Final assignment: CO_2 emissions

Climate change has been a political issue since the 1970s, with United Nations Conference on the Human Environment in Stockholm in 1972, identifying the need to work on a global scale. From the 1990s onwards, multiple agreements and treaties have been put in place to reduce or at least slow down the growth of greenhouse gas emissions. Despite such pledges and commitments, the atmospheric concentration of CO_2 and other greenhouse gases continues to rise.

In this report, we will be considering three questions: What predicts CO_2 output? Which countries have succeeded in reducing their CO_2 output? And, finally: Which non-fossil fuel energy technology will have the best price in the future?

1. Biggest predictor of CO_2 output per capita

There are different ways to compare CO_2 and other greenhouse gas (GHG) emissions. Here, we will be using 'consumption-based CO_2 emission', as opposed to 'production-based CO_2 emission'. Consumption-based means that emissions embedded in export have been subtracted, emissions embedded in import have been added. This represents therefore, more fairly the CO_2 emissions of a particular country. The dataset available on Our World In Data combines multiple sources. Data on CO_2 emissions from the Global Carbon Project are calculated per capita, using information on population from the UN World Population Prospects.[1]

Contributing factors

What could be a predictor of CO_2 output of a country? First of all, it would seem very likely that the energy sources that are used, determine for a large part a country's CO_2 emission level. Therefore, we will include data on consumption of oil, gas and coal. This is the primary consumption per capita in kilowatt-hour, adjusted for trade.[2] 'Primary energy' refers to the energy available as resource: raw, unprocessed input into the energy system.

Secondly, the way that energy is used might also make a difference. Are we using energy in a certain way or is our way of living such that we contribute to CO_2 emission levels? Let us consider some factors that might give an indication:

- Air pollution worsens as countries industrialize and transition from low to middle incomes.[3] It is calculated as a weighted average (between rural and urban areas) of the level of exposure to concentrations of suspended particles measuring less than 2.5 microns in diameter (PM2.5).[4] Because of limitations in monitoring, this 'should be considered only a general indication of air quality, intended to inform cross-country comparisons of the health risks due to particulate matter pollution'.

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[1] https://github.com/owid/co2-data/.
[2] https://ourworldindata.org/grapher/per-capita-coal, https://ourworldindata.org/grapher/per-capita-oil and https://ourworldindata.org/grapher/per-capita-gas.
[3] https://ourworldindata.org/outdoor-air-pollution: There are also higher values in the Middle East and North Africa, due to drier conditions: 'much of the local air pollution could be derived from dust and sand particles as opposed to anthropogenic sources of industry and agriculture'.
[4] https://ourworldindata.org/grapher/PM25-air-pollution.

- The use of motor vehicles. This is measured as ownership of road motor vehicles per 1000 people, including automobiles, SUVs, trucks, vans, buses, commercial vehicles and freight motor road vehicles, but excluding motorcycles and other two-wheelers.[5]
- Meat and dairy production and consumption are said to have a relatively large carbon-footprint. Meat production is strongly correlated with Gross Domestic Product (GDP), so is excluded here. Milk production is measured in tons.[6]
- Following the same principle, we could consider vegetable supply. This refers to the average supply of vegetables for consumption across the population, measured in kilograms per person per year. It accounts for wastage along distribution chains, but not at the consumption-level (such as in retail, restaurant and household setting) and therefore overestimates the amount of food actually consumed.[7]
- According to Our World in Data, improved crop yields are one way to reduce emissions from food production and agriculture: 'Sustainable intensification of agriculture allows us to grow more food on less land. This could help to prevent deforestation from agricultural expansion, and frees up land for replanting, or giving back to natural ecosystems.'[8] There is data on yields (in ton) per hectare for maize, potato, wheat, soy, rice cultivation.[9]

Information on vehicle ownership is only published for 2013, on daily kilocalories and crop yields only for 2014. For these years, consumption CO2 emission levels are available for 120 countries.

Correlation

When gathering data for these factors, as well as some others (see *Appendix, Table 4)*, there were some outliers: such as Singapore for oil consumption per capita and Qatar and Trinidad and Tobago for gas consumption per capita. For that reason, Spearman's rank correlation coefficient was used to calculate the correlation between the factors and CO2 emission. The correlation coefficient for data from 2014 is represented in *Figure 1*, from 2013 in *Figure 2*.

While GDP is strongly correlated with CO2 emission (as 'consumption' in *Figure 1* and *Figure 2*), it was not used to create a model, as GDP is also strongly correlated with oil consumption. For the same reason primary energy consumption (as 'energy') was also discarded as factor, as to avoid multicollinearity. As shown in *Figure 2*, access to electricity is correlated with urbanization, but neither factors have a correlation with CO2 emission.

For 2014 (*Figure 1*), we can see that CO2 emission is strongly correlated with oil consumption (0.88), vehicle ownership (0.84) and gas consumption (0.7) and to a lesser extent with use of fertilizers, vegetable supply, air pollution and milk production (0.51-0.43). For 2013 (*Figure 2)* we find approximately the same values. Crop yields have correlations between 0.41 and 0.69 (maize) and kilocalories have a correlation coefficient of 0.73 with CO2 emission. In the models (*Table 1*) 'crop yields' refers to the values for potato, wheat and rice, as these seemed to have the greatest effect on R-squared and BIC values.

[5] https://ourworldindata.org/grapher/motor-vehicle-ownership-per-1000-inhabitants.
[6] https://ourworldindata.org/grapher/milk-production-tonnes. This refers to the total production of fresh milk, excluding the milk for young animals, but including milk fed to livestock. The dataset is incomplete, particularly for African and Asian countries.
[7] https://ourworldindata.org/grapher/vegetable-consumption-per-capita.
[8] https://ourworldindata.org/co2-and-other-greenhouse-gas-emissions.
[9] https://ourworldindata.org/grapher/key-crop-yields. This refers to crops harvested for dry grain only, excluding crops harvested for hay or harvested green for food, feed or silage or used for grazing.

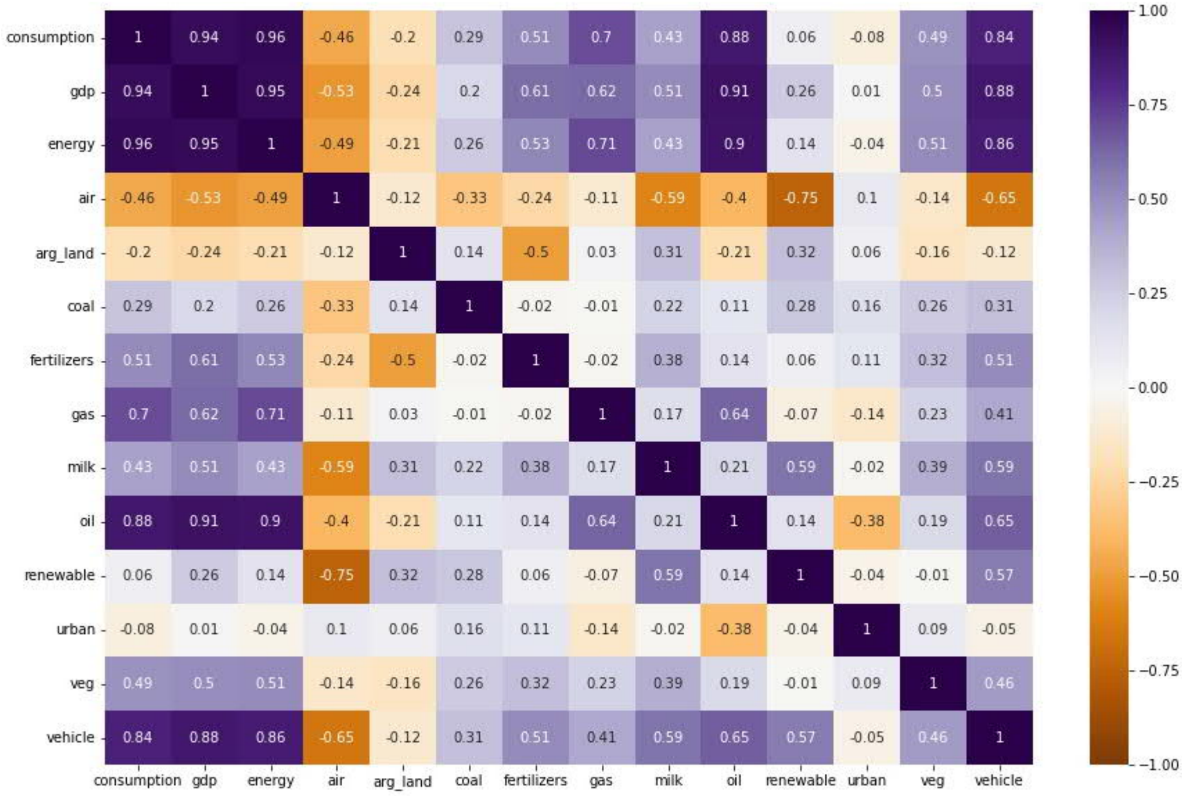

Figure 1 Spearman's rank correlation coefficient for 2014

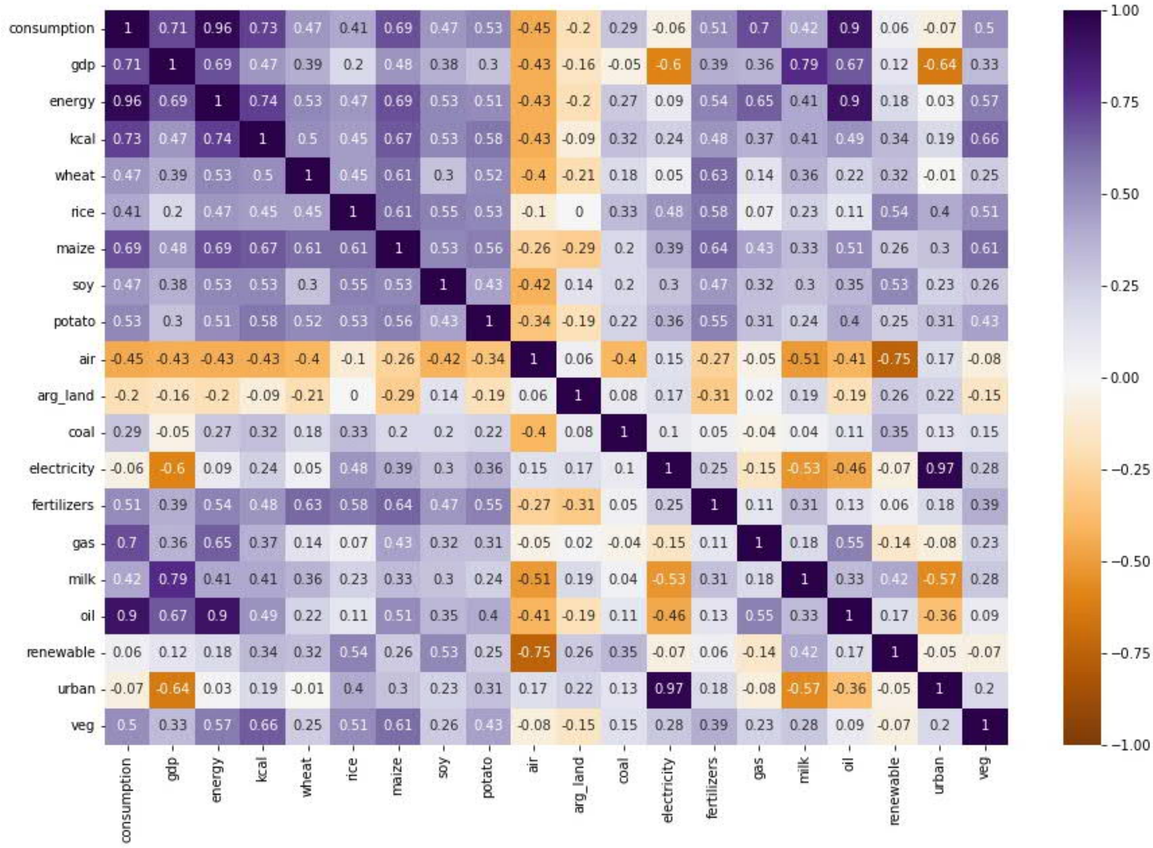

Figure 2 Spearman's rank correlation coefficient for 2013

In *Table 1* we can compare different Ordinary Least Squares regression models (made with statsmodels), which predict the log value for consumption CO2 emission using the log value of different factors. Shown here are the Adjusted R-squared, Bayesian information criterion (BIC), Root Mean Squared Error (RMSE) and Mean Absolute Error (MAE) values. It is clear that predicting CO2 emission with the consumption of fossil fuels alone (model 1), is not enough. Adding factors such as vegetable supply, air pollution and crop yields (model 5), result in a better model.[10]

Model	Year	Factors	Adj. R^2	BIC	RMSE	MAE
1	2014	oil, gas, coal	0.894	20.84	6.813	7.167
2	2014	oil, gas, coal, veg, air	0.930	-2.373	6.719	6.742
3	2014	oil, gas, coal, veg, air, vehicle	0.934	-3.897	6.735	6.747
4	2013	oil, gas, coal, veg, air, milk	0.935	-2.007	5.005	6.868
5	2013	oil, gas, coal, veg, air, crop yields	0.978	-38.50	4.702	4.448
6	2013	oil, gas, coal, milk, air, crop yields	0.978	-37.63	4.738	4.455

Table 1 Models to predict consumption CO2 emissions (for R^2 higher is better, otherwise: lower is better).

2. Countries decreasing CO2 output

Globally atmospheric CO2 concentration is still on the rise, although CO2 emissions from fossil fuels may have peaked in 2019.[11] Which countries have succeeded in reducing their CO2 output?

Again, let us consider the annual consumption-based emission of CO2. To verify that the increase or decrease in consumption CO2 emission for each country is not due to an increase or decrease in population, we can calculate the annual CO2 emission per capita (measured in tons). These data are available since 1990 and up until 2019 for 118-120 countries.[12]

1990: baseline

Agreements to reduce greenhouse gas emissions have been in place since the 1990s, with the first binding target being recorded in the 1997 Kyoto Protocol. For these agreements the goals for reductions were different for 'developing' and 'developed' countries or low-income countries. The United Nations Framework Convention on Climate Change established this concept in 1992: 'The Parties should protect the climate system for the benefit of present and future generations of humankind, on the basis of equity and in accordance with their common but differentiated responsibilities and respective capabilities. Accordingly, the developed country Parties should take the lead in combating climate change and the adverse effects thereof.'

The Kyoto Protocol had 192 parties with binding targets (52 countries) or without, and with targets in the first (2008-2012) and/or second period (2013-2020). For most countries, 1990 was set as the base year, and commitments were set as a percentage of the base level of emissions.

Table 2 shows the 15 countries that had the largest decrease in consumption CO2 emission between 1990 and 2019. The 'Change' column represents the CO2 emission value for 1990 minus the value for 2019. A positive value therefore indicates a decrease, a negative value indicates an increase in CO2 emissions. Note that despite this decrease, United Arab Emirates and Singapore are still in the top 15 countries with the highest CO2 emission levels for 2019.

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[10] The plotted residuals however, show heteroscedacity.

[11] https://ourworldindata.org/explorers/climate-change and https://thebreakthrough.org/issues/energy/peak-co2-emissions-2019.

[12] The dataset includes 230 countries, but the information on consumption CO2 is not available for all.

Country	1990	2019	Change	Net-zero target
Bahrain	23.39	11.55	11.84	Yes
United Arab Emirates	30.71	20.65	10.06	Yes
Estonia	20.26	11.26	9.00	Yes
Kazakhstan	17.78	12.32	5.45	Yes
Slovakia	13.73	8.43	5.30	No
Germany	15.05	9.88	5.17	Yes
Ukraine	9.83	4.88	4.95	Yes
Czechia	14.59	9.68	4.90	No
Finland	16.05	11.29	4.76	Yes
Netherlands	13.41	8.65	4.76	No
Singapore	23.71	19.11	4.60	Yes
Greece	9.40	5.13	4.26	Yes
Russia	13.83	9.82	4.01	Yes
United Kingdom	11.70	7.71	3.99	Yes
Denmark	12.00	8.27	3.73	Yes

Table 2 Change in annual consumption CO2 emission (ton per capita), 2019 vs 1990 (a positive value indicates a decrease).

2005: Kyoto protocol in force

Although the Kyoto protocol was established in 1997, it was only put in force as of 2005. *Table 3* shows the same calculated 'Change' column as *Table 2*, now comparing emissions levels for 2005 and for 2019. A positive value indicates a decrease in CO2 emission. In *Table 3* we find more countries belonging to the top 15 with the highest CO2 output per capita (*Appendix, Table 5*): United Arab Emirates, Singapore, Qatar, Belgium, United States and Kuwait. While having high emission levels, these countries have somewhat succeeded in bringing down those levels since 2005.

Country	2005	2019	Change	Net-zero target
United Arab Emirates	35.74	20.65	15.09	Yes
Singapore	32.20	19.11	13.09	Yes
Ireland	17.10	8.45	8.65	Yes
Qatar	32.91	27.08	5.83	No
Belgium	20.29	14.87	5.43	No
United States	22.36	17.10	5.26	Yes
United Kingdom	12.05	7.71	4.34	Yes
Kuwait	25.55	21.32	4.23	No
Finland	15.52	11.29	4.23	Yes
Denmark	12.41	8.27	4.13	Yes
Spain	9.47	5.83	3.64	Yes
Greece	8.65	5.13	3.52	Yes
Italy	10.51	7.43	3.08	Yes
Netherlands	11.72	8.65	3.07	No
Germany	12.87	9.88	2.99	Yes

Table 3 Change in annual consumption CO2 emission (ton per capita), 2019 vs 2005 (a positive value indicates a decrease).

Net-zero targets

Were countries that set a net-zero target for CO2 emission better at decreasing their CO2 emission levels? In *Table 2* three countries have a net-zero target, in *Table 3* four out of fifteen. Note that none of these net-zero targets were in place in 1990.

Yet, there is significant difference (p=0.0079) between the net-zero-target-group and the no-target-group when comparing the change in CO2 emissions between 1990 and 2019 and between 2005 and 2019 (p=0.0056).[13] *Figure 3* indicates this difference for 2005-2019.

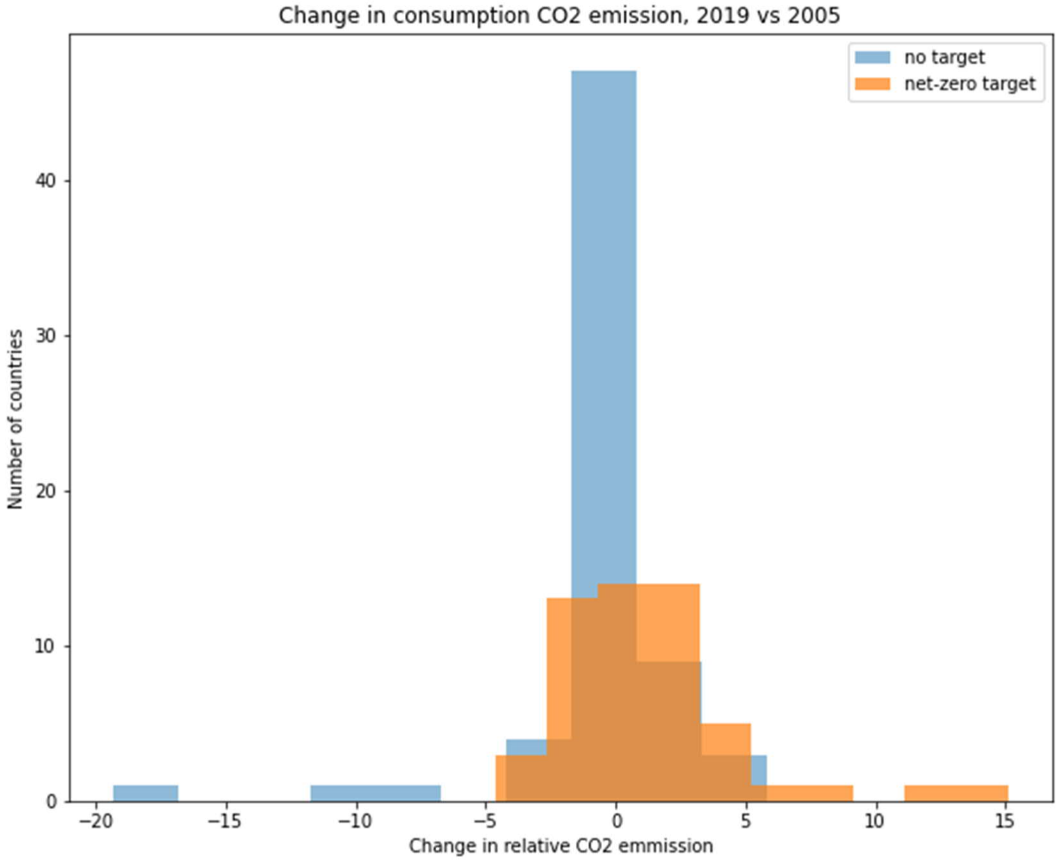


Figure 3 Change in consumption CO2 emission, 2019 vs 2005 (a positive value indicates a decrease).

For this comparison, the countries are recorded as having a net-zero target or not. In reality, the targets vary widely, as does the quality of the plans to achieve them.

For instance, the United Arab Emirates have made a pledge to reduce CO2 and other greenhouse gas emissions compared to projected emissions, 'reduction against Business as Usual', as it is called. The first interim target year is 2030, the target year is 2050. The pledge does not cover consumption CO2, whether it includes international aviation and shipping is not specified. According to the Net Zero Tracker the plan is incomplete, with no formal accountability, a reporting mechanism with a frequency less than annual and no statement as to how the target 'represents a fair or equitable contribution to limit global warming'.[14]

In comparison, Germany's Climate Change Act has legal force. It is an emission reduction target with the aim to decrease annual CO2 and other GHGs emissions compared with the historical baseline of 1990: a first target of 65% less CO2 in 2030 and climate neutrality in 2045. The target does not cover

[13] Based on a Two Sample T-Test with 66 countries with a net-zero target, 53 countries without.
[14] Net Zero Tracker for United Arab Emirates, https://zerotracker.net/countries/united-arab-emirates-cou-0122.

historical emissions or emissions from consumption or international aviation and shipping.[15] The Net Zero Tracker has no record of a concrete plan, but there is an annual reporting mechanism in place and the target statement refers to equity.

3. Price of non-fossil fuel energy in the future

Which non-fossil fuel energy technology will have the best price in the future?

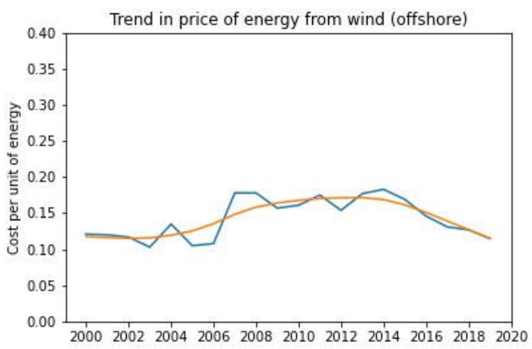
Levelized cost of energy

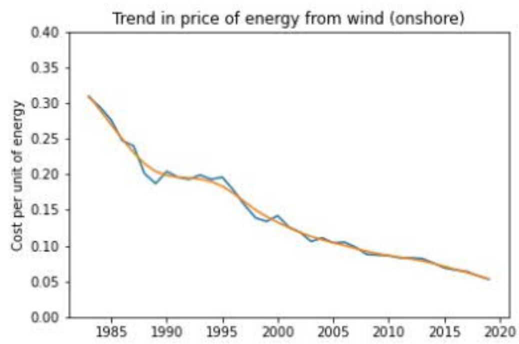
To compare different energy sources, their cost is calculated as a levelized cost of energy (LCOE): 'the average cost per unit of energy generated across the lifetime of a new power plant', measured in 2019 US dollars per kilowatt-hour (kWh). The LCOE captures the cost of building a power plant and the ongoing costs for fuel and operation over the power plant's lifetime. It does not take into account such systemic costs as when storage or backup power is needed, due to the variable output from wind and solar power.

A weighted average for the world, calculated by the International Renewable Energy Agency (IRENA), is available on the website Our World in Data for the following energy sources: Concentrated solar power (CSP), Hydropower, Solar photovoltaic (PV), Onshore wind, Offshore wind, Bioenergy and Geothermal.[16] Data on the cost of wind energy is available over a longer period, for the other sources it covers the period 2010-2019.

Figure 4 show the trends in LCOE per technology. There is a clear downward trend for onshore wind, solar PV and CSP, a slight downward trend in recent years for offshore wind and a slight downward trend for bioenergy, although there is an increase for 2018-2019. The cost for hydropower and geothermal (not shown) is increasing. Note that the starting cost for hydropower and bioenergy is lower: approximately 0.04 USD/kWh and 0.08 USD/kWh respectively.

While the cost of CSP is decreasing, it is not decreasing as rapidly as the LCOE for solar PV and onshore wind. CSP refers to solar power concentrated by mirrors or lenses, which is converted to solar thermal energy and can incorporate thermal energy storage. It has some disadvantages, such as use of land for the large-scale power plants and use of water for cooling. Due to technical difficulties and high prices, it has a slower growth than solar PV technology.





[15] Net Zero Tracker for Germany, https://zerotracker.net/countries/germany-cou-0028 and 'Intergenerational contract for the climate', 25 June 2021, https://www.bundesregierung.de/breg-de/themen/klimaschutz/climate-change-act-2021-1936846.
[16] https://ourworldindata.org/grapher/levelized-cost-of-energy?country=~OWID_WRL.

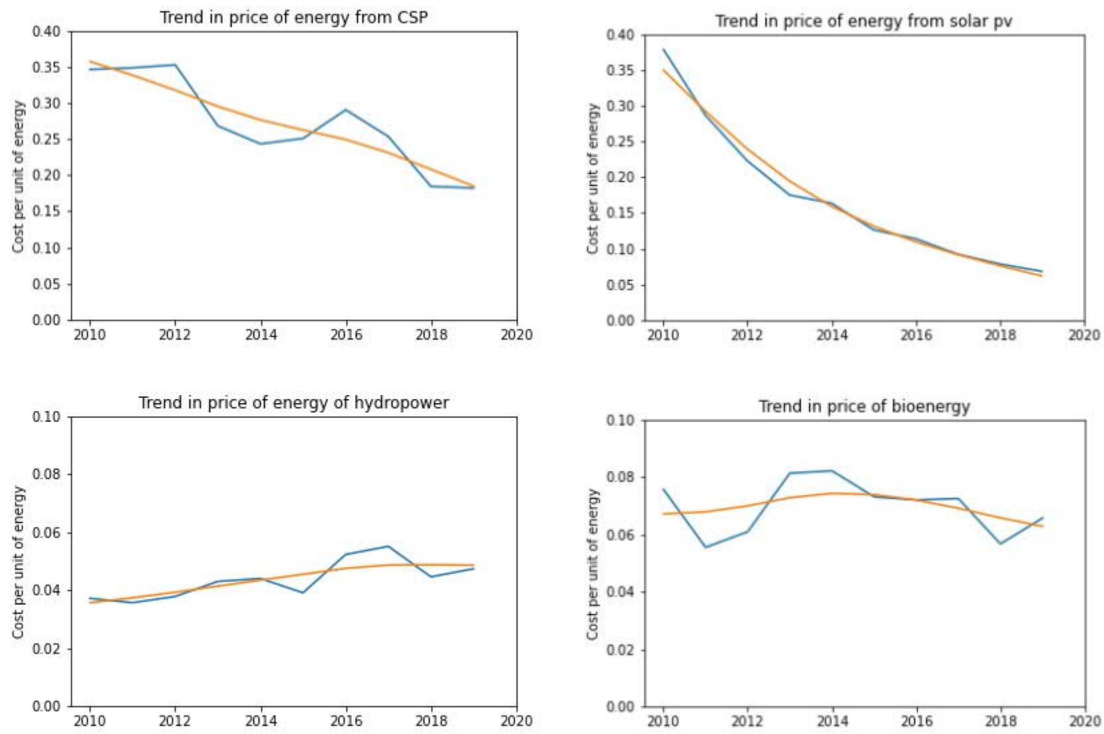


Figure 4: Trend in LCOE per energy source (trend in orange).

As argued by Max Roser (founder and director of Our World in Data), non-fossil fuel energy technologies have a learning curve, meaning that 'with each doubling of the cumulative installed capacity their price declines by the same fraction'.[17] This occurs mostly because the determining factor in the cost of renewable energy, is the cost of the technology itself. Roser calls it a 'virtuous cycle of increasing demand and falling prices' where, as installed capacity increases exponentially, the price of electricity declines exponentially.

The learning curve is certainly steep for solar and onshore wind energy. In *Figure 5* the LCOE for solar PV and onshore wind are plotted against the consumption of solar and wind energy in terawatt-hour.[18] For these data on energy consumption, there is no distinction between onshore and offshore wind or solar PV and CSP, but offshore wind and CSP generate 5,97% and 0,15% of wind and solar energy respectively.[19]

[17] Max Roser, ' Why did renewables become so cheap so fast?', 01 December 2020, https://ourworldindata.org/cheap-renewables-growth.
[18] https://ourworldindata.org/grapher/primary-sub-energy-source. Categories are: oil, coal, gas, hydropower, nuclear, wind, solar, biofuels and 'geothermal biomass and other renewables'.
[19] IRENA, 'Wind energy', https://www.irena.org/wind and 'Solar energy', https://www.irena.org/solar. In 2019 onshore wind energy produced 1,328,054 GWh and offshore wind 84,330 GWh, solar PV produced 678,999 GWh and solar thermal 1,064 GWh.

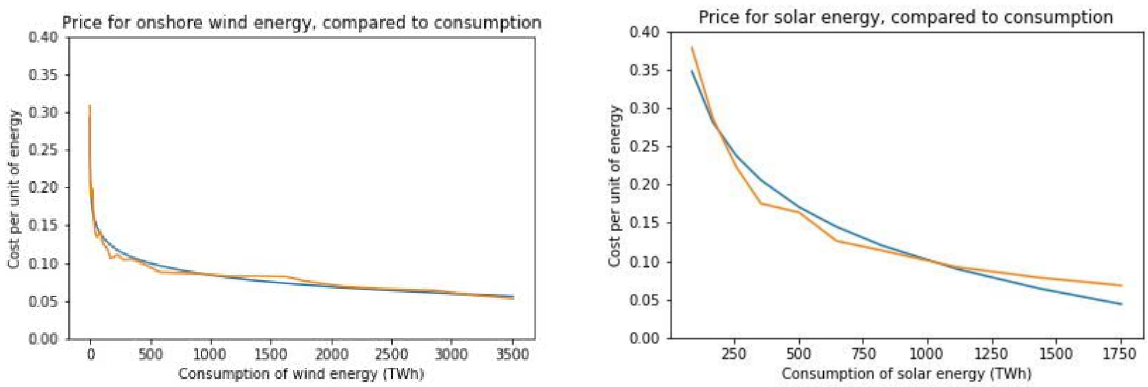


Figure 5: LCEO for wind and solar energy, compared to consumption (fitted curve in blue).

The LCOE for onshore wind power is 0.0530 USD/kWh, for a consumption of 3511.70 TWh.

Fitting a curve (with scipy.optimize) results in the equation:

*LCOE onshore wind = -0.0224 * log(consumption wind energy) + 0.2389*

R-squared is 0.9668.

The LCOE for solar PV is 0.0684 USD/kWh, for a consumption of 1752.96 TWh.

Fitting a curve results in:

*LCOE solar PV = -0.1013 * log(consumption solar energy) + 0.8007*

R-squared is 0.9624.

The LCOE for solar PV started at a higher point, but is decreasing more rapidly with increasing consumption of solar energy.

Clean, safe and sustainable

Considering the renewable energy with the best price for the future, not only should we expect that price to decrease with increasing consumption, we would also want the technology concerned to be sustainable and therefore suitable for increasing consumption.

Hannah Ritchie (head of research at Our World in Data) investigated the 'safest' and 'cleanest' energy sources, but states that there is no energy source that is completely safe: 'They all have short-term impacts on human health, either through air pollution or accidents. And they all have long-term impacts by contributing to climate change. But, their contribution to each differs enormously.'[20]

Ritchie measured the 'safety' in terms of deaths per terawatt-hour of electricity production: 4.6 for biomass, 1.3 for hydropower, 0.04 for wind and 0.02 for solar. This accounts for deaths from air pollution, caused by the burning of fossil fuels and biomass, and accidents. The death rate for hydropower is almost completely based on one accident: the Banqiao Dam Failure in China in 1979 which killed approximately 171,000 people. For solar and wind energy, there are accidents in the supply chains, 'ranging from helicopter collisions with turbines; fires during the installation of turbines or panels; and drownings on offshore wind sites'.[21]

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[20] Hannah Ritchie, 'What are the safest and cleanest sources of energy?', 10 February 2020, updated July 2022, https://ourworldindata.org/safest-sources-of-energy.

[21] Ibidem.

'Cleanness' of an energy source is measured in emission of CO2-equivalents per gigawatt-hour of electricity over the lifecycle of a power plant. For biomass this variates between 78 and 230 tons, for hydropower it is calculated at 34 tons, for solar at 5 and for wind at 4 tons. This is based on the needed fuels, transportation and maintenance.

Another study on lifecycle energy use and GHG emissions from different sources of electricity found that fossil fuels, hydropower and bioenergy require 'significantly' more energy to build power stations and provide them with fuel and other input, than nuclear, wind and solar power.[22] As to direct and indirect GHG emissions: nuclear, wind and solar have a much smaller footprint than coal, hydropower or bioenergy. The footprint of hydropower and bioenergy is highly variable and uncertain. The numbers for both the lifecycle energy use and GHG footprint indicate that solar PV is 'cleaner' than CSP, and wind slightly cleaner than solar energy. Although this study uses a global average, it mentions that wide geographical variation is particularly apparent for solar and hydropower.[23]

The required energy and GHG emissions alone are not enough to determine the 'cleanness' of an energy technology. What about the availability of materials? Is the production process sustainable or does it rely on non-renewable sources?

Solar PV requires metals and minerals. Hazardous materials are used in the production. With a lifespan of 20-30 years, the recycling methods for solar PV panels are still very much lacking.[24] Granted, the technologies for recycling and production are constantly being updated. The development of PV cells is classified in 'generations'. The first two generations are actually mainly responsible for the commercial sector. The first generation PV cells are made with crystalline silicon, the second generation uses thin-film semiconductors between panes of glass. This can be made with CIGS (copper indium gallium selenide), CdTe (Cadmium telluride) or Amorphous silicon (a-Si). Third generation PV cells are being developed using thin-film technologies with organics materials and other compounds.[25] All in all, solar PV requires silver and other elements such as silicon, germanium, gallium, indium, selenium and tellurium and structural materials such as glass. The production of batteries, potentially needed for energy storage, also relies on minerals.

For wind turbine production, structural materials consist of concrete, steel, fiberglass, resin or plastic, aluminum, chromium, copper, iron or cast iron.[26] It also requires specific materials such as the rare-earths used in permanent magnets-based wind turbines, and metals.[27] Wind turbines are for

[22] Simon Evans, 'Solar, wind and nuclear have 'amazingly low' carbon footprints, study finds', 8 December 2017, https://www.carbonbrief.org/solar-wind-nuclear-amazingly-low-carbon-footprints/.
[23] Ibidem: 'The best solar technology in the sunniest location has a footprint of 3g CO2/kWh, some seven times lower than the worst solar technology in the worst location (21g CO2/kWh). Even at this top end, however, solar's footprint is very low compared to other sources.'
[24] Institute for Energy Research, 'The mounting solar panel waste problem', 12 September 2018, https://www.instituteforenergyresearch.org/renewable/solar/the-mounting-solar-panel-waste-problem/. The lead, cadmium, and other toxic chemicals can leach into the soil (and drinking water) when solar panels break – as can happen during a storm or when disposed of in a landfill. The cost of recycling is generally higher than the value of the recovered material.
[25] Conor Prendergast, 'Solar panel waste. The dark side of clean energy', 14 December 2020, https://www.discovermagazine.com/environment/solar-panel-waste-the-dark-side-of-clean-energy mentions a material called perovskite and lead from recycled batteries or nontoxic metals such as tin or germanium, as an alternative to silicon. See also: Mahmood Shubbak, 'Advances in solar photovoltaics. Technology review and patent trends', 15 August 2020, https://media.suub.uni-bremen.de/handle/elib/4326.
[26] As well as manganese, molybdenum, nickel, and zinc.
[27] 'Raw materials demand for wind and solar PV technologies in the transition towards a climate-neutral Europe', 22 April 2020, https://eitrawmaterials.eu/raw-materials-demand-for-wind-and-solar-pv-technologies-

the most part recyclable, except the turbine blades. The lifetime of turbine blades made with a fiberglass-epoxy composite is about 20-25 years. So far there has been little technology or market to recycle them: with the materials difficult to separate and every form of disposal and transport costing energy, most discarded turbines blades will end up in a landfill. There have been experiments with other materials to make blades with a longer lifespan. There are some companies developing ways of recycling the discarded blades.[28]

IRENA estimates that by 2050 there could be 78 million tons of solar PV waste accumulated, globally; by the same year the waste material of wind turbine blades could reach 43 million tons.[29]

Production of solar panels, wind turbines and batteries all come with human rights and environmental risks associated with the mining of metals and rare-earth elements, such as radioactive waste and acidic wastewater. These processes also pose a possible risk to biodiversity and other ecosystem functions such as generating clean air and water, as rare-earth element mining areas overlap with regions designated as protected areas, key biodiversity areas and remaining wilderness.[30]

In the future

Using the data for 2010-2019, it is impossible to predict the development of offshore wind production and price (see *Figure 4*).[31] Offshore fixed and floating foundations are still relatively expensive. But offshore wind is expected to become cheaper in the coming years, primarily due to larger turbine sizes, with access to stronger and more consistent wind.[32] IRENA also sees potential in floating foundations farther from shore and the creation of combined-technology power plants. A report from 2021 states: 'By the end of 2020, the installed offshore wind capacity is more than 34 GW [Gigawatt], which represents an increase of 6 GW of new installations from 2019 and around 11 folds increase from 2010 with nearly 3 GW installed capacity. Europe represents 90% of installed capacity but the fastest growth is observed in China (3 GW installed in 2020). IRENA foresees a promising outlook growing to around 380 GW in 2030.'[33]

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in-the-transition-towards-a-climate-neutral-europe/. The rare-earths used in wind turbines are dysprosium, neodymium, praseodymium and terbium.

[28] Such as making them into skis or source material: 'Old Dutch wind turbine blades becomes new skis', 10 June 2022, https://group.vattenfall.com/press-and-media/newsroom/2022/old-dutch-wind-turbine-blades-becomes-new-skis and Christina Stella, 'Unfurling the waste problem caused by wind energy', 10 September 2019, https://www.npr.org/2019/09/10/759376113/unfurling-the-waste-problem-caused-by-wind-energy?t=1658257937336.

[29] IRENA, 'End-of-life management: solar photovoltaic panels', June 2016, https://www.irena.org/publications/2016/Jun/End-of-life-management-Solar-Photovoltaic-Panels and Pu Liu and Claire Barlow, 'Wind turbine blade waste in 2050', April 2017, https://www.sciencedirect.com/science/article/abs/pii/S0956053X17300491.

[30] Tobi Thomas, 'Mining needed for renewable energy "could harm biodiversity"', 1 September 2020, https://www.theguardian.com/environment/2020/sep/01/mining-needed-for-renewable-energy-could-harm-biodiversity. Underlying study: https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7463236/.

[31] The price for offshore wind energy has a correlation of 0.14 with consumption of wind energy and 0.66 with investment in wind energy. Data for investment is only available for 13 years. Trying to put this in a model (with statsmodels.OLS) resulted in adjusted R-squared of only 0.419.

[32] Simon Evans, 'Wind and solar are 30-50% cheaper than thought, admits UK government', 27 August 2020, https://www.carbonbrief.org/wind-and-solar-are-30-50-cheaper-than-thought-admits-uk-government/. The UK Department for Business, Energy and Industrial Strategy expects offshore wind to become cheaper than onshore by the mid-2030s.

[33] IRENA, 'Energy from the sea. An action agenda for deploying offshore renewables worldwide', 21 May 2021, https://www.irena.org/events/2021/May/An-Action-Agenda-for-Deploying-Offshore-Renewables-Worldwide/.

In a report on offshore renewables IRENA also identifies the potential for other offshore energy technologies such as tidal and wave energy and floating solar PV. Out of these options, offshore wind has the best LCOE: with a 2020 global average of 0.089 USD/kWh for fixed and a 2019 global average of 0.160 USD/kWh for floating offshore wind structures. IRENA expects the LCOE for offshore wind to reach 0.05-0.08 USD/kWh in 2023 for fixed and 0.13 USD/kWh by 2024 for floating foundations.[34]

Conclusion

Although data for consumption-based CO2 emissions is only available for 120 countries, it seems clear that consumption of fossil fuel alone is not enough to predict CO2 emissions per capita. Other factors, such as vegetable supply, air pollution and crop yields should be considered as well.

Some of the largest emitters have succeeded in decreasing their CO2 emission levels since 2005: United Arab Emirates, Singapore, Ireland, Qatar, Belgium (of which Qatar ranks in the top 5 largest emitters). There seems to be a (positive) difference in he reduction of CO2 emission when countries make pledges towards CO2 neutrality, regardless of the quality of the plan to accomplish this.

Based on the virtuous circle of consumption and price since 2010, energy from solar PV, followed by onshore wind, appears to have the best price. We have seen that solar PV has the steepest learning curve: its prices are decreasing the fastest, as consumption of solar energy increases.

Predicting the best price for the future however, is complicated. Firstly, this price is largely determined by the price of the technology itself, which is constantly evolving. Although is it unclear from the data presented here, offshore wind energy apparently has great potential, based on expected technological development.

Secondly, the data on the levelized cost of energy per energy source does not account for the safety, cleanness and sustainability of energy production. When considering the future, these factors need to be taken into account as well. Studies have shown that compared to solar PV, onshore wind results in slightly less GHG emission and needs slightly less energy in production and operation. Yet all these 'renewables' rely on non-renewable resources and other materials that pose serious vulnerability and risk, in production as well as in recycling. It is impossible to truly compare solar PV and onshore wind energy here in terms of sustainability. It seems that wind energy has at least less dangerous waste material, yet the disposal of that material might costs a lot of energy.

Lastly, all these assumption are concerned with the global average, meaning that the more these technologies are used globally, the more their price will decrease, but the price and the technology with best return for that price will differ per location.

[34] IRENA, 'Offshore renewables. An action agenda for deployment', July 2021, https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2021/Jul/IRENA_G20_Offshore_renewables_2021.pdf

Appendix

Table 4: Variables used to find correlation with consumption CO2 emission.

Abbreviation	Measurement
air	PM2.5 air pollution, mean annual exposure (µg/m³)
arg_land	Agricultural land per capita (ha)
coal	Coal consumption per capita (kWh)
consumption	Annual consumption-based emissions of CO2 per person (tons)
electricity	Access to electricity (% of population)
energy	Primary energy consumption per capita (kWh)
fertilizers	Nutrient nitrogen N per area of cropland (kg/ha)
gas	Gas consumption per capita (kWh)
gdp	Gross domestic product (international-$), with 2011 prices used to adjust for inflation and price differences between countries
kcal	Daily caloric supply per capita (kcal)
maize	Maize yields (ton/ha)
milk	Milk production (tons)
oil	Oil consumption per capita (kWh)
potato	Potato yields (ton/ha)
renewable	Renewables (% sub energy), not including traditional biofuels
rice	Rice yields (ton/ha)
soy	Soybean yields (ton/ha)
urban	Urban population (% of total population)
veg	Annual vegetable supply per capita (kg)
vehicle	Motor vehicles per 1000 people
wheat	Wheat yields (ton/ha)

Table 5: Countries with highest annual consumption CO2 emission levels (tons) in 2019 per capita.

Country	1999	2005	2019
Luxembourg	30.97	31.80	36.44
Qatar	22.55	32.91	27.08
Brunei	17.20	11.47	23.00
Mongolia	4.13	3.45	22.75
Trinidad and Tobago	9.62	14.28	21.68
Kuwait	18.70	25.55	21.32
United Arab Emirates	30.71	35.74	20.65
Singapore	23.71	32.20	19.11
Saudi Arabia	11.94	15.05	18.83
United States	19.96	22.36	17.10
Canada	17.63	17.92	15.38
Australia	14.50	16.98	14.90
Belgium	15.43	20.29	14.87
Hong Kong	15.31	14.39	14.55
South Korea	7.47	11.80	13.61