of nuclear energy use till 2022. The corollary of these decisions is that over the last 10 years one CO₂-free power replaces another one. Only in the last two years the share of fossil power was reduced slightly and the CO₂ emission by power production dropped accordingly.

Figure 4 plots the CO₂ emissions from electricity generation of Germany and France over a longer period from 1960 to 2020. This is twice the time span from now to 2050, when the world has to be decarbonised to meet the Paris goals. Compared to Germany, France started this process well ahead and, since decades, avoids the emission of about 300 Mill tons of CO₂ a year. The history of nuclear power development of Germany is compared in Ref. [16].

As national CO₂ emissions can easily be calculated on the basis of fuel-specific emission intensities—Fig. 4 shows also the hypothetical reduction of CO₂, if Germany had decided to shut down lignite burning power stations in the steps nuclear power was actually abandoned specifically after Fukushima. In 2020, the integral CO₂ savings would have been in the order of 800 Mill tons. Thus, Germany could have avoided the amount of one year of GHG emissions.

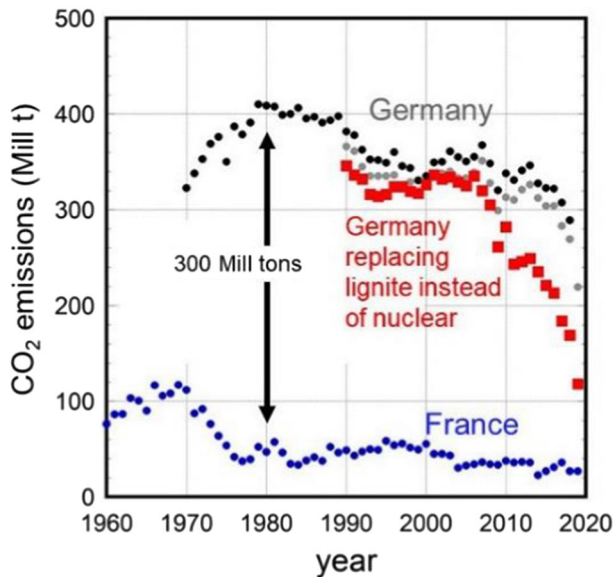


Fig. 4 Comparison of the CO₂ emission from electricity generation from France and Germany for 60 years. The difference of 300 Mill tons per year is indicated. For Germany, data from two data [35, 36] source are plotted. The hypothetical development for the case that electricity production by lignite had been reduced in the steps of nuclear power production is also plotted (red squares)

3.4 Statistical analysis of the three databases

3.4.1 European databases DBeu and DBeu

Figure 5 shows the variation of the main independent parameters f_{fos} , f_{res} , and f_{nuc} for the 26 selected European countries of DBeu. The same data are differently ordered; in Fig. 5 left, the fossil fraction is ordered in descending sequence; in Fig. 5 middle, it is the renewable fraction, and in Fig. 5 right, the nuclear fraction. The total electricity consumption of the European countries considered here adds up to 3490 TWh (2018). The average fractions are: $f_{\text{fos}} = 0.41$, $f_{\text{res}} = 0.40$, and $f_{\text{nuc}} = 0.19$. The maximum/minimum shares for f_{fos} , f_{res} and f_{nuc} are: 0.91/0.01; 0.98/0.09; 0.72/0. These figures define the range for the statistical analysis.

Figure 6 plots the CO₂pc emission from electricity generation versus the renewable (res) energy fraction f_{res} . The black dots represent the whole database DBeu; the black solid line is a linear fit to the data. CO₂pc reduces with increasing f_{res} down to nearly zero emission in case of Norway. The data scatter is high but the coefficient of determination $R^2 = 0.26$ tells us that 26% of the variation of CO₂pc is accounted for by f_{res} . The red dashed line is the fit to the 15 nuclear countries of DBeu. It falls well below the black line. The two blue dashed lines are fits to a reduced number of members from the DBeu database. The dark blue line represents those countries employing a high coal fraction, the lower light blue line countries burning little coal. The border between these two sub-sets is determined by the median of the coal fraction (see Fig. 5). The high-coal line lies above the black trend line of all data of DBeu; the low-coal line is flatter because these countries demonstrate a lower CO₂ level already at a lower f_{res} . Toward $f_{\text{res}} = 1$, these curves have to merge, because there is no

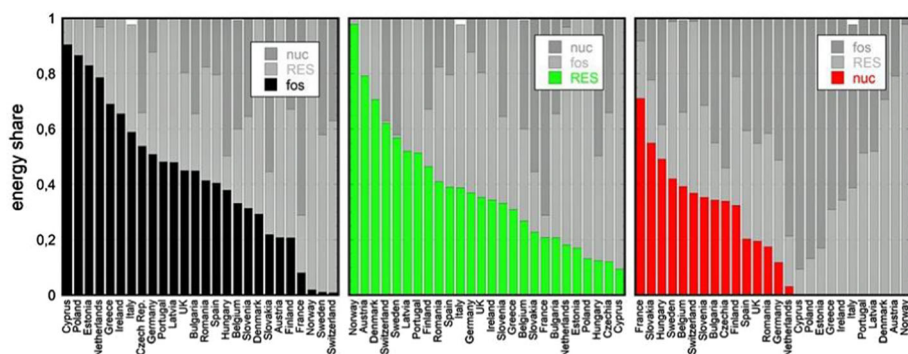


Fig. 5 Power share of 26 European countries sorted into fossil (fos), renewable (res) and nuclear (nuc) power

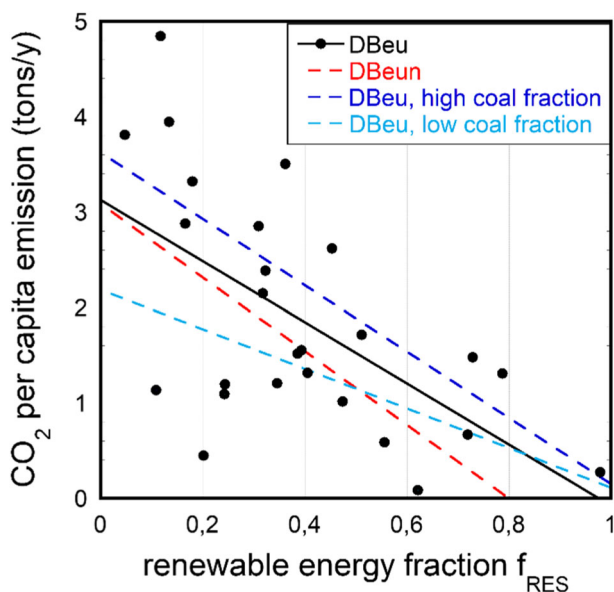


Fig. 6 CO_2pc , versus the renewable energy fraction f_{res} for the 26 countries of DBeu. The black line is the linear fit to the black data points. The red dashed line is the fit to the subset DBeu of the nuclear countries. The dark blue dotted line is the fit to the subset of DBeu with a coal fraction above and the light blue dashed line with a coal fraction below the median

room for the use of coal any longer. This analysis shows that the high variability of the data in Fig. 6 is more systematic than arbitrary.

Table 1 summarises the slopes of the fit lines and the R^2 values of Fig. 6— CO_2pc versus f_{res} —for the total databases DBeu and the one restricted to nuclear countries, DBeu_{nuc}. For both cases, CO_2pc decreases with increasing renewable fraction.

We repeat this analysis but now with the nuclear power fraction f_{nuc} as independent variable. This part is restricted to the 15 nuclear countries of DBeu_{nuc}. Figure 7 plots CO_2pc versus the nuclear fraction, f_{nuc} . Like in case of renewables, we observe a reduction of CO_2 emission by nuclear power with similar slopes and relevance. The key analysis parameters are also summarised in Table 1. Outliers in Fig. 7 are the data points of Czech Republic and

Table 1 Linear fits yield slope coefficient and parameter of determination, R^2 , to the relation CO_2pc versus the renewable fraction f_{res} or the nuclear fraction f_{nuc} , respectively, for the two European databases DBeu and DBeuN

	All European countries, DBeu		Nuclear countries, DBeuN	
	Slope (tons)	R^2	Slope (tons)	R^2
f_{res}	− 3.2	0.34	− 3.5	0.16
f_{nuc}	− 3.3	0.20	− 3.3	0.20

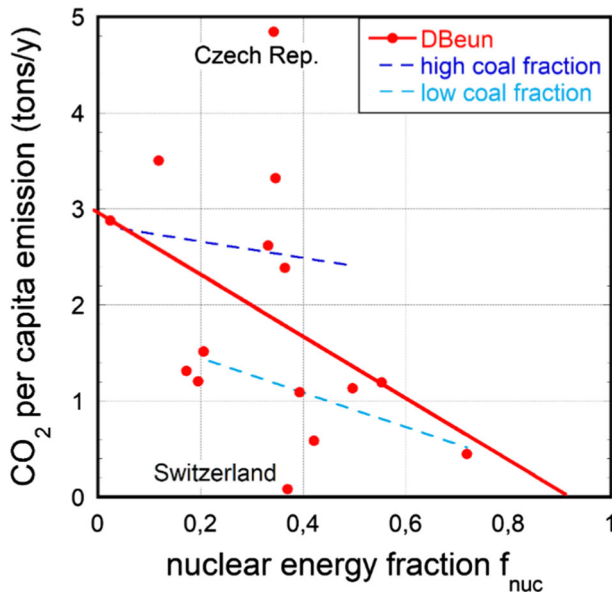


Fig. 7 CO_2 per capita emission from electricity generation versus the nuclear energy fraction f_{nuc} for the 15 nuclear countries of DBeu. Like in Fig. 6 the linear fits to the high- and low-coal fraction countries are indicated by dashed lines

Switzerland though they share nearly the same nuclear power fraction of $f_{\text{nuc}} \sim 0.35$. The high emission value of the Czech Republic is due to a high fossil fraction of 50% whereas Switzerland additionally employs hydropower with a share of 55% (see Fig. 5). The fits to the sub-data sets—high- and low-coal fractions—are also plotted. There is a distinct difference in CO_2 emission between these two classes, which will be picked up again in Sect. 4.5. We confirm that the scattering of the data is rather systematic and not of statistical origin. Removing the atypical countries—three with a coal-share $> 30\%$ and Switzerland—increases R^2 from 0.20 to 0.34.

Table 2 summarises the correlation coefficients between the different variables. Dependences on the nuclear fraction, f_{nuc} , can only be identified employing DBeuN. Otherwise, the data are affected by the variable distribution along the $f_{\text{nuc}} = 0$ axis and countries without nuclear power would co-define the relation between CO_2pc and f_{nuc} . Because of the small sample size and the larger number of independent variables, the results are rather suggestive than significant in some cases. The coefficient of determination, R^2 , and the p value allow qualifying the statistical description of a setting. The obvious correlation between CO_2 emis-

Table 2 Correlation coefficient r , parameter of determination R^2 , and p value are tabulated for the two databases DBeu and DBeun

	Nuclear countries, DBeun				All European countries, DBeu		
	CO ₂ pc	GDPpc	f_{nuc}	f_{res}	CO ₂ pc	GDPpc	f_{res}
GDP _{pc}	$r = -0.28$ $R^2 = 0.08$ $p \text{ value} > 5\%$	–			– 0.31 0.10 > 5%	–	
f_{nuc}	– 0.44 0.12 > 5%	– 0.12 0.01 > 5%	– > 5%	– 0.17 0.03 > 5%			
f_{res}	– 0.40 0.16 > 5%	0.61 0.37 *		– > 5%	– 0.58 0.34 **	0.49 0.24 *	–
f_{fos}	0.65 0.43 **	– 0.34 0.11 > 5%	– 0.71 0.50 **	– 0.57 0.33 *	0.70 0.50 ***	– 0.38 0.14 > 5%	– 0.60 0.36 **

The correlation is carried out for the variables of relevance here—CO₂pc as response variable for the regression analysis and the global domestic product per capita, GDPpc, the nuclear (f_{nuc}), and renewable fractions (f_{res}) as independent variables and, for completion, the fossil fraction f_{fos} . This table corresponds to Table 1 of [3]. p values are classified in the standard form: *** $p < 0.001$; ** $p < 0.01$; * $p < 0.05$

sion and fossil power fraction, f_{fos} , is clearly reproduced in both databases. The correlation coefficient is positive and about 50% of the variance is caught by the regression with f_{fos} . The p value is lower in case of DBeu because of the larger number of countries in this database.

The following observations are made:

- (1) The global domestic product per capita, GDPpc, does not correlate with CO₂pc with any statistical relevance. GDPpc correlates only with f_{res} in a noteworthy manner. The positive correlation can be interpreted in the sense that wealthier European countries could afford to invest more into renewable energies.
- (2) Like renewable energy, nuclear power correlates negatively with CO₂pc. The dependence of CO₂pc on f_{res} is stronger and more significant within DBeu than DBeun with 26 instead of 15 data samples. The analysis of the European nuclear countries yields a fairly symmetric reduction in CO₂ emission by nuclear power or renewable power, respectively. We conclude that both technologies qualify as clean CO₂-free energies.
- (3) f_{nuc} and f_{res} are negatively correlated, which has been interpreted in [3] as “*mutual crowding out*” of these two technologies. But in case of the European countries the statistical criteria do not attribute any significance to this correlation.

Next, we analyse the databases DBeu and DBeun by linear multiple regression in the hierarchical fashion as adopted in [3]. The dependent variable is in all cases CO₂ per capita emission (CO₂pc). As independent variables, we single out the gross domestic product per capita (GDPpc) and the generation shares of nuclear (f_{nuc}) and renewable (f_{res}) energies. For special issues, we also employ the fossil energy share, f_{fos} . The analysis will be carried out in 4 steps. The first step is the regression with GDPpc, the first independent variable. Though this parameter has turned out not to carry any relevance (see Table 2) we add it to maintain the parallelism to [3]. In the second step f_{nuc} , in the third step f_{res} is added. The ansatz of

Table 3 Results from hierarchical linear regression analyses with CO₂pc as independent variable are compiled starting with GDPpc and ending with adding two moderators

		Nuclear countries, DBeu			All European countries, DBeu		
		R^2	bi	p value	R^2	bi	p value
Step1	GDPpc	0.08	− 0.28	0.319	0.10	− 0.31	0.124
Step2	GDPpc	0.31	− 0.33	0.194	0.15	− 0.33	0.103
	f_{nuc}		− 0.48	0.070		− 0.23	0.252
Step3	GDPpc	0.43	− 0.07	0.827	0.54	0.03	0.868
	f_{nuc}		− 0.52	0.044		− 0.48	0.006
	f_{res}		− 0.45	0.149		− 0.77	0.000
Step4	GDPpc	0.46	− 0.12	0.742	0.57	− 0.03	0.881
	f_{nuc}		− 0.61	0.06		− 0.51	0.005
	f_{res}		− 0.55	0.22		− 0.84	0.000
	Mod GDPpc \times f_{nuc}		0.04	0.895		− 0.01	0.951
	Mod GDPpc \times f_{res}		0.22	0.497		0.22	0.235

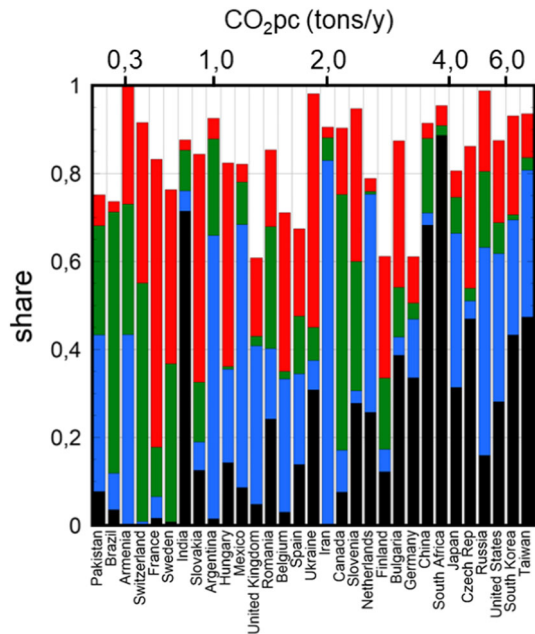
bi are the regression coefficients in the ansatz: $y = b_0 + b_1 \times x_1 + b_2 \times x_2 + \dots$. The variables are z-standardised. p values denote the significance whereas relations below the 5% level are marked in bold

step 4 is: $\text{CO}_2\text{pc} = b_0 + b_1 \times \text{GDPpc} + b_2 \times f_{\text{nuc}} + b_3 \times f_{\text{res}} + b_4 \times \text{Mod GDPpc} \times f_{\text{nuc}} + b_5 \times \text{Mod GDPpc} \times f_{\text{res}} + e$. In this step, two moderators are involved to test the strength of the main effects of f_{nuc} and f_{res} on CO₂pc. bi are the regression coefficients; e represents the remaining error. All parameters have been z-standardised.

Table 3 shows the main results from the regression analysis which can be summarised as follows:

- (1) GDPpc is not a significant variable for CO₂pc (see Sect. 4.2); the parameter of determination, R^2 , is small; the p value indicates that the null hypothesis cannot be excluded. A black-box use of standard stepwise regression [17] identifies f_{nuc} and f_{res} as the only significant explanatory variables. Obviously, the selected European countries are representatives of a comparably homogeneous economic region with regard to their energy mix. In order to explore the role of GDPpc in more detail, DBeu was split by the median into two groups. Both groups—characterised by low or high GDPpc—benefit emission-wise from the use of nuclear energy. In all cases, CO₂pc decreases with f_{nuc} .
- (2) R^2 increases in a distinct step by $\Delta R^2 = 0.23$ (DBeu) as soon as the nuclear fraction is included and in another distinct step when f_{res} is additionally added, whereas the dependence of CO₂pc on GDPpc becomes weaker and loses further significance (p value increases). In case f_{res} instead of f_{nuc} is first to follow GDPpc, $\Delta R^2 = 0.08$. Both parameters are able to improve the predictability of the dependent variable.
- (3) For both cases, the slope coefficients bi are negative indicating that CO₂pc decreases with increasing nuclear and renewable fraction. Both technologies seem to act rather symmetrically in reducing CO₂ emissions. The p values indicate significance for both f_{nuc} and f_{res} in the larger database DBeu and only for f_{nuc} in DBeu.
- (4) Including the moderators, the quality of the regression does not improve. The related p values indicate a lack of significance.

Fig. 8 The electricity shares of the countries of DBgln ordered according to the annual CO₂pc emissions as given by the upper abscissa. Red denotes the nuclear-, green the hydro-, blue the gas- and black the coal fraction. The missing part up to 100% is shared by oil used for electricity generation and wind and PV power and other renewables (geothermal, bio-waste...)



DBeu benefits from the larger number of data samples (26 instead of 15) but suffers from a lack of balance between data contributing to f_{res} and those to f_{nuc} . In this data array, 11 countries show $f_{\text{nuc}} = 0$. Nevertheless, the outcomes of DBeu are more-or-less confirmed by the analysis of DBeu.

3.4.2 Global databases DBgl and DBgln

The bar plot Fig. 8 introduces the countries of DBgln (as listed in Appendix A). The parameters selected are f_{nuc} , the hydroelectricity fraction f_{hydro} , the coal and gas fractions f_{coal} and f_{gas} . The graph displays directly the emissions of the different electricity generation technologies. The countries are ordered according to their CO₂pc emissions in ascending sequence (see top scale). It is obvious that a large hydro and nuclear fraction gives rise to low emissions. The most prominent cases are Brazil with a high renewable and France with a high nuclear fraction. Brazil has a very low nuclear share (2.6%) but the CO₂pc is nevertheless low thanks to a high $f_{\text{hydro}} = 0.65$. Switzerland and Sweden demonstrate that the combination of nuclear and hydro-generation pays-off in low emissions. Coal dominates toward higher CO₂pc emissions whereas the use of gas with a lower CO₂ emission intensity (see Table 7 in Appendix B) leads to placements more in the middle of the diagram. This is all comprehensible. India represents an exception because its position seems to be wrong as it is on the low-CO₂pc side with a high coal fraction. The reason is simply that the abscissa is ordered according to CO₂ per capita emissions, the dependent parameter used in many similar studies [26, 27, and references therein]. The location of India in this plot is not due to low-CO₂ emission technologies employed rather due to its large population. The choice of CO₂pc as dependent variable favours large populations with the association of clean electricity generation. Indeed, the ratio of $f_{\text{res}}/f_{\text{nuc}}$ increases with population introducing a bias favouring f_{res} for low emission. This topic will be picked up again in Sect. 4.2.

The statistical processing of DBgl and DBgl_n yields the following correlation and regression results:

1. Correlation results:

In agreement with the analysis of the European countries:

- (1) CO₂pc increases clearly with f_{fos} ;
- (2) both f_{nuc} and f_{res} show a relevant and strongly negative correlation with f_{fos} ;
- (3) GDPpc is not a relevant variable for per capita CO₂ emission;
- (4) both for DBgl and DBgl_n, f_{fos} and GDPpc show a strong and substantial negative correlation: the larger GDPpc is, the lower seems to be the use of fossil power;
- (5) f_{res} correlates positively with GDPpc—as identified in the European databases and interpreted there;
- (6) f_{nuc} and f_{res} are not correlated;
Unlike the European database, f_{nuc} correlates positively with GDPpc though without statistical relevance. This is only mentioned here to stress the lack of credibility of the sign of correlation coefficients under conditions of missing significance.

2. Regression results:

- (1) The regression coefficients with CO₂pc as dependent and f_{nuc} and f_{res} as independent variables are negative—as expected; the significance for f_{nuc} is at the 7% level; the one of f_{res} at the 1% level.
- (2) Again, the moderation with GDPpc carries no statistical significance.

3.4.3 Global database DBw(t)

This database compiles parameters of the world electricity generation and the related global CO₂ emissions over the last 30–35 years. In this period, electricity consumption rose by 120% and CO₂ emissions nearly doubled owing to an increase in fossil electricity generation by a factor of 2.2. GDP quadruplicated and GDPpc is—unlike the previous cases—highly correlated now with CO₂pc ($r = 0.97$) because of the joint evolution over a long period. CO₂pc showed a moderate increase by 30%. This historical view might help to anticipate the complexity expected for the next 30 years up to 2050, when also electricity has to be generated carbon-free.

Figure 9 summarises the temporal development of world electricity parameters related to the question of this paper. The average total CO₂pc emission increased moderately, the average annual CO₂pc emission in conjunction with electricity generation increased from 1.5 to 1.9 tons/y. The increase to new levels occurred mostly in the second half of the period considered. Also, GDPpc develops differently in this period with a steep rise in the second half. Both, f_{nuc} , the nuclear share, and f_{res} , the renewable share, hardly move initially. In this period, f_{res} is basically f_{hydro} . There is more dynamic in the second half with f_{res} increasing and f_{nuc} decreasing. To the increase of f_{res} , wind and PV power contribute: with respect to renewables, a technology change happens in the second half of the time window of Fig. 9.

Table 4 summarises the hierarchical regression results from DBw(t) for the period 1990–2014. CO₂pc decreases both with the use of renewable or nuclear power. The relations are significant. The moderators do not change the picture. The major difference to the previous finding is that GDPpc shows a strong and positive correlation with CO₂pc. Both develop in a period of growing economic prosperity, which, however, is mostly based on the use of fossil fuels and not of CO₂-free energies. In step 2 of the hierarchical regression, the sign of bi- f_{nuc} is negative but statistically insignificant. This changes in step 3 to the correct

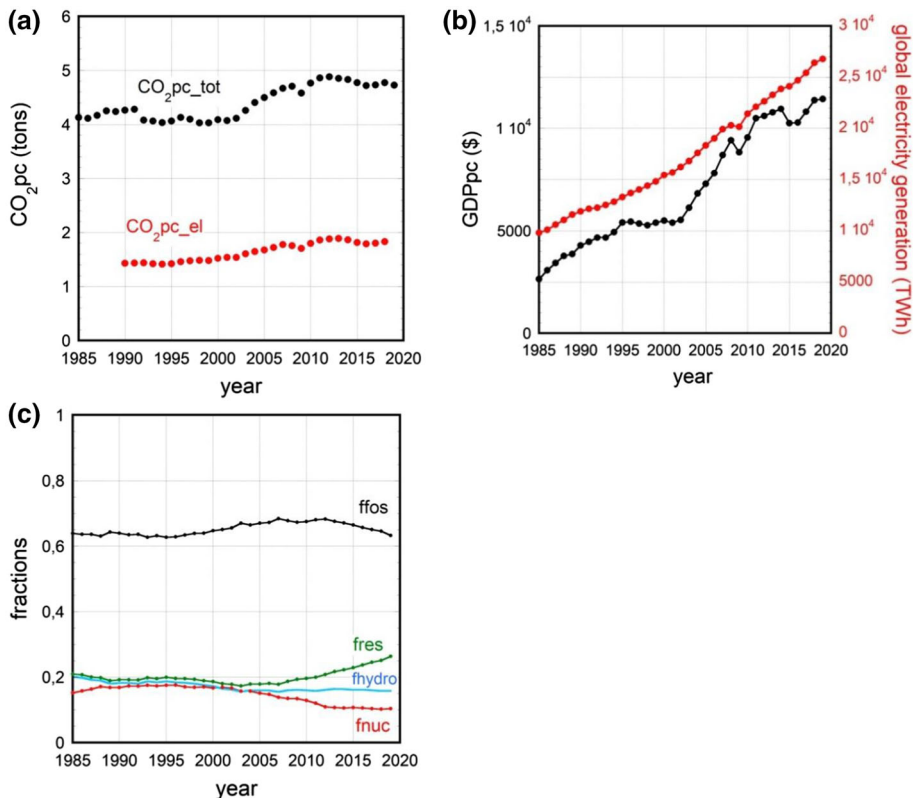


Fig. 9 The three graphs show results from the DBw(t) database in the time window from 1985 to 2019. **a** Shows the world annual per capita CO₂ emission CO_2pc_{tot} (black) and the one caused by electricity generation CO_2pc_{el} (red); **b** Plots the world global domestic product per capita, GDPpc, (black) and the world electricity generation (red); in **c**, the world fossil fraction f_{fos} , the renewable fraction f_{res} , the hydroelectricity fraction f_{hydro} , and the nuclear fraction f_{nuc} are plotted

sign, now with high statistical significance. With respect to the credibility of the analysis, it is interesting to note that the sign of $bi-f_{nuc}$ changes and becomes positive in step 2 when the analysis is extended from 2014 up to 2018. This is again mentioned only to illustrate the little robustness of the sign of statistics results under conditions of low significance.

3.5 Intermediate summary

The analysis of both European and more global data shows that both renewable and nuclear technologies allow a reduction of CO₂ emissions with comparable efficacy. This is obvious but also revealed by the statistical analysis of many countries grouped for cross-sectional analysis or by the analysis of a time series. As the use of nuclear power does not lead to CO₂ emission, this technology is therefore not subject to the European ETS CO₂ certificate system [18]. No evidence was found that countries using nuclear power systematically employ more fossil fuels preferentially coal to the extent that the emission-free nature of nuclear energy is not only offset thereby but even overcompensated. Such a conjecture is not supported by the analyses of the databases presented here: the average fossil shares are 50% and 61% in the complete databases DBeu and DBgl and with 34% or 41%, respectively, lower in the nuclear

Table 4 Results from step-wise linear regression analyses of the world database DBw(t) with data covering the range of 1990–2014

	World, DBw(t)	R^2	bi	p value
Step1	GDPpc	0.96	0.98	***
Step2	GDPpc	0.96	0.75	**
	f_{nuc}		− 0.24	> 5%
Step3	GDPpc	0.99	0.49	***
	f_{nuc}		− 0.60	***
	f_{res}		− 0.21	***
Step4	GDPpc	0.99	0.18	> 5%
	f_{nuc}		− 0.23	> 5%
	f_{res}		− 0.43	**
	Mod GDPpc $\times f_{\text{nuc}}$		− 0.18	> 5%
	Mod GDPpc $\times f_{\text{res}}$		0.94	> 5%

The variables are the same as in Table 3. The critical p values are defined in Table 2

databases DBeun and DBgln. In all cases, f_{res} or f_{nuc} , respectively, correlate negatively with f_{fos} with correlation coefficients of typically − 0.65.

There is perfect understanding of CO₂ emission by fossil fuels, which allows predictions and there is actually no need for any statistical assessment as carried out in this paper and many others [26, 27 and references therein]. If a statistical analysis is nevertheless of interest, the most obvious independent variables are total (E_{tot}), nuclear (E_{nuc}) and renewable (E_{res}) electricity generation. E_{tot} would allow to include considerations on additional electricity consumption by mobility and heating or, alternatively, on energy savings. E_{res} and E_{nuc} would limit E_{fos} and define the remaining emissions. A corresponding regression analysis using DBgln yields: $\text{CO}_2\text{el (Mill t)} = 0.083 + 0.91E_{\text{tot}} (\text{TWh}) - 1.73 E_{\text{nuc}} - 0.64 E_{\text{res}}$. The same analysis but with DBeun yields: $\text{CO}_2\text{el} = -2.87 + 0.76E_{\text{tot}} - 0.79 E_{\text{nuc}} - 0.69 E_{\text{res}}$ and with DBw(t): $\text{CO}_2\text{el} = 3108 + 0.81E_{\text{tot}} - 1.2 E_{\text{nuc}} - 1.08 E_{\text{res}}$. In the example of DBgln, the increase of E_{tot} by 1 TWh at constant E_{nuc} and E_{res} causes a CO₂ increase of 0.91 Mill tons; the increase of E_{nuc} or E_{res} , respectively, gives rise to corresponding emission decreases. $\text{adj}R^2$ of this relation is 0.99, the p value is below the 1% level for all dependent variables. The specific emission intensity of Germany, calculated on this basis, is 0.473 kg/kWh; the German data in DBeun together with the fuel-specific intensities of Table 7 of Appendix B yield 0.449 kg/kWh; the EU publishes as official figure for Germany 0.441 kg/kWh [19]. These numbers agree quite well.

We have to admit, however, that the regression of the total CO₂ emission with E_{tot} , E_{res} and E_{nuc} as independent variables does not provide any new or deeper insight; specifically, it does not open the door to the discovery of more speculative inner relationships and correlations with cultural and sociological factors as searched for in Ref. [3].

4 Comparison with other studies

4.1 Brief literature search

In the last decade, specifically economists have explored the correlation or even causality between energy consumption and CO₂ emission using statistical techniques. Iwata et al. [20] identified a uni-directional causality relationship from nuclear energy to CO₂ emissions confirming that nuclear power generates electricity emission-free. Apergis et al. [21] showed in

2010 that the relation between emissions and energy consumption has a statistically significant negative association in case of nuclear energy and a positive one in case of renewable energies. In the same year, Menyah and Wolde-Rufael [22] concluded that nuclear energy can help to mitigate CO₂ emissions, whereas renewable energy has not yet reached a level where it can make a significant contribution. The study of Jaforullah and Alan King [23] from 2015 indicated that CO₂ emission levels are negatively related to the use of renewable energy, but are unrelated to nuclear energy consumption. Guidolin and Guseo [24] demonstrated in 2016 that renewables crowd out nuclear power in Germany and have a measurable effect in determining the observed decline of nuclear power consumption. Jin and Kim [25] concluded in their 2018 study “that nuclear energy does not contribute to carbon reduction unlike renewable energy. Thus, the development and expansion of renewable, not nuclear, energy are essential to prevent global warming”. Hassan et al. [26] compared the effectiveness of both nuclear and renewable power in reducing emissions for the BRICS countries and concluded that nuclear power is less effective. Refs. [3] and [4] have already been introduced in Sect. 1.

Reference [27] provides an overview over 18 papers dealing with the “nuclear energy and CO₂ emission nexus”. These papers do not question the basic CO₂-free operation of nuclear power rather search for hidden relations, as stated in Ref. [3], “that higher political, institutional or infrastructural attachments or wider cultural attachments to either nuclear power or renewable energy tend to associate with a lower attachment to the other technology”. It is indeed the case that the energy transition of the last two decades is not organised technology-open in by far the most countries. Rather strong political and societal orientations pave one way or the other. A typical case is Germany, where strong political interests sacrifice nuclear power and have it replaced by renewable ones.

4.2 The selection of GDP_{pc} as independent variable

In the following, we will comment on some peculiarities of the databases used. A general problem of these statistical analyses could be the replacement of the energy/electricity use by GDP_{pc} as proxy. GDP subsumes many facets of economic activities including those which lead to environmental damages. Therefore, its inclusion might allow access to variables, which cannot directly be identified or expressed as data. The relation between energy or electricity on one hand and economic growth, represented by GDP on the other, is a vital field in economic research. A major issue is whether the availability of energy drives GDP, e.g. in a manner comparable to labour and capital. In numerous papers (see references in [27] and [28]), four causality hypotheses are tested—the growth hypothesis, the conservation hypothesis, the feedback hypothesis, and the neutrality hypothesis. The statistical analysis is supposed to attribute the energy-GDP relation to one of these four possibilities. Each of them has largely different consequences and leads to rather different policy advice, which is the main purpose of these studies. Two papers commented the status of understanding the energy-economic growth relation by critically reviewing the literature available at the time. Ozturk [27] came to the conclusion “that the literature produced conflicting results and there is no consensus neither on the existence nor on the direction of causality between energy consumption (electricity consumption) and economic growth”. Omri [28] published a more advanced literature survey discriminating between four topics—the roles of energy, electricity, renewable and nuclear electricity and their impact on economic growth. The author concluded: “Overall results from the reviewed studies in this subsection show that the literature on energy consumption—growth nexus produced inconclusive results and there is no consensus neither on the existence nor on the direction of causality among energy con-

sumption and economic growth”. “Energy” stands here for energy proper, and the other three energy forms, electricity, nuclear and renewable energy. Omri exemplifies the complexity in finding a consistent pattern in the energy-GDP relation by quoting explicitly results from two papers, which study specifically the nexus between nuclear energy and economic growth. Ref [29] reports on the growth hypothesis for Japan, Netherlands and Switzerland, the conservation hypothesis for Canada and Sweden and the feedback hypothesis for France, Spain, UK and USA. The authors of [30] came to contradictory results though they used the same analysis methods: Canada, Germany and UK follow the feedback hypothesis, USA the neutrality hypothesis and Japan the conservation hypothesis. As a clear causality between energy or electricity, respectively, and economic growth is not established in a broader sense, it might be a problem to select GDPpc as proxy for energy consumption. But a meaningful proxy needs a close correlation with the variable it replaces. One might also worry if a secondary aspect like mutual crowding out of renewable and nuclear technologies can be identified by statistical means if this procedure does obviously not allow to clarify unambiguously a first-order causality.

4.3 The normalisation of variables

Figure 8 shows India in the middle of countries, which justify their placement by low CO₂pc values. The normalisation to the population awards the merits of clean electricity production also to large countries in spite of fossil fuel use. Figure 10 provides more detail to this circumstance by selecting the low-CO₂pc emitting countries of DBgl with CO₂pc < 1 ton/y. The maximal CO₂pc value in this database is 8.3 tons per person. This selection is plotted in an f_{res} versus f_{fos} plane. Three observations can be made: (1) countries without nuclear power have to lie on the bisecting line; (2) countries with nuclear power deviate from this line because: $f_{\text{fos}} + f_{\text{nuc}} + f_{\text{res}} = 1$; (3) two classes of countries meet the above CO₂pc criteria:—clean countries with $f_{\text{fos}} < 0.3$ employing often also nuclear power and countries with $f_{\text{fos}} > 0.6$ with larger populations and generally little or no nuclear power. The selection of CO₂pc as independent variable mixes countries using clean electricity generation with populous ones.

4.4 The role of the leading CO₂ emitting countries

The data of DBgl and DBgln fall apart basically into two classes, the five largest CO₂ emitters China, USA, India, Russia and Japan on one side and the rest on the other. The corollary is a spreading of the data which governs some of the statistical results. These five large countries are responsible for 70% (82%) of the CO₂ emissions of all members in database DBgl (DBgln) and, therefore, play a prominent role for any policy advice, the quintessential aim of Ref. [3].

A separate analysis of these five countries yields the following results:

The total emission, CO₂_el, increases linearly with E_{fos} , the electricity generation by fossil fuels. The slope is 0.95 Mill t/TWh; $R^2 = 0.94$. These values compare well with the relation of all data of DBgl yielding a slope of 0.91 Mill t/TWh with $R^2 = 0.97$. This quality is totally lost after the normalisation to CO₂pc and f_{fos} . Whereas Japan and China occupy the corners and USA resides in the middle of a CO₂_el versus E_{fos} plot, USA and India are at the corners and China is in the middle of a CO₂pc versus f_{fos} plot. Whereas the spread in E_{fos} is large between Japan on one side and China on the other, allowing credible analysis, it is small when E_{fos} is replaced by f_{fos} (0.63–0.77). Nevertheless, a good linear fit is possible with a negative slope of -33 Mill t with $R^2 = 0.91$: the emission decreases with rising f_{fos} .

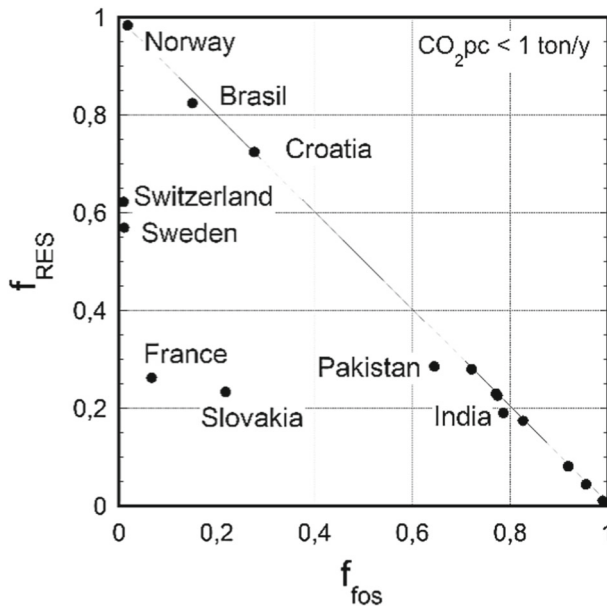


Fig. 10 A $f_{\text{res}}-f_{\text{fos}}$ diagram using DBgl data of low CO_2pc emitting countries ($\text{CO}_2\text{pc} < 1 \text{ ton/y}$) only. Countries without nuclear power are placed at the bisecting line. Countries in the lower right corner (like India) can have low per capita emissions owing to large populations

The results of this formal treatment are obviously nonsense. Nevertheless, the p value turns out to be 1%.

We have to conclude that a better statistical analysis is not possible in this case. *E.g.*, India and USA show similar f_{res} -values (0.21 vs. 0.19) but large differences in CO_2pc (0.87 vs. 5.7); India has a low CO_2pc thanks to her large population and a low f_{nuc} which define the CO_2pc versus f_{nuc} relation also in a large data sample giving unavoidably rise to a positive slope between CO_2pc and f_{nuc} . We have to conclude here that 66% of the world CO_2 emissions caused by electricity generation cannot be treated on statistical grounds using common normalisation. As a consequence, also for the less emitting countries, a policy advice on statistical ground does not seem to be feasible. Regarding the five large countries, there is hardly any evidence for the speculation that cultural attachments would favour nuclear power against renewables. Apart from Russia, the other four nuclear countries take positions between 1 and 8 in the Recai list of AY [11]. The Recai index reflects the market attractiveness for investments into renewable energies of 40 countries and is based on economic considerations.

4.5 The role of fossil power in the databases

In the following, we try to elucidate the impact of the fossil power fraction on the relations of CO_2pc with f_{res} and f_{nuc} in more detail. The fossil fraction varies in DBgl between 100% (Saudi Arabia) and 1% (Switzerland) and in DBgl between 92% (Iran) and the value of Switzerland. To explore the role of fossil power in more detail, DBgl was split into four groups: $f_{\text{fos}} > 2/3$; $2/3 \geq f_{\text{fos}} \geq 1/3$; $f_{\text{fos}} < 1/3$; and $f_{\text{fos}} < 2/3$. As DBgl contains a smaller sample of 31 data points, the two groups $f_{\text{fos}} > 2/3$ and $f_{\text{fos}} < 2/3$ were formed. Table 5 shows the regression results for CO_2pc with the three independent variables GDPpc , f_{nuc} and f_{res}

Table 5 Results of regression analyses are shown for all data of the databases DBgl and DBgl_n and of sub-groups restricted in the fossil fraction, f_{fos} . The regression of CO₂pc is carried out versus the independent variables GDPpc, f_{nuc} and f_{res} (= step 3 in the hierarchical analysis)

	R^2	biGDPpc	bi f_{nuc}	bi f_{res}	PGDPpc	p_{nuc}	p_{res}	$r_{\text{ffos};f_{\text{nuc}}}$
<i>DBgl</i>								
All data	0.34	0.44	− 0.2	− 0.62	0	0.064	0	− 0.57
$f_{\text{fos}} > 2/3$	0.44	0.94	0.53	− 0.28	0.001	0.425	0.526	− 0.32
$2/3 \geq f_{\text{fos}} \geq 1/3$	0.4	0.27	− 0.28	− 1.04	0.101	0.218	0.017	− 0.6
$f_{\text{fos}} < 1/3$	0.6	0.26	− 0.7	− 1.14	0.041	0.01	0.006	− 0.26
$f_{\text{fos}} < 2/3$	0.37	0.22	− 0.22	− 0.56	0.041	0.058	0	− 0.32
<i>DBgl_n</i>								
All data	0.41	0.44	− 0.29	− 0.64	0.014	0.072	0.001	− 0.69
$f_{\text{fos}} > 2/3$	0.68	0.5	1.41	− 0.84	0.221	0.177	0.266	− 0.26
$f_{\text{fos}} < 2/3$	0.45	0.36	− 0.53	− 0.71	0.05	0.016	0.002	− 0.42

The positive coefficient of CO₂pc with f_{nuc} of the group with $f_{\text{fos}} > 2/3$ is highlighted in italic. p values indicating significance are in bold. The variables had been z -standardised. The last column gives the correlation coefficient r between f_{fos} and f_{nuc}

(= step 3 in the hierarchical analysis). Of interest are the regression coefficients of f_{nuc} and f_{res} —their signs and relative magnitude—and the related p values.

For the $f_{\text{fos}} > 2/3$ group, CO₂pc is found to increase with f_{nuc} in both databases (marked in italic in Table 5). Regression analysis can yield a positive relation and it does not reproduce the correct action of this CO₂-free technology. The result is formal and has no significance (judged by the 5% p -level). For variables with significance at the 5% level, the p values in Table 5 are marked in bold. With less fossil power, the regression results for both f_{res} and f_{nuc} gain more significance. In these categories, both nuclear and renewable power reduce CO₂pc. We have to conclude that the actual and expected dependence can be hidden by samples with high fossil power fractions. However, for both databases, DBgl and DBgl_n, the correlation between f_{fos} and f_{nuc} is negative for all f_{fos} -groups (last column of Table 5). This confirms our previous findings: a hypothetical lack of CO₂ emission reduction when using nuclear power is not indirectly caused by an inherently higher fossil power share.

4.6 The role of hydroelectricity

Within renewable energies, hydroelectricity has the largest share with 15% in both databases, DBgl and DBgl_n. It is larger than the nuclear fraction of 12% (DBgl_n), or 11% (DBgl), respectively. In DBw(t), the hydro-share is 17%, whereas wind and solar electricity (with photovoltaic power, PV, being the dominant part) contribute with only 2%; in DBgl, the two figures are 15% and 7%. In case of Europe, wind and PV are with 15% at about the level of the hydroelectricity share. Table 6 summarises the results from correlation analysis where f_{res} is first replaced by f_{hydro} , the fraction of hydroelectricity, and then by $f_{\text{W+PV}}$, the fraction of wind and solar power. The results are shown only for DBgl. The first row of Table 6 repeats previous results: CO₂pc correlates negatively with f_{res} , which itself has no correlation with f_{nuc} whereas renewables replace or crowd out fossil power. The quality factors R^2 and the p value are also listed. In the next row, f_{res} is replaced by f_{hydro} . Rather similar correlation results are obtained. This is not surprising as f_{hydro} represents the dominant share within f_{res} . In the last row, f_{res} is replaced by $f_{\text{W+PV}}$, which accounts for 7% of the total generation.

Table 6 Correlation coefficients of f_{res} (f_{hydro} , $f_{\text{W+PV}}$) with CO_2pc , f_{nuc} and f_{fos}

DBgl	CO_2pc	R^2	p value	f_{nuc}	R^2	p value	f_{fos}	R^2	p value
f_{res}	− 0.45	0.2	***	− 0.02	0	>5%	− 0.81	0.66	***
f_{hydro}	− 0.4	0.16	**	− 0.01	0	>5%	− 0.66	0.42	***
$f_{\text{W+PV}}$	− 0.12	0.02	>5%	− 0.09	0	>5%	− 0.26	0.07	*

The respective R^2 and p values are also given; p values are defined in Table 2

R^2 does not indicate any meaningful correlation between CO_2pc and $f_{\text{W+PV}}$. In the standard regression analysis with CO_2pc depending on the three variables GDPpc , f_{nuc} and f_{res} the data variance is described less and less by the selected independent variables when replacing f_{res} by f_{hydro} or $f_{\text{W+PV}}$, respectively. f_{hydro} , however, turns out to be significant like f_{res} ; no significance at the 5% level could be observed for $f_{\text{W+PV}}$.

A recommendation to further develop renewable energies, which is based on the present data situation and uses statistical techniques, is foremost a recommendation to expand hydro-electricity. Though wind and solar power are the only technologies, which can be scaled to large power levels, their share is too small at present for their virtues to be resolved by statistical means. But hydroelectricity is exploited in many countries in Europe up to the limit of undue inroads into biodiversity [31] and is therefore no recommendation which can be generalised. The examples of Sweden and Switzerland demonstrate, however, that hydropower goes along well with nuclear power.

5 Conclusions

We conclude from the analysis presented here that both, nuclear and renewable power allow a reduction of national CO_2 emission levels. The negative correlation between CO_2pc and both f_{nuc} and f_{res} is the reason why the German energy policy—green electricity replaces CO_2 -free nuclear electricity—was not very effective in recent years to reduce CO_2 emissions.

The analysis of the databases employed in this study did not yield evidence for any further hidden variables, national CO_2 emission might possibly depend on. Specifically, no evidence for “crowding-out” can be detected. This may not be surprising because in the past, countries exploited first their own energy reservoirs and established the related technologies, which fixed the forms of electricity supply over decades. In case of nuclear power, the build-up of nuclear power reactors was nearly complete in 1990. The decisions to build nuclear reactors were taken years before. Within the first ten countries, listed in the latest Recai index [10], nine use nuclear power. Obviously, EY does not expect that the presence of nuclear power gives rise to losses of investments into renewable energies; rather the opposite seems to be the case [10].

It has to be recognised that nuclear energy is as capable as renewable power is in reducing CO_2 emissions. Several European countries may not have the natural conditions to meet the future national electricity demand by wind and PV power alone and because of high population density, it may not be possible to provide the required space for these low-energy density supplies. This is specifically crucial during the higher-demand winter months when PV power basically fails. European countries which protect the climate by employing nuclear power and are proficient in its development and use are to be encouraged to continue along this path to maintain their environmental standards, to continue meeting the electricity demand

of their industries by providing secured electric power, and to avoid the high expenses of importing renewable energies in the future in still unknown quantities and forms, from yet unknown suppliers made available there by technologies not yet proven at industrial scales. Chapter 2 of the 2018 ICPP report, Mitigation Pathways Compatible with 1.5 °C in the Context of Sustainable Development, summarises many of the related discussions and concludes on page 130: “By mid-century, the majority of primary energy comes from non-fossil fuels (i.e., renewables and nuclear energy) in most 1.5 °C pathways [32]”.

The environmental benefits of these two technologies have been confirmed in this paper.

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Data availability All data are from publicly open sources as given in the references.

Code availability Not applicable.

Declarations

Conflict of interest The author has no relevant financial or non-financial interests to disclose.

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Appendix

Appendix A: Countries compiled in the two databases (nuclear countries are underlined)

DBeu: Austria, Belgium, Bulgaria, Croatia, Cyprus, Czech Republic, Denmark, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Latvia, Netherlands, Norway, Poland, Portugal, Romania, Slovakia, Slovenia, Spain, Sweden, Switzerland, UK.

DBgl: Algeria, Argentina, Armenia, Australia, Austria, Belgium, Brazil, Bulgaria, Canada, Chile, China, Croatia, Cyprus, Czech Republic, Denmark, Egypt, Estonia, Finland, France, Germany, Greece, Hungary, India, Indonesia, Iran, Ireland, Israel, Italy, Japan, Jordan, Kazakhstan, Kenya, Latvia, Malaysia, Mexico, Morocco, Netherlands, Norway, Pakistan, Philippines, Poland, Portugal, Romania, Russia, Saudi Arabia, Serbia, Slovakia, Slovenia, South Africa, South Korea, Spain, Sweden, Switzerland, Taiwan, Thailand, Turkey, Ukraine, United Arab Emirates, United Kingdom, United States, Uzbekistan, Vietnam.

Table 7 Fuel-specific emission intensities ($\text{gCO}_2/\text{kWh}_{\text{el}}$) of fossil fuels

	Hard-coal	Lignite	Gas	Oil
Literature values typical for Germany [42]	929	1074	487	591
DBeu	1020	1094	424	(431)
DBgl	1000		449	(435)
DBw(t)	1119		(118)	(1480)

Literature values typical for the German power mix [42] and regression results to compare with are listed for the three databases studied here. In DBeu, lignite and hard coal are provided separately. The values in brackets are without statistical significance

Appendix B: databases and data handling

All data used in this paper are related to electricity generation and they are collected from publicly accessible sources. Three sets of databases are put together – one with European data only (DBeu and DBeun), one with global data (DBgl and DBgln) and one with world data (DBw(t)). DBeun and DBgln are subsets restricted to countries employing nuclear power. DBeu (DBeun) lists 26 (15) countries; DBgl (DBgln) lists 62 (31) countries. The countries of DBeu and DBgl are listed in appendix A. The European and the global data are from 2018 and are used in cross-sectional studies. DBw(t) looks at the temporal development of electricity-related data from 1990 to 2018.

Each database contains the CO_2 emission per capita in tons per year, CO_2pc , as response variable. Independent parameters are the nuclear power fraction, $f_{\text{nuc}} = E_{\text{nuc}}/E_{\text{tot}}$ and the renewable power fraction $f_{\text{res}} = E_{\text{res}}/E_{\text{tot}}$ with E_{nuc} , E_{res} , E_{tot} being the annual nuclear, renewable and total electricity energy. E_{res} is added up from hydropower, wind, PV, biomass, and waste. The fossil fuel share of electricity generation $f_{\text{fos}} = E_{\text{fos}}/E_{\text{tot}}$ is added up from coal, gas and oil consumption for electricity production. A direct dependence of CO_2 emission on E_{fos} can be expected. f_{fos} , f_{res} and f_{nuc} add up to one. Following general practice, we also include the gross-domestic-product per capita, GDPpc .

The data of the European databases are average values from different sources. Electricity generation data are used preferentially from IEA [15], AGORA Energiewende [33], and bp Statistical Review of World Energy [34]. CO_2 emission-related data are provided by references [15, 35–38]. Historical data (1960 and thereafter) are obtained from CLIMATEWATCH [39] and the energy history project of the Joint Center for History and Economics [40]. World Bank data are used for GDP and population [41]. The data of the global databases DBgl and DBw(t) are exclusively from IEA [15].

The reliability of the European data for DBeu and DBeun is controlled in two steps. First, we compare published CO_2 -emission intensities measured in $\text{gCO}_2/\text{kWh}_{\text{el}}$ with the calculated emissions based on the shares of coal, gas, and oil in electricity generation. The fuel-specific emission factors, necessary to calculate the specific CO_2 contributions are taken from the literature [42] and are representative for German fossil power generation. The parameters are listed in Table 7 for the four fossil fuel forms. For those cases where coal is quoted without discrimination between lignite and hard coal, we take the average. Figure 11 compares the calculated specific emission intensities with averaged published values [35–37]. The horizontal bars indicate the respective maximal and minimal country value in the different data sources. This plot should provide a visual impression of the overall data quality. Data of Estonia, Lithuania, Luxemburg, and Malta have been omitted as they are obvious outliers

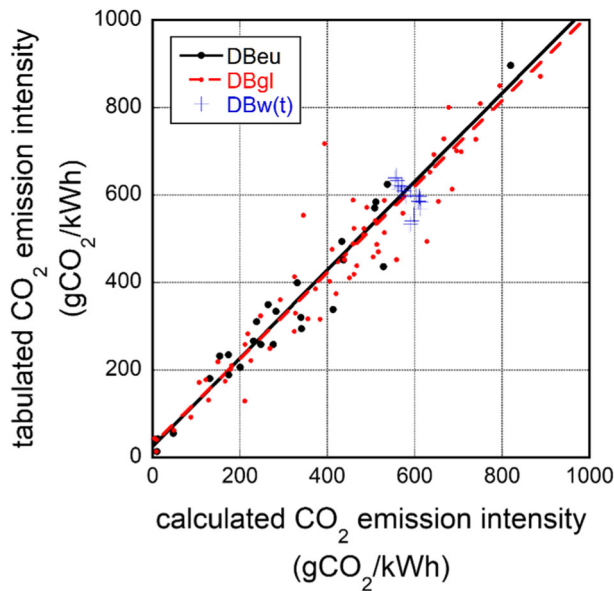


Fig. 11 For the three databases DBeu (black), DBgl (red), and DBw(t) (blue) calculated CO₂ emission intensities from electricity generation are compared with values taken directly from the data sources [15, 35–38]. The calculated emission intensities are obtained from the fuel-specific values of Ref. [42]. The black dots of DBeu represent the average values of the data sources

indicating inconsistencies in the databases. In case of Lithuania and Luxemburg, one reason could be the high electricity import, falsifying the consistency of the data if ignored. Estonia may be a special case as it uses shale oil for most of its electricity generation.

After this step, the final European database comprises 26 countries, 24 from EU (without the four eliminated EU members) and with Norway and Switzerland. 15 of these countries use nuclear energy.

In a second step of scrutinising the consistency of the data, the three databases were regression analysed (total CO₂ emission by electricity generation versus electricity from coal, gas and oil) yielding the fuel-specific emission intensities. The results are listed in Table 7 for the three databases and can be compared with the standard results provided by Ref. [42] (first line in Table 7). The *p* values indicate “significance” for all specific CO₂-intensities apart from oil and gas in case of DBw(t). One reason is the little use of oil in electricity generation (~5% in the average).

We conclude from Table 7 and the results shown in Fig. 11 that the emission factors—total CO₂ emissions or specific emission intensities—are fairly well reproduced by the country-specific shares of fossil power and that the data quality allows the statistical analyses as presented here.

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