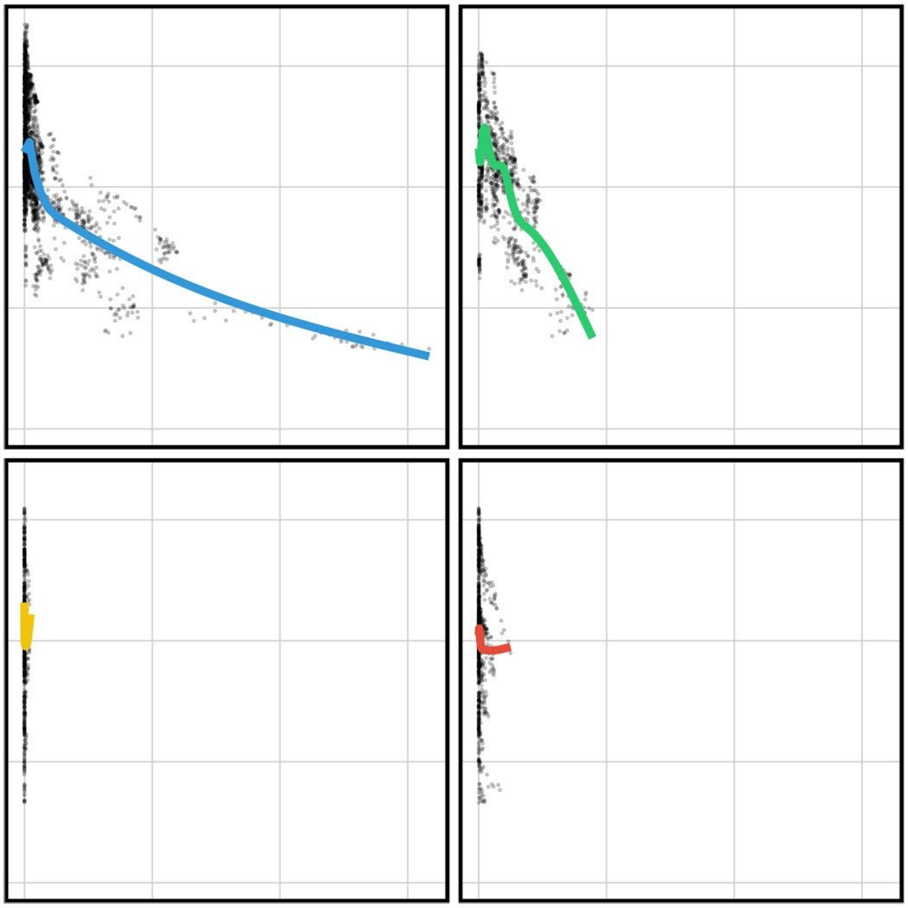

THE POWER TO DECARBONIZE

Characterizing the Impact of Hydroelectricity, Nuclear, Solar, and Wind on the Carbon Intensity of Energy

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Introduction

By Michael Shellenberger

This report was born from an ongoing effort by the staff and research fellows of Environmental Progress and other researchers to understand the fastest way to decarbonize national economies (i.e., reduce emissions per unit of gross domestic product) in order to mitigate anthropogenic climate change. We publish it to fill a gap in the scientific literature and the regularly issued reports by the Intergovernmental Panel on Climate Change (IPCC), which are overwhelmingly focused on modeling future scenarios with little regard for real-world historical trends.

My own involvement in analyzing decarbonization began a half-decade ago when I was president of Breakthrough Institute. In 2012, we published an analysis that decomposed the two drivers of carbon intensity of the economy: changes to the energy intensity of the economy and changes to carbon intensity of energy.[1] The study found that five nations decarbonized their economies at rates double the global historic average. Sweden and France did so mostly by decarbonizing energy supply, while the United Kingdom and Ireland did so mostly by reducing the energy intensity of their economies. Belgium did so through a roughly equal contribution of the two.

The Breakthrough study concluded that state-led efforts to deploy nuclear energy caused the decarbonization of energy in France and Sweden while the shift to service economies caused the decline in energy intensity in the UK and Ireland. Contrary to widespread opinion at the time, the decline in energy intensity was driven not through increased energy efficiency but sectoral shifts largely independent of state policies. Moreover, those nations that had decarbonized rapidly by reducing energy intensity were outliers. "[E]xcepting Ireland," the Breakthrough analysis concluded, "in no cases are sustained energy intensity improvement rates observed much in excess of 2 percent per year, with most nations experiencing rates ranging from 1 to 1.5 percent per year."

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[1] Jenkins, J., Mansur, S., Borofsky, Y., & Burgess, J., April 3, 2012. "Historic Paths to Decarbonization," Breakthrough Institute. Available at: https://thebreakthrough.org/archive/which_nations_have_reduced_car.

As such, the Breakthrough analysis reached a conclusion that was, at least at the time, surprising: state-led efforts to deploy nuclear power plants are the only *proven* way for governments to deliberately and rapidly decarbonize economies. If there were other ways for governments to achieve the same outcome, they hadn't been proven. The analysis reads:

> *While sectoral economic transitions are largely outside the domain and impact of energy policy, and deindustrialization is hardly a global strategy for rapid decarbonization, it appears that history presents at least one replicable strategy to accelerate the pace of decarbonization: the directed decarbonization of global energy supplies via the state-led development and deployment of scalable zero-carbon energy technologies.*

The analysis was surprising to me for a different reason. The data appeared to contradict what Breakthrough and I had been arguing for several years. Until then, we had been calling for state-led efforts to accelerate technological innovation to make clean energy — principally renewables like solar and wind, but also nuclear — cheap.[2] But the analysis concluded that what mattered most was "standardization, economies of scale, rapid construction and quick installation" of nuclear plants.

Renewable energy advocates responded that the Breakthrough findings had to be wrong because it takes so much longer to build a nuclear power plant—with much of the protracted timeframes owing to construction delays—than, say, a solar or wind farm. This response was specious, since it compared solar and wind farms that generated far less electricity than nuclear plants—a point that would be made one year later in a then-novel analysis by Geoff Russell, a mathematician in South Australia, for Breakthrough.[3]

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[2] Shellenberger, M., et al., February, 2008. "Fast Clean and Cheap: Cutting Global Warming's Gordian Knot," *Harvard Law and Policy Review*. Available at: https://thebreakthrough.org/blog/Fast%20Clean%20Cheap.pdf.

[3] Russell, G., June 20, 2013. "Nuclear Has Scaled Far More Rapidly Than Renewables," Breakthrough Institute. Available at: https://thebreakthrough.org/index.php/programs/energy-and-climate/nuclear-has-scaled-far-more-rapidly-than-renewables.

Russell's analysis compared the total amount of clean, electrical energy added by different nations during 11-year periods of peak deployment. (Russell calculated *per-capita* added energy to control for population.) He found that Sweden, France, and Belgium produced seven, two, and five times more electrical energy, respectively, with nuclear during their 11-year peak deployment periods than did Germany during its own 11-year peak deployment period with solar. As such, Russell noted, it could be said that nuclear was "faster" in decarbonizing than solar or wind.

Part of the power of these studies was the fact that no complex modeling was required to reach their conclusions and thus could be easily replicated by lay analysts without need for publication in peer-reviewed scientific journals. Even so, a team of six respected scientists, including Environmental Progress (EP) Senior Science Advisor, James Hansen, published a bar chart of "Average annual increase of carbon-free electricity per-capita during decade of peak scale-up" in *Science* in August last year.[4] (See Figure II.) That chart used more recent data than Russell and, generously, combined solar and wind into a single bar. But even then the chart showed the peak deployment of nuclear was up to 12 times faster than the peak deployment of solar and wind.

Then, in the summer of 2017, EP Senior Analyst Mark Nelson and EP Research Fellow Arun Ramamurthy took these analyses of energy decarbonization a step further. Where I had simply sought to update existing analyses, Mark and Arun were after something far more ambitious. Why only compare decades of peak deployment between a small set of countries, they reasoned, when there was publicly available data covering 68 nations over 52 years (1965 - 2016)? And why only look at solar, wind, and nuclear? Why not include hydroelectricity, which is the largest source of clean electricity globally?

I was both surprised and unsurprised when they showed me an early version of the four-square chart (See Figure IV.) that aggregated the national cases depicting the relationship, or lack thereof, between the per-capita deployment of nuclear, hydro, wind, and solar and carbon intensity of energy. I was unsurprised in that it showed what I had come to

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[4] Cao, J., et al*.,* August 5, 2016. "China-U.S. Cooperation to Advance Nuclear Power," *Science.* Available at: http://science.sciencemag.org/content/353/6299/547

expect: the deployment of nuclear was strongly correlated with declining carbon intensity of energy. I also wasn't particularly surprised by the correlation between the deployment of hydroelectricity and energy decarbonization, given how much power large dams generate.

On the other hand, I was surprised to see no correlation between solar or wind and the carbon intensity of energy at an aggregated level. After all, both clean energy sources are associated with the decarbonization of *electricity*, and the deployment of wind appears to have caused the decarbonization of energy in Denmark. Additionally, the decadal "peak deployment" bar graphs had suggested some correlation between solar and wind deployment and decarbonization, albeit a far more modest correlation than that between nuclear and hydro deployment and decarbonization. (I was further surprised nobody had conducted a similar analysis before — something we address directly in this report.)

While the deployment of nuclear (and hydro) at national scales for some countries can be safely said to have *caused* reductions in carbon intensity, we err on the side of caution and refrain from claiming a causal connection at aggregated national levels. In the context of a single nation like France, the deployment of nuclear energy very clearly drives energy decarbonization.

The causal relationship between nuclear and changes to carbon intensity are further demonstrated when nuclear plants are closed, as they were in Japan following the 2011 Fukushima accident. When their nuclear plants were closed, the Japanese energy supply recarbonized immediately, and there is no doubt as to why. There are too many other factors that could confound such a strong claim of causality at aggregated national levels, however.

In service to transparency, we have reproduced all 68 national carbon intensity of energy charts used in this analysis in Appendix C, in addition to publishing the aggregated national charts in Appendix B.

Ten years after my initial forays into this subject area I am more than ever of the view that a future-facing climate policy must be informed by backward-facing energy analysis. The attention given by energy analysts, policymakers, and the IPCC to scenarios ungrounded from history is wildly disproportionate to the attention given to the real world experience of deploying clean energy technologies and their impact, or lack thereof, on carbon intensity and emissions. Given what's at stake, this constitutes a grave error. Those who insist on ignoring the past, to modify Santayana, should not be allowed to force the rest of us to repeat it.

Section I. Climate Policy and the Decarbonization of Energy

Stabilizing atmospheric concentrations of greenhouse gas emissions requires significant decarbonization of energy supplies around the world.[5] Decarbonization of energy—quantified here as the reduction of carbon dioxide emitted per unit of primary energy consumption—is driven by transitions from energy sources which are more carbon-intensive (like coal, oil, and natural gas) to those which are less carbon-intensive (like water, uranium, wind, and sun) . Past energy transitions include the transition from biomass, principally wood and dung, to coal; from coal to oil; and from coal to natural gas.[6]

The International Panel on Climate Change (IPCC) notes that the rate of decarbonization globally over the last two centuries averaged 0.3 percent per year. If that rate were to persist, then the complete transition away from fossil fuels would occur in the latter half of the 22nd century,[7] far too late to keep global temperatures below levels deemed dangerous under the United Nations Paris climate agreement.

There is significant policymaker interest in which policies decarbonize energy most rapidly, and for good reason: the higher the rate of decarbonization, the more quickly atmospheric greenhouse gas emissions could stabilize, and the lower the cost of climate change mitigation.[8] As such, the IPCC and other institutions inform policymaker choices by creating different decarbonization scenarios based on different assumptions about future energy transitions. For instance, the IPCC notes:

> *In the majority of low-stabilization scenarios, the share of low-carbon electricity supply (comprising RE, nuclear and [carbon capture and storage] CCS) increases from the current share of*

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[5] IPCC, 2014. "Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change." Pachauri, R., & Meyer, L., (eds.). IPCC, Geneva, Switzerland, p. 100.

[6] Grübler, A., Nakićenović, N., & Victor, G., 1999. "Modeling Technological Change: Implications for the Global Environment." *Annual Review of Energy and the Environment*, 24(1). pp. 545–569. Available at: https://doi.org/10.1146/annurev.energy.24.1.545 .

[7] Grubler, A., et al., 1999. From 1965 to 2016, the rate of energy decarbonization was 0.37 percent per year.

[8] IPCC, 2014, p. 17.

> *approximately 30% to more than 80% by 2050, and fossil fuel power generation without CCS is phased out almost entirely by 2100.*[9]

Over the last decade, governments and private investors around the world have followed IPCC recommendations and made significant investments in solar and wind in an effort to mitigate greenhouse gas emissions.

According to Bloomberg New Energy Finance (BNEF), public and private actors spent $1.1 trillion on solar and over $900 billion on wind between 2007 and 2016.[10] According to BNEF, global investment in these clean energies hovered at about $300 billion per year between 2010 and 2016.

To put this roughly $2 trillion in investment in solar and wind during the past 10 years in perspective, it represents an amount of similar magnitude to the global investment in nuclear over the past 54 years, which totals about $1.8 trillion.

While this cost comparison is inexact, we sought to make it a practical aid to understanding. First, we inflated the dollar amounts for overnight cost of capital for historic nuclear reactors as presented in Lovering et al.[11] from 2010 dollars to 2016 dollars. Second, we added to the total overnight capital costs an estimated total interest charges of 25 percent. (Lovering et al. does not attempt to estimate or include interest costs.) Lastly, we supplemented the inflated and interest-adjusted totals derived from Lovering et al. with similarly estimated costs for the roughly one-third of historical and under-construction reactors that were not included in the Lovering et al. analysis, assuming similar overnight capital costs and interest charges.

The majority of the investment in renewables, occurring between 2010 and 2016, were made during a period marked by declines in the cost of

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[9] Bruckner, T., et al., 2015. "Energy Systems," IPCC AR5. Available at: https://www.ipcc.ch/pdf/assessment-report/ar5/wg3/ipcc_wg3_ar5_chapter7.pdf.

[10] Liebreich, M., 2017. "London Summit 2017: Breaking Clean," *Bloomberg New Energy Finance*. Available at: https://data.bloomberglp.com/bnef/sites/14/2017/09/BNEF-Summit-London-2017-Michael-Liebreich-State-of-the-Industry.pdf.

[11] Lovering, J., Yip, A., Nordhaus, T., 2016. "Historical construction costs of global nuclear power reactors," *Energy Policy*, Volume 91, pp. 371-382. Available at: https://doi.org/10.1016/j.enpol.2016.01.011.

solar and wind projects and unusually low interest rates. By contrast, most reactors in North America and Europe were constructed and financed during a period of high inflation, with construction delays and cost overruns heavily influencing their costs.

Solar and wind capacity growth has often exceeded forecasts by official energy agencies. This growth above expectations has been extreme. In 2004, for example, the International Energy Agency (IEA) predicted that yearly installed wind capacity would rise to 11 GW by 2015, and that global yearly installed solar capacity would rise to 2 GW. Nearly every year since 2004, IEA has revised its forecasts for solar and wind capacity additions upward. And for good reason: the amount of wind capacity installed in 2015 was not 11 GW, but instead about 63 GW[12], a factor of six higher. Installed solar capacity for 2015 was about 51 GW[13], a factor of 25 higher.

Over the last several years, capacity additions of solar and wind have outpaced additions of all other sources of electricity including coal, natural gas, and nuclear. In 2016, while solar and wind added 75 GW and 55 GW of capacity respectively, coal, natural gas, and nuclear added 57 GW, 29 GW, and 10 GW respectively.[14]

As a result, the installed capacity of solar and wind has grown 292 GW and 393 GW respectively, which is an increase of 2,655 percent for solar and 418 percent for wind. BNEF notes that after 2011, new installed capacity significantly outpaced new investment, with renewable energy capacity growing year-on-year between 2010 and 2016 even as annual public and private investment flattened during that period.

IPCC's scenarios, and most tests of the efficacy of clean energy policies for climate mitigation, assume that different sources of low-carbon energy have the same impact on carbon intensity. IPCC calculates solar, wind, nuclear, and hydroelectricity to all generate very few carbon emissions per unit of energy.

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[12] Liebreich, 2017.

[13] IEA, 2016. "TRENDS 2016 IN PHOTOVOLTAIC APPLICATIONS." Available at: http://www.iea-pvps.org/fileadmin/dam/public/report/national/Trends_2016_-_mr.pdf.

[14] "Renewables 2017," International Energy Agency. Available at: https://www.iea.org/renewables/.

However, IPCC does not offer policymakers retrospective analyses of real world deployments of these clean energy sources on carbon intensity of energy—a significant omission. A broader geographical and temporal understanding is required for policymakers to gain more robust understandings of the decarbonizing capabilities of different energy sources.

Section II: Clean Energy Deployment and Carbon Intensity of Energy

The deployment of hydro, nuclear, solar, and wind over the last half century offers the evidence base for evaluating their energy decarbonization potential at national levels, and correlations between their deployment and the decarbonization of energy at aggregated levels.

This analysis looks at the relationship between the carbon intensity of energy and the per-capita consumption of electricity because solar, wind, nuclear, and hydro almost exclusively produce electricity and not other kinds of energy.

Using publicly available World Bank and BP Energy data, this analysis calculates the annual carbon intensity of energy of 68 nations from 1965 to 2016, and compares these values with the per-capita annual electricity generation from hydro, nuclear, solar and wind for each country. It then examined the correlations between the annual carbon intensity of energy and the amount of electricity coming from those energy sources in that year.

We use a per-capita value for electricity production because it allows for countries of differing population and wealth to be compared. For example, China has received significant attention for having the largest deployed capacity of nuclear, wind, and solar, but these represent relatively low per-capita quantities given China's large population. Considering population is the largest driver of carbon emissions, using per-capita quantities isolates population from the other factors contributing to carbon emissions.

A. Decarbonization of Energy by Clean Energy Deployment in National Case Studies

We present case studies in Appendix B showing the relationship between the deployment of hydro, nuclear, solar and wind for all 68 nations covered by the publicly available data provided by BP. We show slides to make transparent the data being used to create the nationally aggregated analysis, and to illuminate the causal relationships that can be seen between the deployment of clean energy at a national level and its impact or lack thereof on carbon intensity of energy.

There is already a significant body of evidence showing that both deploying and phasing out nuclear plants have significant impacts on carbon intensity of energy at national levels. New nuclear construction was the key decarbonizing factor in both Sweden and France, two of the world's currently least-carbon-intensive economies, after the international oil crisis in the 1970s.

At the time, both Sweden and France scaled up new nuclear power development in attempts to completely displace oil from their electricity mixes.[15] Sweden underwent a period of rapid nuclear construction between 1970 and 1986, during which it added to its extensive hydroelectricity production and displaced its remaining fossil power plants—extending its electricity usage deep into its economy.[16]

France, while adding a much smaller amount of hydro than Sweden, also displaced nearly all fossil fuels from its electricity mix while extending the use of electricity into its economy by developing its nuclear sector.

With a recent increase in wind and drop in nuclear, Sweden now generates about 90 percent of its total electricity from zero-carbon sources, with the majority comprised of nuclear and hydroelectric power. With recent disruption in its nuclear fleet operations, France now generates above 70 percent of its electricity from nuclear and 90 percent from zero-carbon sources.[17]

Japan acts as a different sort of case study for isolating nuclear's potential causal role in driving decarbonization. Japan steadily added nuclear to its electricity supply between 1965 and 1998, the peak year of nuclear

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[15] Qvist, S., Brook, B., 2015. "Potential for Worldwide Displacement of Fossil-Fuel Electricity by Nuclear Energy in Three Decades Based on Extrapolation of Regional Deployment Data," *PLOS ONE*, 10(5). Available at: http://journals.plos.org/plosone/article?id=10.1371/journal.pone.0124074#pone.0124074.ref025

[16] According to the Swedish Energy Agency, between 1970 and 1986 electricity consumption more than doubled, while total primary energy usage increased by just 30%. Available at: http://www.energimyndigheten.se/en/facts-and-figures/publications/

[17] RTE, October 29, 2017. "Power Generation by Energy Source." Available at: http://www.rte-france.com/en/eco2mix/eco2mix-mix-energetique-en

electricity generation in Japan. During that period, Japan experienced a steady drop in carbon intensity as it added nuclear electricity, dropping from 249 gCO_2 per kWh to 200 gCO_2 per kWh primary energy over the deployment period.

Because Japan did not increase its per-capita solar, wind, or hydro in significant quantities between 1965 and 1998, and because nuclear directly replaced carbon-intensive fossil fuels used for producing electricity, we can conclude that nuclear caused the decarbonization of energy in Japan during the period between 1965 and 1998.

Adding robustness to this causal claim is the recarbonization of Japanese energy supplies following the replacement of nuclear plants with fossil fuels after 2011. In the two years following the 2011 nuclear accident in Fukushima, Japan halted nuclear electricity generation and replaced it with fossil fuels including coal, oil, and natural gas. After that occurred, the carbon intensity of energy in Japan rose to 236 gCO_2 per kWh, undoing 36 gCO_2 per kWh of the 49 gCO_2 per kWh of emissions reduction progress Japan made between 1965 and 1998 in just two years.

The remaining gap of 13 gCO_2 per kWh primary energy between Japan's 2013 carbon intensity and its 1965 carbon intensity is likely related to the increasing role of imported natural gas in the Japanese economy, increasing from one percent of imported fossil fuel by energy in 1965 to 24 percent by energy in 2013 according to BP data.

In summary, when Japan increased its production of nuclear energy, it decarbonized; when Japan decreased its production of nuclear energy, it recarbonized.

B. Correlations Between Clean Energy Deployment and Decarbonization in Aggregated National Cases

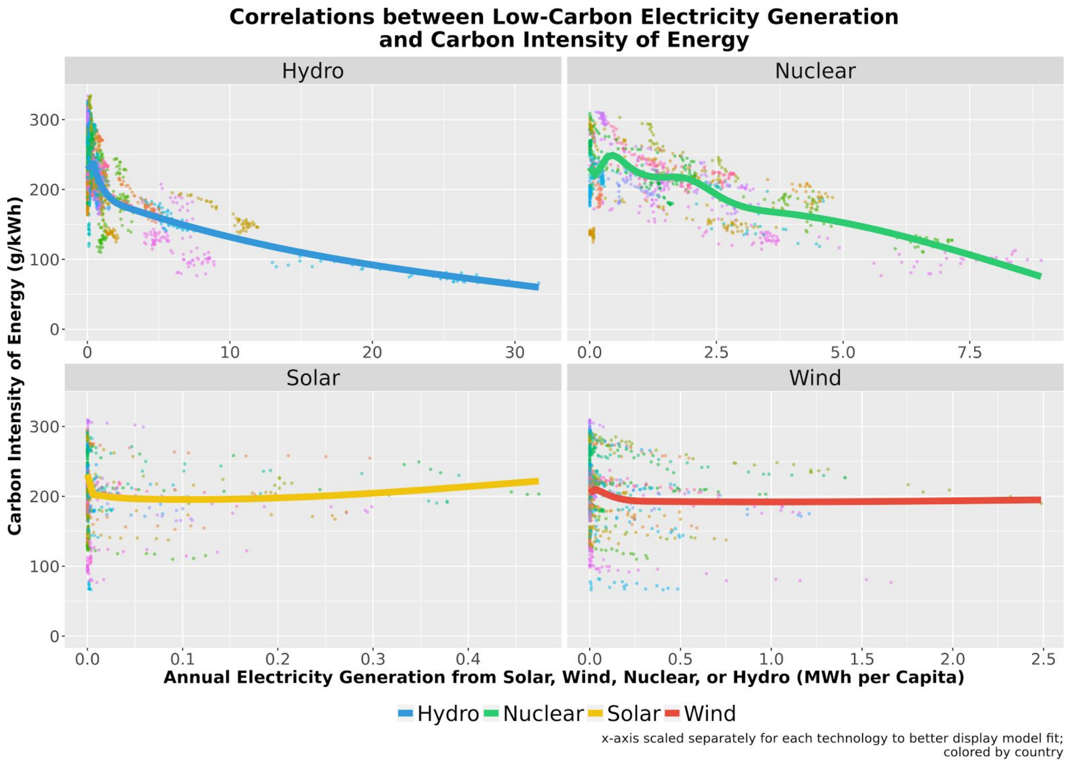
Our analysis finds that additions of hydroelectricity and nuclear power to national energy systems have been accompanied by the decarbonization of energy in historic aggregated national data.

According to our simple linear regression model, the deployment of each additional megawatt-hour per-capita of hydroelectricity is correlated with a decline in carbon intensity of energy of 8.14 gCO_2 per kWh on average. The deployment of each additional megawatt-hour per-capita of nuclear electricity is correlated with a decline in carbon intensity of energy of 17.12 gCO_2 per kWh on average.

Second, we find that additions of solar and wind electricity to national energy systems are not correlated with the decarbonization of energy at nationally aggregated levels. While some individual nations like Denmark experienced declines in the carbon intensity of their energy supplies that correlate with their deployment of solar or wind, other countries experienced increases in carbon intensity that correlate with these deployments.

In the visualizations found below and in Appendix B., Figures IV. and V. show the aggregated relationships between annual per-capita electricity generation from hydro, nuclear, wind, and solar and national carbon intensity of energy.

Figure IV.

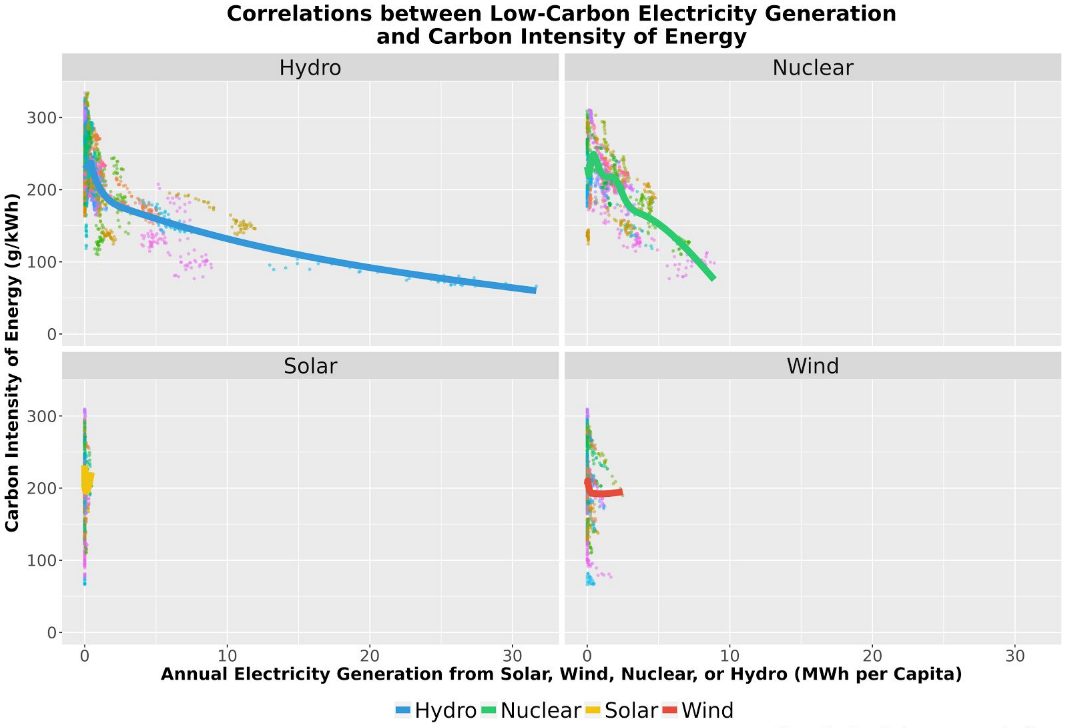


Each datapoint in these graphs represents the annual per-capita electricity generation for a single source during a single year in a single country, with countries represented by color. For each energy source, the regression analysis excludes data points for countries that have no electricity generation from that particular technology.

The first visualization has a different x-axis for each energy source to better showcase individual data points and the fit of the generalized additive regression models. As indicated by the downward slope of their regression lines, there is a negative correlation between per-capita hydro and nuclear electricity generation and carbon intensity of energy.

By contrast, the almost-flat regression lines for solar and wind indicate that, according to aggregated historical data for these 68 nations, solar and wind electricity are not correlated with reductions in carbon intensity of energy.

Figure V.



All axes fixed to display true regression lines;
colored by country

Figure V shows identical data and uses the same generalized additive models as the first visualization, but places per-capita electricity generation from each technology on the same fixed scale, allowing the slopes of the regression lines to be compared. The contrast between the steep, downward slopes of the regression lines for nuclear and hydro and the flat slopes of the regression lines for solar and wind can be better seen in this display, as can the general low per-capita electricity generation from solar and wind as compared to hydroelectricity and nuclear power.

A possible justification for the the lack of a correlation between solar and wind deployments and energy decarbonization at nationally aggregated levels is under-investment of public and private funds towards their deployment. However, as noted in Section I, the last decade alone has seen public and private investments in solar and wind roughly equal to half a century of investments in nuclear plants, and corresponding deployments of capacity larger for the former than the capacity additions from all other energy sources combined.

The correlation between the deployment of nuclear and the decarbonization of energy at nationally aggregated levels emerges in data from national nuclear energy expenditures which occurred decades before the most recent initial expenditures of the newest projects considered as part of the $1.8 trillion capital expenditures for nuclear, with this dollar amount including dozens of reactors that will not be in service for several more years.

Section III. Three Hypotheses on the Varying Correlations Between Clean Energy Deployment and Energy Decarbonization

We propose three hypotheses for future study that may explain why deployments of nuclear and hydro have correlated with decarbonization of energy at nationally aggregated levels, while the similar investments and capacities of solar and wind have not.

- The Weak Energy Hypothesis: solar and wind generate too little electricity relative to their installed capacity and material cost to overcome other factors driving carbon intensity of energy. This is a result of their fundamental physical nature as diffuse, natural energies.

- The "Energy Transition" Hypothesis: the decarbonization potential of many of the most aggressive national solar and wind deployments is undermined by simultaneous nuclear-energy phase-outs. Like with Germany's Energiewende, these simultaneous policies, often termed "Energy Transitions," are necessarily executed as part of a single, integrated energy policy and thus must compromise decarbonization.

- The Electrification Hypothesis: national hydro and nuclear deployment has historically correlated with expansion of national electricity usage as calculated as a ratio of electricity consumption to total primary energy, whereas national solar and wind construction may not be encouraging similar expansions. Deep electrification, seen by many as a critical step in future decarbonization, has been correlated in the past with decarbonization of primary energy.

A. The Weak Energy Hypothesis:

The first hypothesis for why solar and wind have not decarbonized energy when examining change at the aggregated national level is that, despite their remarkably high capacity deployment, relatively minor amounts of national per-capita generation has been observed, which in turn may be insufficient to produce a correlation with falling carbon intensity of energy.

Examining rates of added low-carbon electricity shows the difficulty nations have broadly faced when attempting to increase solar and wind generation, when compared to hydro and especially nuclear. Periods of peak nuclear and peak hydroelectricity deployments generally resulted in larger amounts of electricity generation than did periods of peak solar and wind deployment. The average deployment rate over national peak decades of deployment of nuclear, hydro, solar, and wind electricity per-capita are 136 kWh, 57 kWh, 8 kWh, and 25 kWh per-capita per year, respectively, among all countries recorded as having at least one of these energy types in the BP database. These values reflect the relatively deep expansion of nuclear electricity in fewer countries, and the relatively shallow expansion, on average, of the other types across many countries.

As noted above, the evidence does not support the suggestion that low levels of peak deployment of solar and wind are consequences of low public and private investment, though it is certainly possible that higher future solar and wind growth will result in higher national peak deployment values. This may occur if future investment rises significantly beyond current flattening trends, or if future solar and wind cost declines are substantial enough to compensate for flattening investment.

The weak output of solar and wind plant relative to their high and growing installed capacity is illustrated by comparing plant area and generation. California's Diablo Canyon nuclear power plant, for example, produces 14 times as much electricity annually as the state's Topaz Solar Farm while its occupied site requires three percent as much land. Diablo Canyon also produces twice the expected future production from the presently under-construction Windcatcher farm in Oklahoma, which upon completion will be the most productive wind farm in the United States.[18] Diablo Canyon occupies 1,500 times less land area than Windcatcher's future area of 1214 km^2.

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[18] Monies, P., July 26, 2017. "PSO, sister utility team up on $4.5 billion Oklahoma wind farm, transmission project," *NewsOK*. Available at: http://newsok.com/article/5557773.

These higher land use requirements stem from the much lower power density[19] of sunlight and wind compared to that of reactors using uranium fuel, and may in the future result in significant reductions in solar and wind's historically high rate of capacity deployment due to regulatory burdens, local resistance, and environmental concerns. This potential sprawl-induced constraint is a concern because leading historical growth rates of solar and wind energy additions, but not capacity additions, remain below that of leading hydro and nuclear energy additions. And while rooftop solar utilizes already-occupied land, it usually suffers from substantially lower energy production and higher costs relative to utility-scale solar plants.

This difficulty faced in the conversion of solar and wind energy into useful electricity can be illustrated by the measure of "energy return on energy invested," or EROEI, the ratio of energy produced to the energy needed to generate it. One recent study[20] calculated that solar energy from photovoltaic panels as installed in Germany achieves an EROEI of just 1.9 with storage and 3.9 without, while wind also installed in Germany has an EROEI of 3.9 with storage and 16 without. By contrast, hydro was calculated to produce an EROEI of 35 with storage and 49 without, and for nuclear an EROEI of 75. If Weißbach et al. are justified in their claim that developed nations require constant energy sources to have an average EROEI of 8 or higher to maintain present living standards, then the relatively low EROEI calculated for solar and wind suggest future difficulty faced by nations attempting the high per-capita energy penetrations often reached by nations using hydro and nuclear.

Figure VI, below, presents EROEI values from the previously mentioned study with another study's finding for the materials throughput required for various energy sources. Nuclear and hydro are both found to achieve high EROEI, while solar and wind are both marked as having high material throughput and low EROEI.

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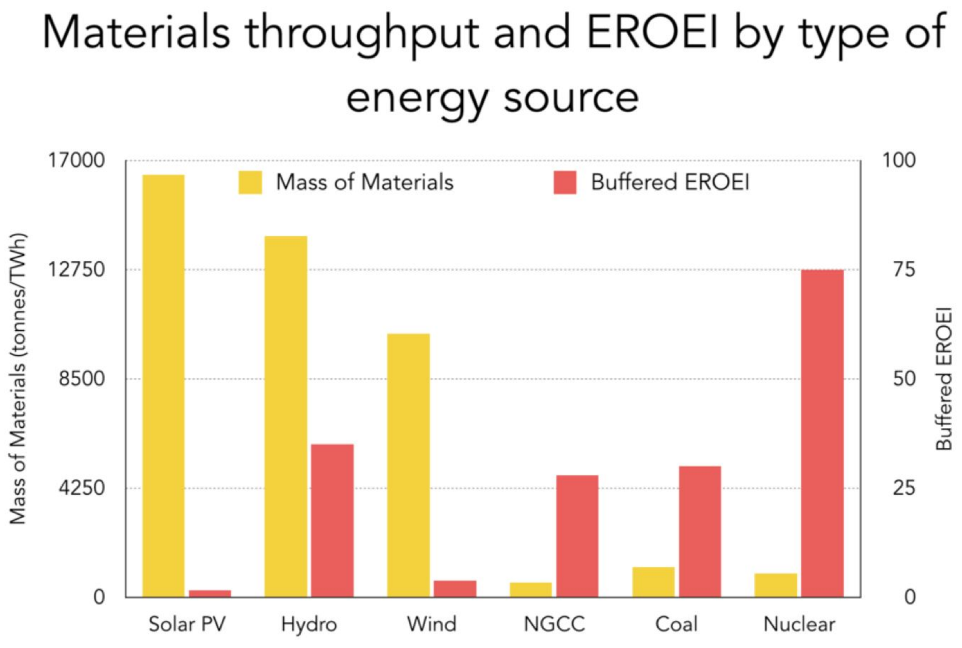
[19] For a full development of the power density concept and its application to solar and wind energy, see Smil, Vaclav. Power Density: A Key to Understanding Energy Sources and Uses. MIT Press, 2015.

[20] D. Weißbach, G. Ruprecht, A. Huke, K. Czerski, S. Gottlieb, & A. Hussein, 2013. "Energy intensities, EROIs (energy returned on invested), and energy payback times of electricity generating power plants," *Energy*, Volume 52, pp. 210-221. Available at: http://www.sciencedirect.com/science/article/pii/S0360544213000492.

Figure VI.



Materials throughput and EROEI by type of energy source

Sources: DOE Quadrennial Technology Review, Table 10.
Murray, R.L. and Holbert, K.E. 2015. Nuclear energy: an introduction to the concepts, systems, and applications of nuclear processes (7th ed.). Elsevier.
Weißbacha, D., Ruprechta, G., Hukea, A., Czerskia, K., Gottlieba, S., & Husseina, A. Energy intensities, EROIs, and energy payback times of electricity generating power plants.

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This hypothesis, therefore, suggests that nations have failed in the aggregate in reducing their carbon intensities while deploying extensive solar and wind because of these sources' fundamental physical nature. Despite rapid capacity addition at the global level, intense material and land usage combined with weak energy output may have prevented this large global capacity of solar and wind from making clear contributions to decarbonization at the aggregate national level.

B. The "Energy Transition" Hypothesis:

This hypothesis assumes that solar and wind as intensively deployed might be capable of demonstrating clear decarbonization at the aggregate national level, and that national nuclear phaseouts are countering this capability. Crucially, however, this hypothesis extends this argument to suggest that solar and wind deployment in key leading countries is inextricably connected, through policy and financial linkages, to the reduction or elimination of national nuclear energy consumption. And, therefore, that these "Energy Transition" policies will continue to suppress the expected contribution of solar and wind deployment to carbon intensity reductions at the aggregate national level.

Support for this hypothesis comes from examining several nations and regions. As a motivating example, during the period between 2006 and 2016 that saw Germany increase the overall share of its electricity production from solar and wind by 15 percentage points, Germany also reduced the share of electricity coming from nuclear by 15 percentage points. During that period, the carbon intensity of Germany's energy changed from 212 to 203 gCO_2 per kWh primary energy, a substantially smaller decarbonization of energy than would be expected from direct fossil fuel substitution by solar and wind without loss of nuclear.

In fact, had Germany kept its nuclear plants online in place of equivalent lignite and hard coal production, the deployment of solar and wind could have quite practically reduced the carbon intensity of German energy by 10 percent, to 180 gCO_2 per kWh primary energy.[21]

However, claiming simply that nuclear phase-outs only unintentionally mask the decarbonizing potential of renewables, and that halting the removal of nuclear would be sufficient to allow solar and wind deployment to lower carbon intensity of energy, may inappropriately assume it is possible to decouple two policymaker motivations—the phase-out of nuclear and the scaling up of solar and wind.

The "Energy Transition" Hypothesis contends that these two goals are not only conjoined for cultural and ideological reasons, but also financial. While it is not inconceivable that many nations could simultaneously finance large-scale deployments of solar, wind, and nuclear, it is notable how rarely this occurs. In the most prominent case, China, the world's leading solar and wind fleets by capacity are growing simultaneously with the world's leading nuclear construction campaign; however, all three

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[21] Assuming, in Germany, 2016 actual wind and solar output but with 2006's 159 TWh of nuclear generation, about 80 TWh of lignite and hard coal generation could have been avoided, representing about 80 MMT of CO_2. Subtracting these 80 MMT from Germany's 2016 total energy emissions of 761 MMT as recorded by BP, Germany's carbon intensity of energy could have been about 180 gCO_2 per kWh primary energy.

power sources added together make only a small contribution to national per-capita energy. Another exception is the UK, which is now constructing nuclear and wind energy simultaneously as a matter of national policy. However, it is more often the case, as in Germany, Sweden, Taiwan, South Korea, Switzerland, and now France, that nations explicitly view "energy transition" policies as acting to scale up solar and wind in order to replace nuclear energy.[22]

Evidence for or against this hypothesis should be forthcoming shortly from around the world, as dozens of reactors are scheduled for imminent closure in countries undertaking large-scale solar and wind deployments, despite intensifying global dialogue and agreement-making around climate change. Should leading solar and wind programs continue to be coupled with nuclear phase-out despite national and international rhetoric about the necessity of decarbonization, the evidence for this hypothesis would be strengthened.

C. The Electrification Hypothesis:

This hypothesis contends that solar and wind struggle to decarbonize energy at an aggregate national level because their expansion is not accompanied by increases in the ratio of national electricity consumption to total energy consumption, while nuclear and hydroelectric deployment has been. Figure VII below presents the correlations between hydro, nuclear, solar, and wind electricity generation and electrification, defined as the ratio between electricity consumption and primary energy consumption for countries in the BP data set.[23]

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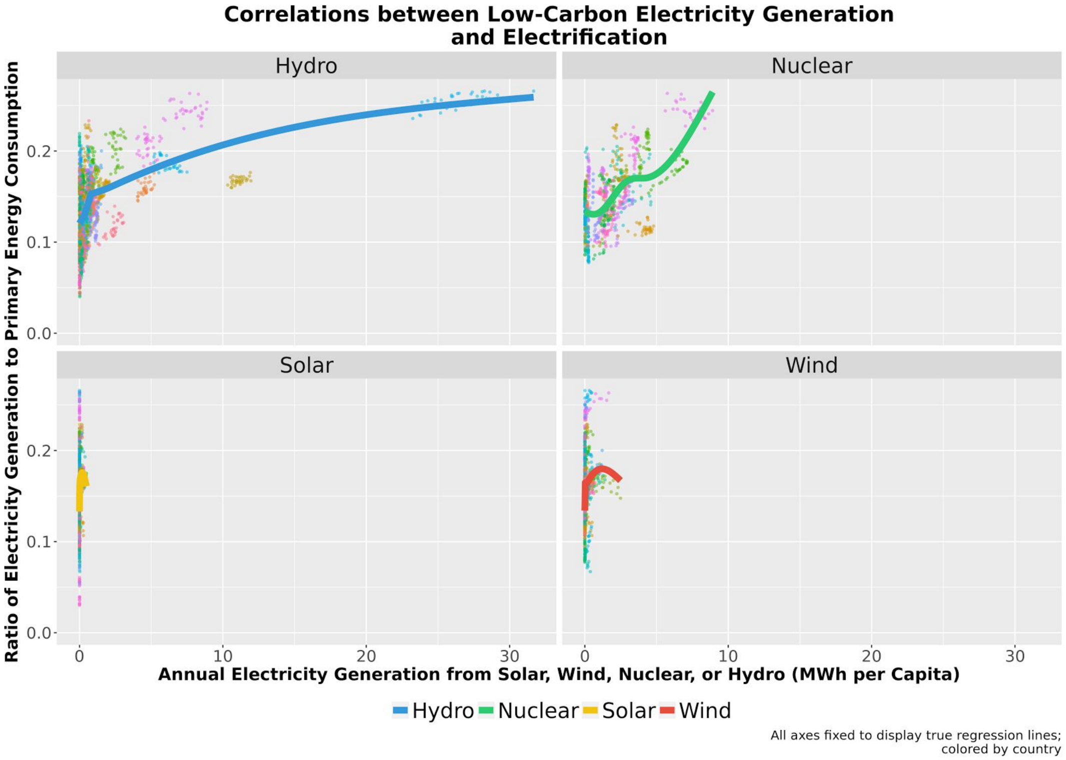
[22] While the United States does not have a national policy to replace nuclear energy with renewables, some leading states, such as California, consider the expansion of solar and wind as sufficient reason to preemptively eliminate nuclear energy.

[23] Unfortunately, BP provides electricity consumption only from 1985 onwards, which removes information from significant periods of hydro and nuclear deployment. Future work will attempt to supplement the BP data with electricity generation data from individual countries with substantial hydro and nuclear deployment between 1965 and 1985.

Figure VII.



See Figure VIII in Appendix C for scaled axis that help visualize solar and wind generation versus electrification.

Additional support for this hypothesis comes from nations that deployed significant quantities of nuclear energy, such as France and Japan. Both nations accompanied the expansion of electricity capacity with high-speed electric rail infrastructure, which competes with both fossil-fueled land and air transportation. Japan and France also encouraged the electrification of heating, where electric heaters replaced heat from wood, coal, liquid fuels, and natural gas.

Rather than encouraging expanded use of electricity, solar and wind may be discouraging further electrification due to system costs imposed on the grid and its users. This may be occurring despite, or even because of, the increasingly cheap wind and solar projects themselves. While the Levelized Cost of Energy (LCOE) from solar and wind has decreased significantly, as noted in the introduction, the cost of integrating intermittent solar and wind energy into electricity grids rises as penetration of these resources rise.

These costs include maintaining idle fossil fuel power plants to operate when sun or wind resources are unavailable; paying electricity customers to take excess solar and wind electricity when market demand is insufficient; building and maintaining erratically-used utility-scale electricity storage systems; and additional human capital to manage increasingly variable transmission systems.

These hidden costs can be only been seen at the level of the electricity system as a whole. One study finds that the value of solar and wind to the electricity grid declines 50 and 40 percent, respectively, as solar reaches 15 percent of electricity generation and wind 30 percent.[24] Nations like Germany and subnational regions like California and Ontario have seen significant increases in electricity costs accompanying their deployment of solar and wind. There are simply higher financial barriers to electrification of off-grid economic activity when electricity system costs are higher than when they are lower.

We may be seeing direct evidence for this hypothesis as solar energy, for example, initiates high initial growth in an increasing number of countries but experiences much slower growth, or even no growth at all, in countries where solar electricity generation is close to 0.5 MWh per person per year, which is the current national high. Evidence for or against this hypothesis will continue to be produced in the near term as solar project cost declines either succeed or fail in increasing solar's maximum national per-capita electricity production from 0.5 MWh per person per year to 1 MWh or beyond.

D. Discussion

These hypotheses put forward claims which, if confirmed by historical data, may describe why the substantial global investment in solar and wind capacity has produced poor correlations with decarbonization in aggregated national data. More importantly, however, will be new data

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[24] Hirth, L., 2013. "The Market Value of Variable Renewables," *Energy Policy*, 38. pp. 218-236. Available at: http://www.sciencedirect.com/science/article/pii/S0140988313000285.

which will serve to strengthen or weaken these claims for future solar and wind deployments and decarbonization.

These three hypotheses, even if strengthened by existing evidence, are easy to dismiss as barriers to future solar and wind success should contradictory evidence emerge from technological and political progress.

Higher solar and wind generator efficiencies, lowered material usage, and reduced environmental impact could weaken the limitations implied by the first hypothesis. A halt to the nuclear phase-downs and phase-outs presently enshrined in law in many of the world's leading solar and wind energy producers would weaken if not eliminate the second hypothesis. And new-found success in the electrification of energy services currently running off-grid in those nations leading the world in per-capita deployment of solar and wind, would allow us to dismiss the constraints implied by the third hypothesis, especially if this success comes faster in nations with burgeoning solar and wind than in those nations that lead the world in hydro and nuclear consumption.

In the case of the Electrification Hypothesis, the growth of electric vehicles alone may be sufficient to expect progress on lowering the carbon intensity of energy while growing solar and wind, even if hydro and nuclear enjoy as much or more of a boost from higher year-round electricity demand. But "Energy Transitions" the world over are if anything gaining strength, with a major fraction of the world's nuclear fleet in danger of unnecessary closure in lock-step with growing global solar and wind. And, even more intimidatingly, there may be little possibility of improving the fundamentally diffuse nature of solar and wind enough to slip the bonds of the Weak Energy Hypothesis.

Section IV. Implications for Energy Analysis and Climate Policy

The finding that the deployment of solar and wind are not correlated with energy decarbonization at nationally aggregated levels, while hydro and nuclear are, challenges several core assumptions underlying the IPCC's 2014 AR5. In its discussion of energy, IPCC authors stress the importance of renewables, particularly solar and wind, to mitigating climate change:

> *Since the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4), many RE technologies have demonstrated substantial performance improvements and cost reductions, and a growing number of RE technologies have achieved a level of maturity to enable deployment at significant scale (robust evidence, high agreement). Some technologies are already economically competitive in various settings.*

The findings in this analysis suggest that increased deployment of solar and wind should no longer be considered climate mitigation policies *a priori*, but rather only those policies that promote technologies already demonstrated to decarbonize energy at aggregated national levels should be considered climate mitigation policies. That solar and wind can, in some instances, decarbonize energy at national scales cannot by itself justify designating the policies that promote them as climate mitigation policies for the world as a whole.

As such, the finding that solar and wind have not decarbonized energy helps explain why, as the IPCC states, "the decade with the strongest-ever mitigation policies was the one with the strongest emissions growth in the last 30 years" is not, in fact, a paradox. What the IPCC is referring to as "strongest-ever mitigation policies" are in reality policies to promote solar and wind; the adjective "strongest" in this case may be referring to investment quantity and capacity construction rather than energy production and carbon intensity of energy drops.

The findings in this analysis point to a significant gap in the assumptions relied upon by the IPCC and possibly even the danger of excessive reliance on forward-looking energy models. While the deployment of solar and wind energy at globally-significant scales is relatively recent, occurring mostly in the last decade, the correlation between hydro and nuclear deployment and energy decarbonization could have been examined well over a decade ago.

Given the extent to which policymakers around the world rely upon the IPCC as a guide for effective climate mitigation policies, these omissions should be corrected in AR6, as well as in the special report the IPCC is preparing on mitigation policies for preventing global temperatures from rising above 1.5 degrees celsius against a pre-industrial baseline.

Author Biographies

Mark Nelson is Senior Analyst at Environmental Progress. He developed and maintains EP's Energy Progress Tracker, the most comprehensive review of nuclear power plants planned, under construction, and at-risk of premature closure.

Mark led the energy analytics research for Environmental Progress's High Cost of Fear Report, whose release and content played a key role in turning the tide in this year's South Korean Citizen's Jury which voted to continue nuclear plant construction in the country.

Mark's research into the environmental impacts of nuclear closures in Germany and California has been cited in the New York Times and other publications. His research on the impacts of the cancellation of reactors in South Carolina has been cited in the New York Times and the Washington Post.

Mark has degrees in Mechanical and Aerospace Engineering and an MPhil in Nuclear Engineering from the University of Cambridge. He has interned at Los Alamos National Laboratory and in 2016 was a Breakthrough Generation Fellow.

Arun Ramamurthy, Research Fellow, Environmental Progress. Arun develops models and visualizations of energy trends on global, national and local scales, using data analytics to study the levers and effects of climate mitigation and energy policy.

Madison Czerwinski, Executive Vice President, Environmental Progress. Madi leads EP's historical, qualitative and quantitative research into the factors driving the construction and cancellation of nuclear power plants.

Michael Light, Senior Writer, Environmental Progress. Michael is an investigative journalist and reporter who oversees EP's reporting and publications strategy.

Michael Shellenberger, Founder and President, Environmental Progress. Michael Shellenberger is a *Time Magazine* "Hero of the Environment" and Green Book Award-winning author and policy expert.

Appendix A: Figures

Figure I.

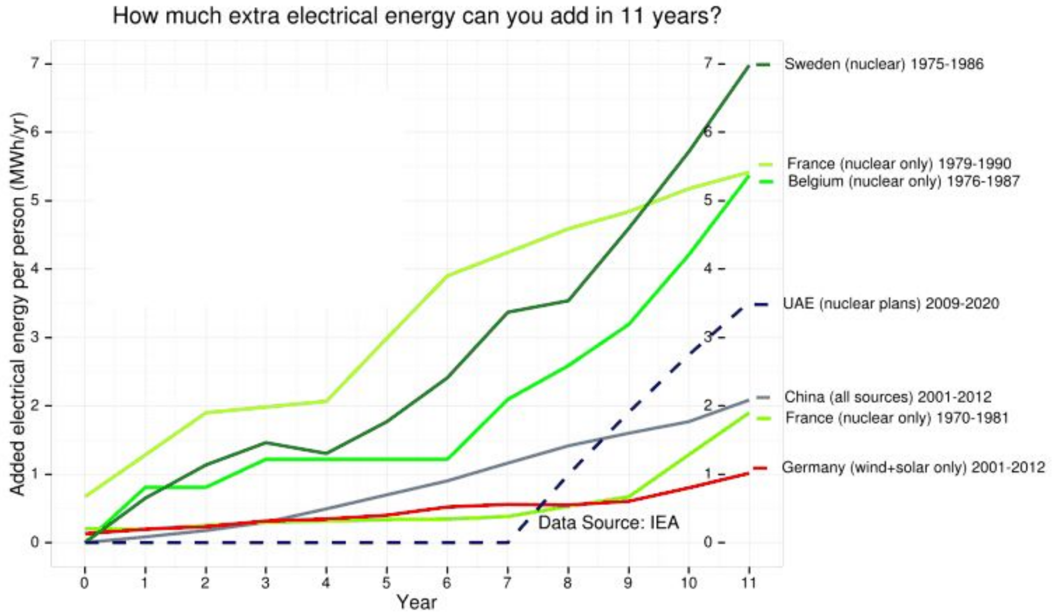
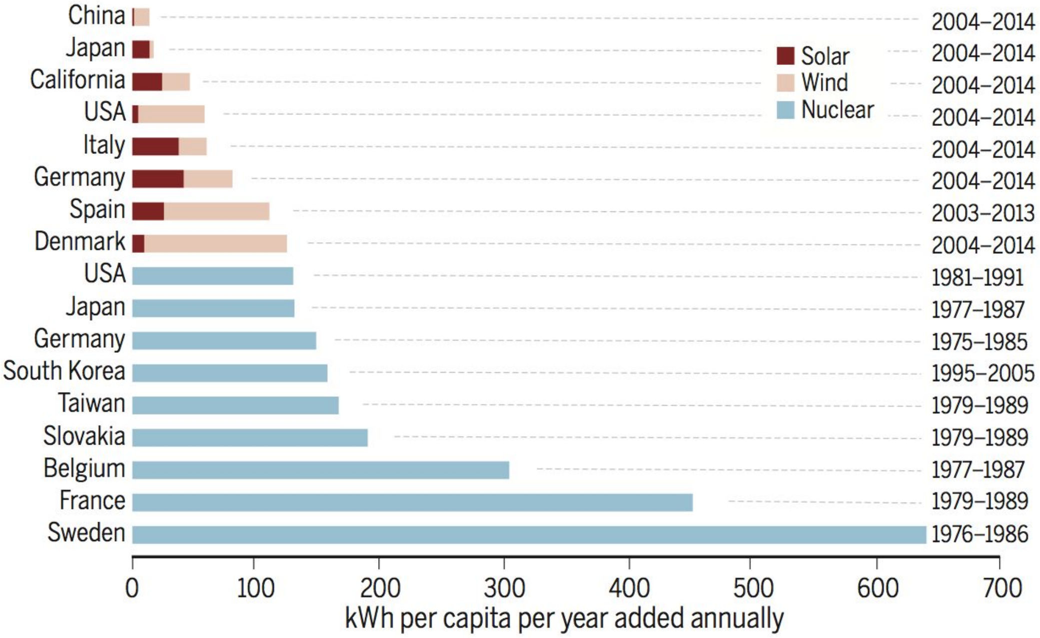


Figure II.



Average annual increase of carbon-free electricity per capita during decade of peak scale-up. Energy data from (*6*) except California renewables data from (*7*). Population data from (*8*). See supplementary materials.

Figure III.

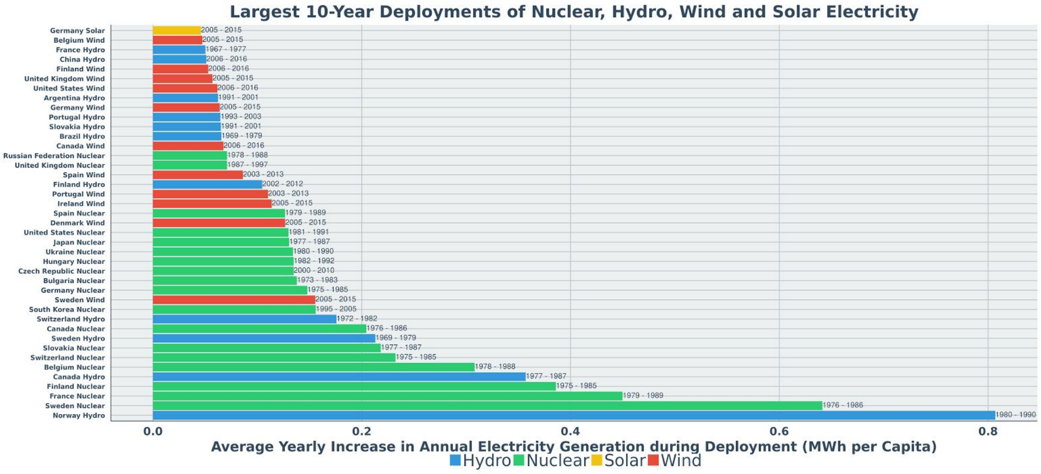
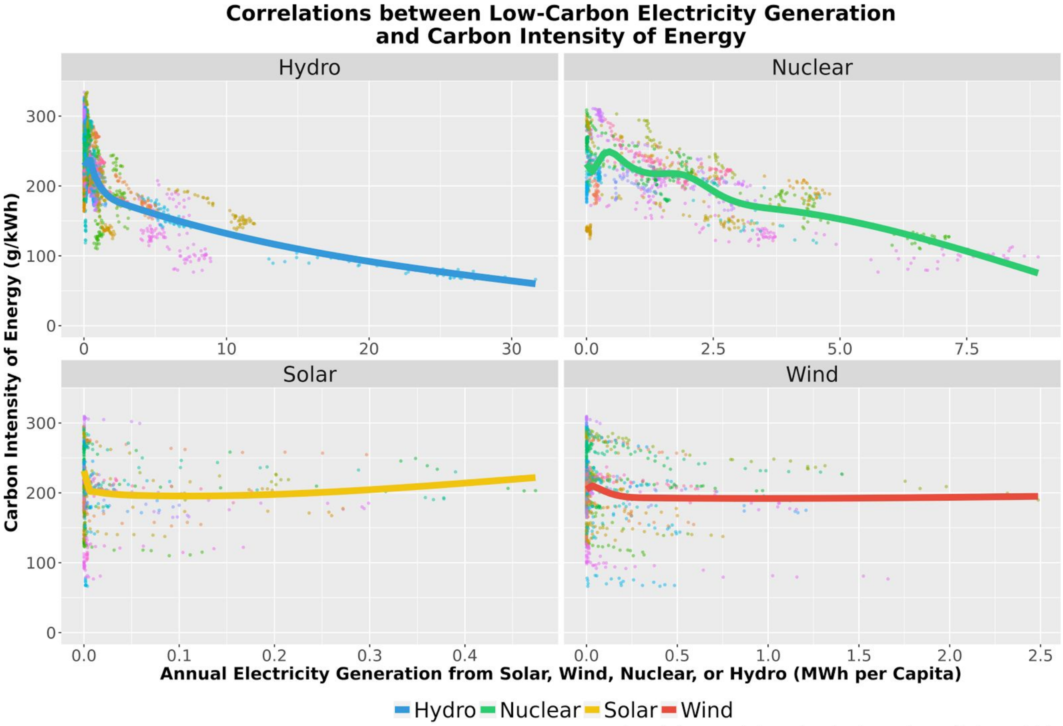


Figure IV.



x-axis scaled separately for each technology to better display model fit; colored by country

Figure V.

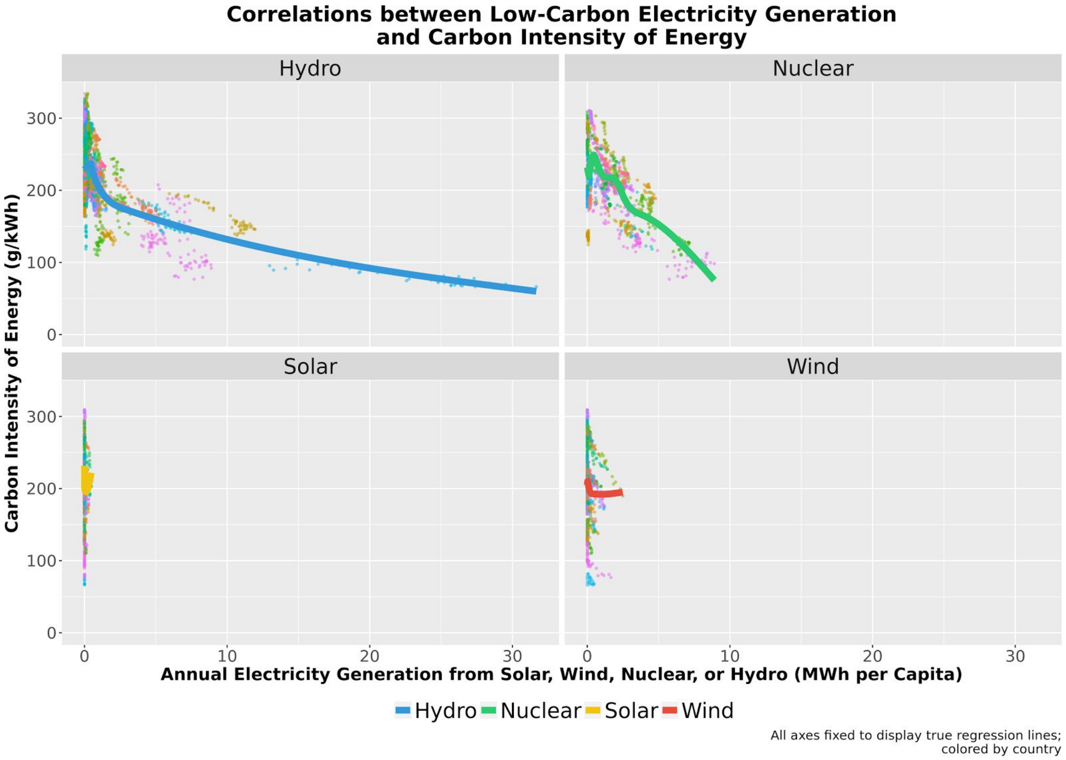
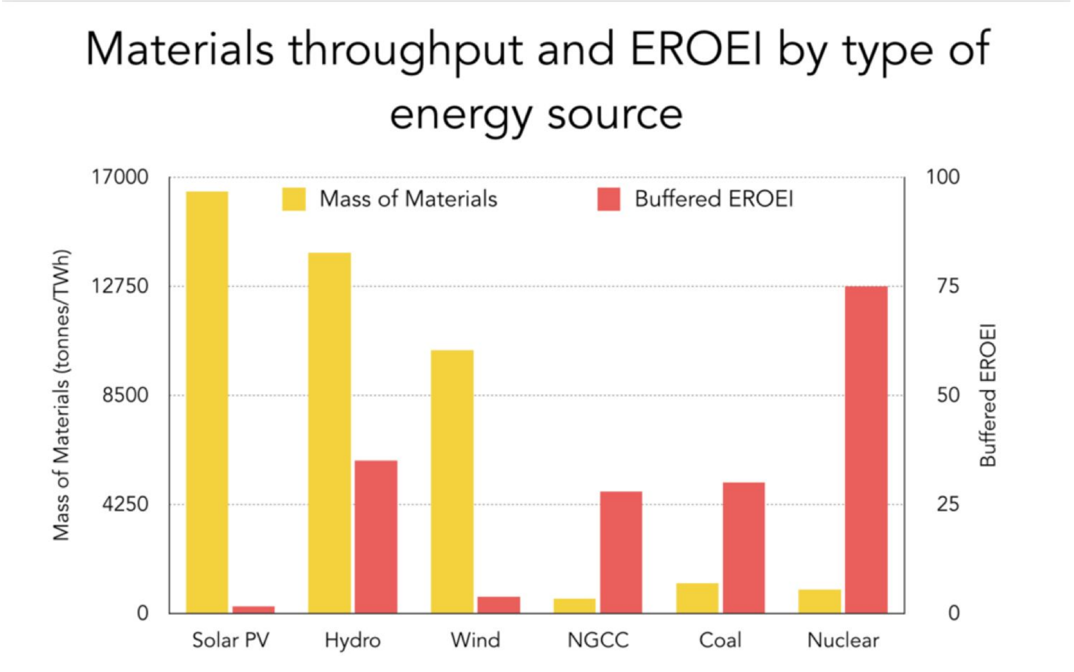
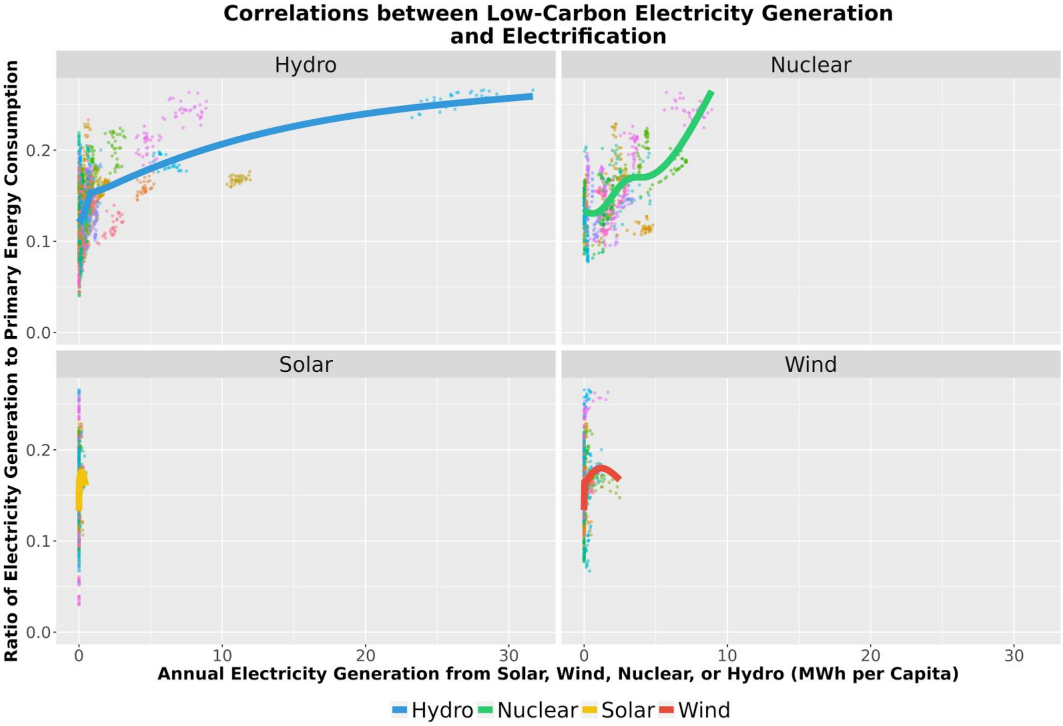


Figure VI.



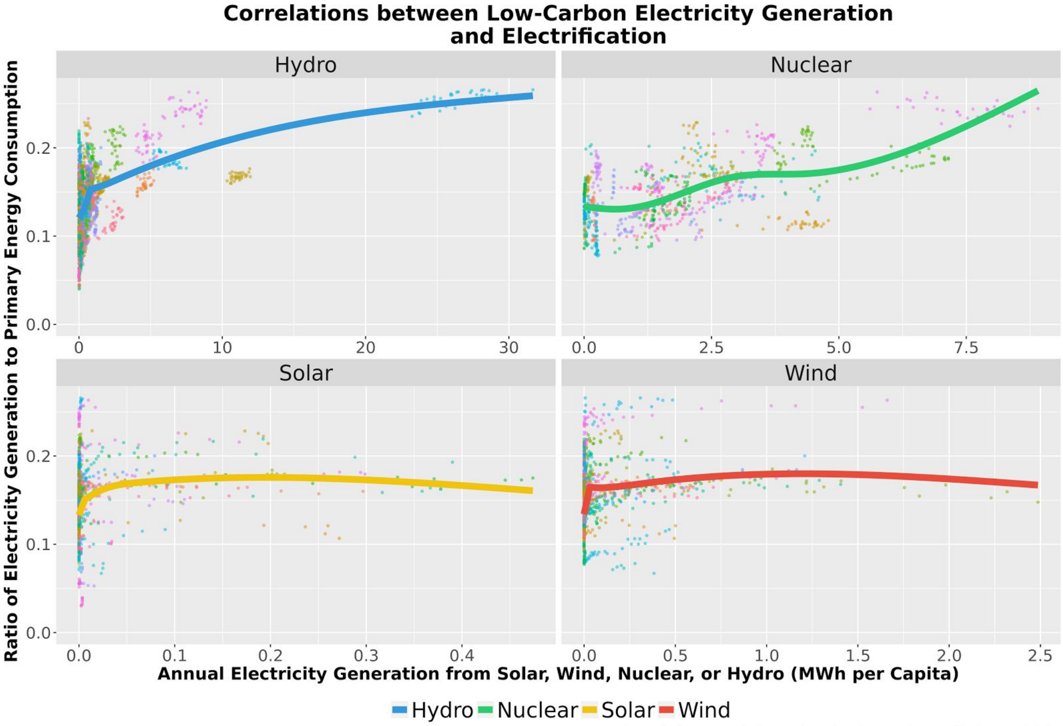
Sources: DOE Quadrennial Technology Review, Table 10.
Murray, R.L. and Holbert, K.E. 2015. Nuclear energy: an introduction to the concepts, systems, and applications of nuclear processes (7th ed.). Elsevier.
Weißbacha, D., Ruprechta, G., Hukea, A., Czerskia, K., Gottlieba, S., & Husseina, A. Energy intensities, EROIs, and energy payback times of electricity generating power plants.

Figure VII.



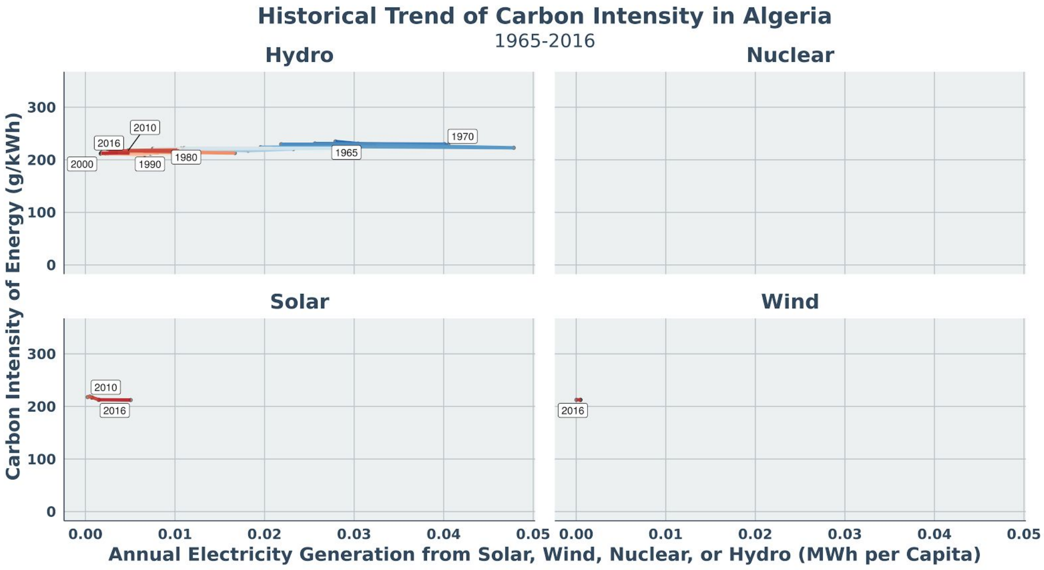
All axes fixed to display true regression lines; colored by country

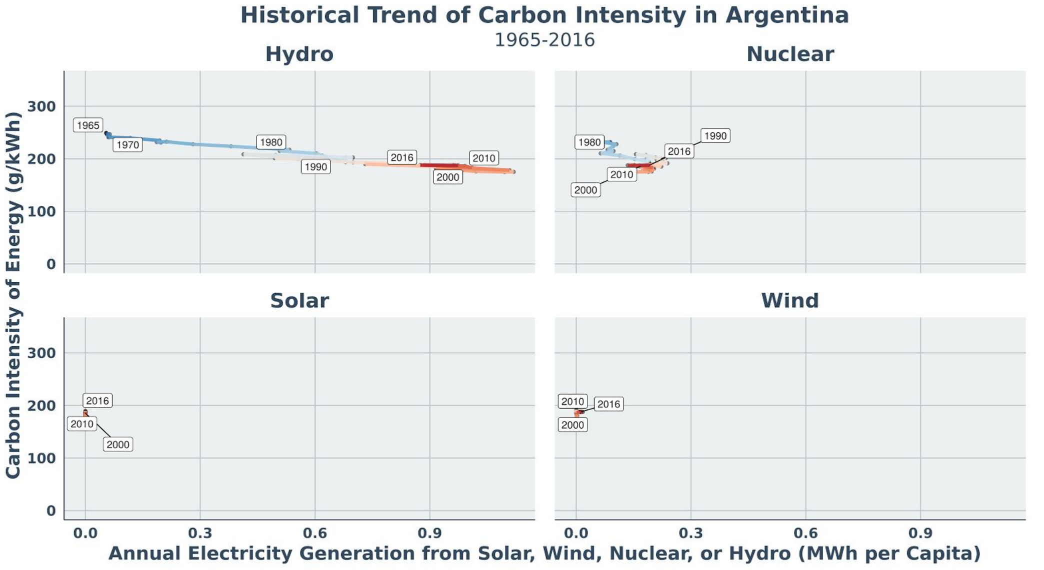
Figure VIII.

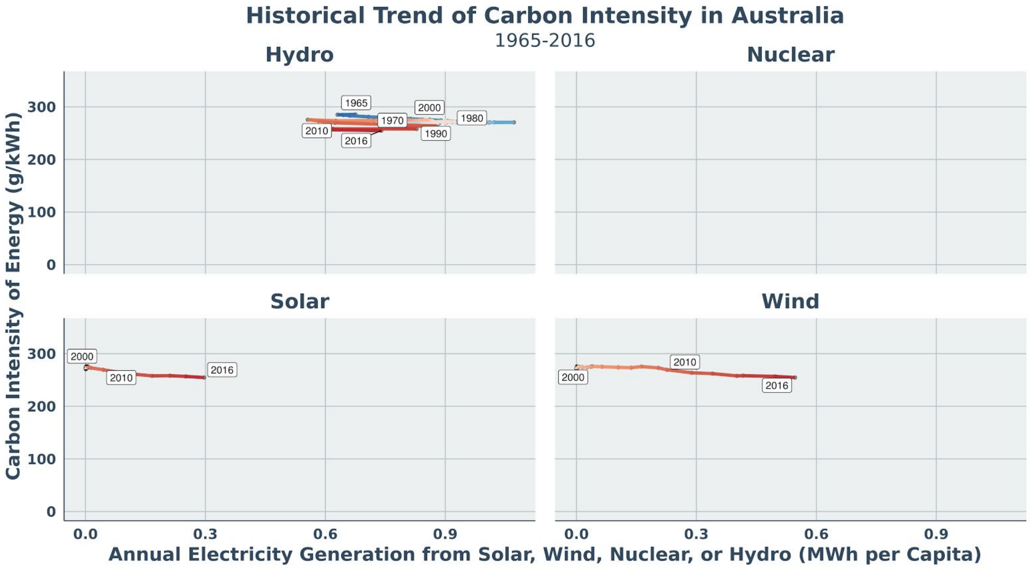


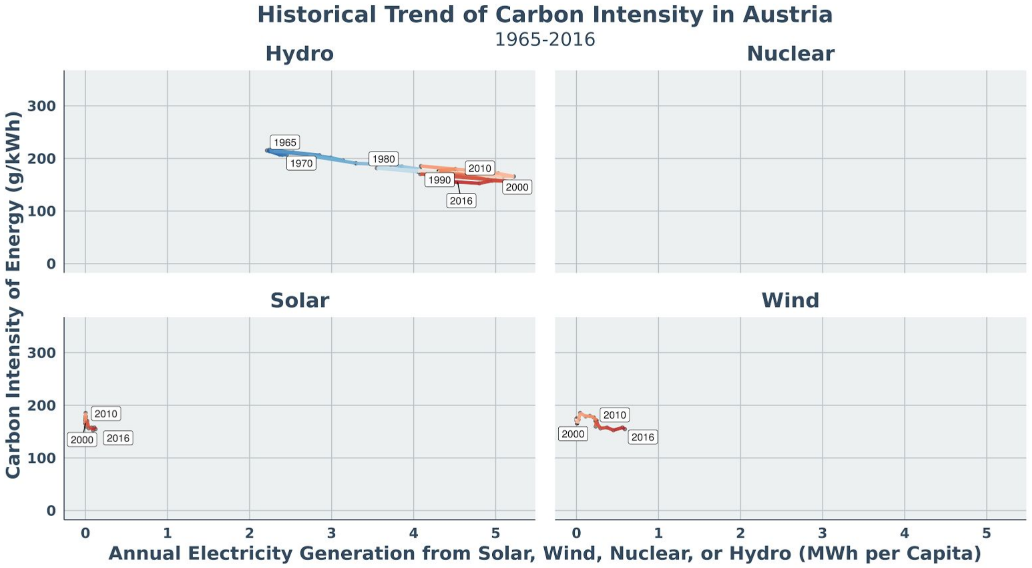
x-axis scaled separately for each technology to better display model fit; colored by country

Appendix B: National Trends in Carbon Intensity of Energy for All Countries in the BP Statistical Review of World Energy 2016



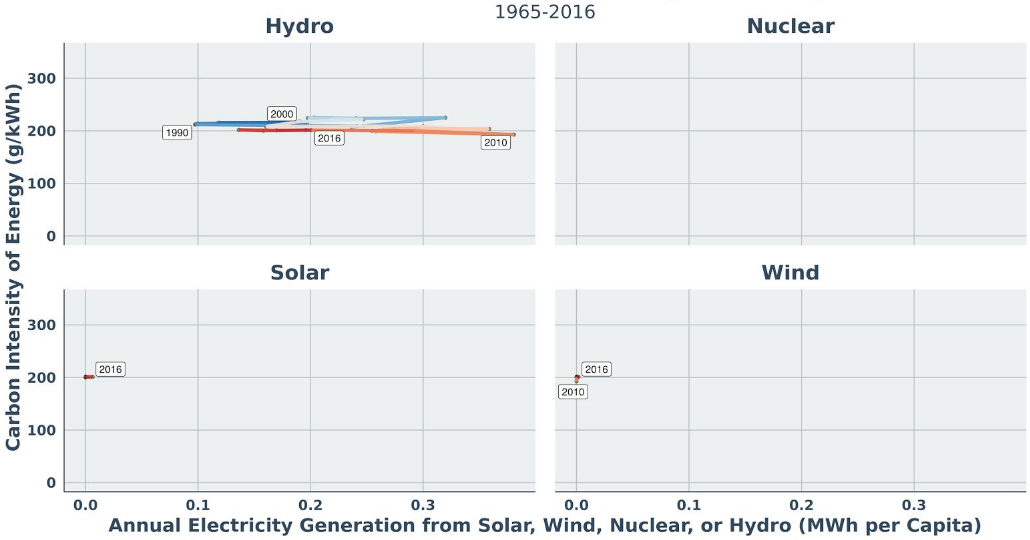



Historical Trend of Carbon Intensity in Australia
1965-2016
Hydro
Nuclear
Solar
Wind
Carbon Intensity of Energy (g/kWh)
0
100
200
300
1965
1970
1980
1990
2000
2010
2016
0.0
0.3
0.6
0.9
Annual Electricity Generation from Solar, Wind, Nuclear, or Hydro (MWh per Capita)


Historical Trend of Carbon Intensity in Austria
1965-2016
Hydro
Nuclear
Solar
Wind
Carbon Intensity of Energy (g/kWh)
0
100
200
300
1965
1970
1980
1990
2000
2010
2016
0
1
2
3
4
5
Annual Electricity Generation from Solar, Wind, Nuclear, or Hydro (MWh per Capita)

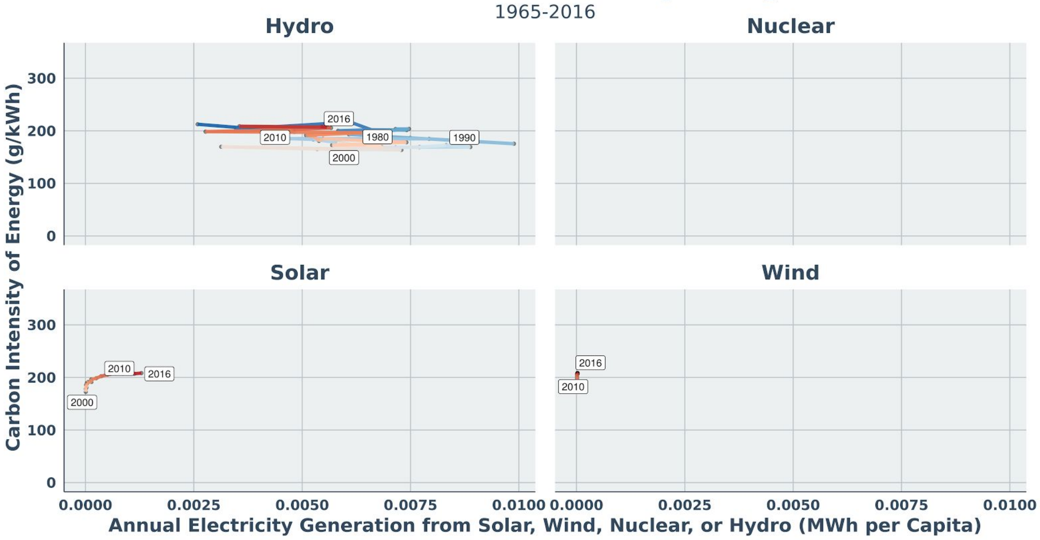
Historical Trend of Carbon Intensity in Azerbaijan

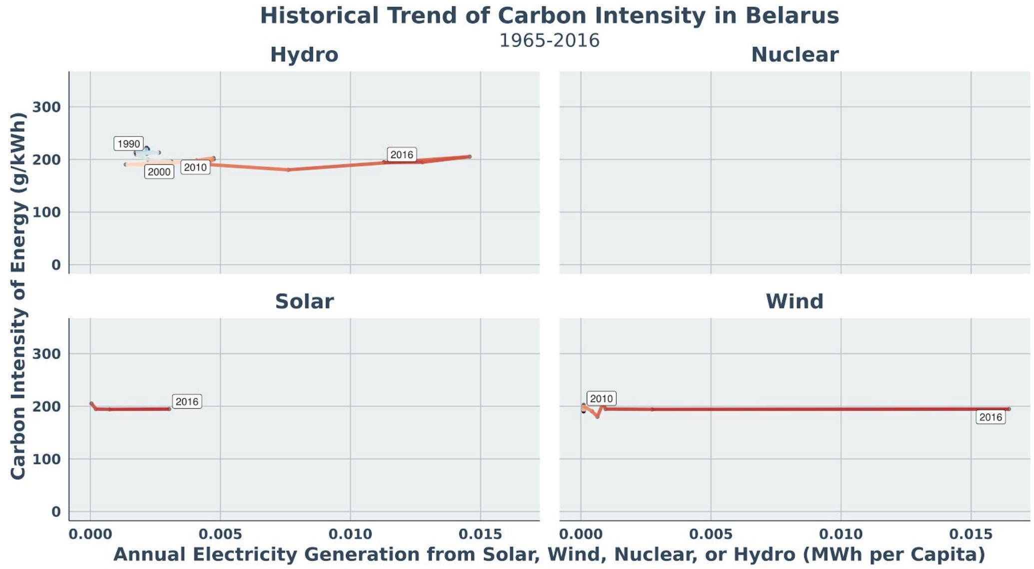
1965-2016



Historical Trend of Carbon Intensity in Bangladesh

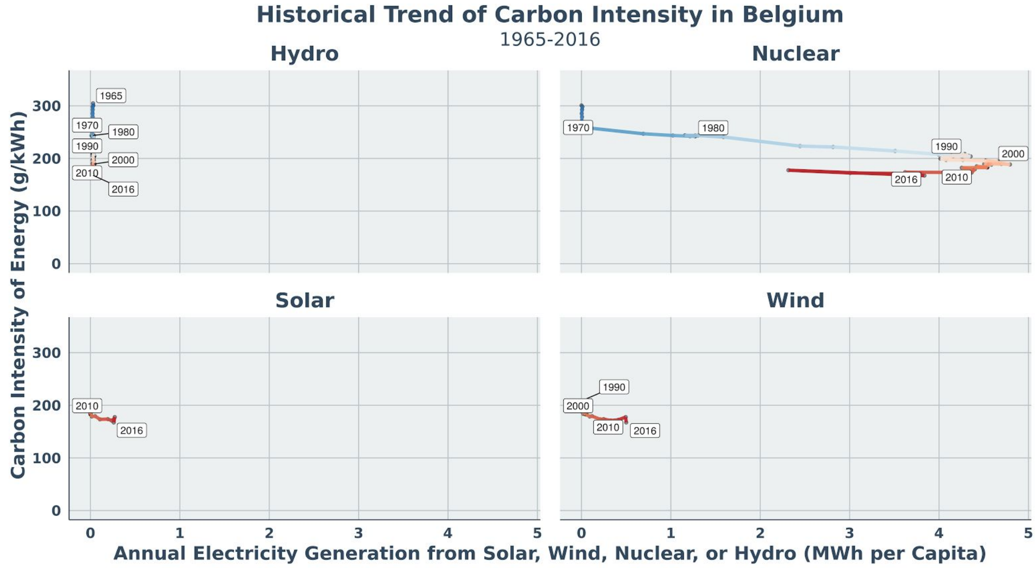
1965-2016





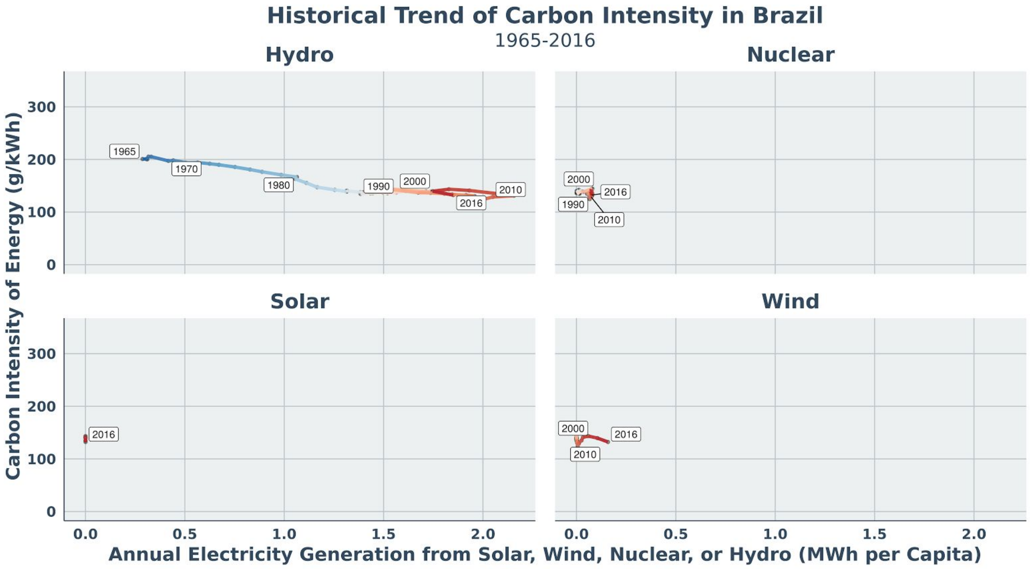
Historical Trend of Carbon Intensity in Belarus

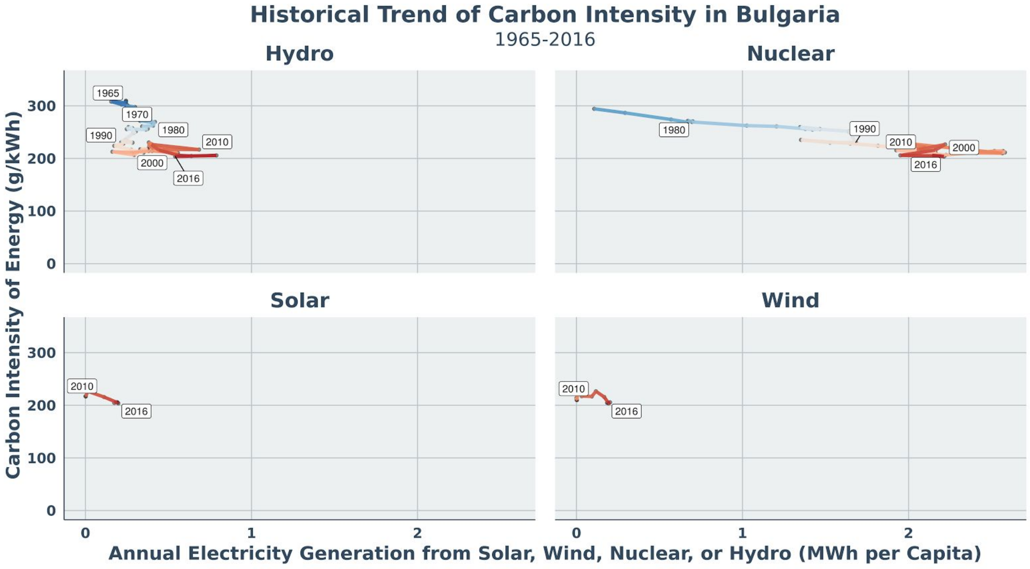
1965-2016

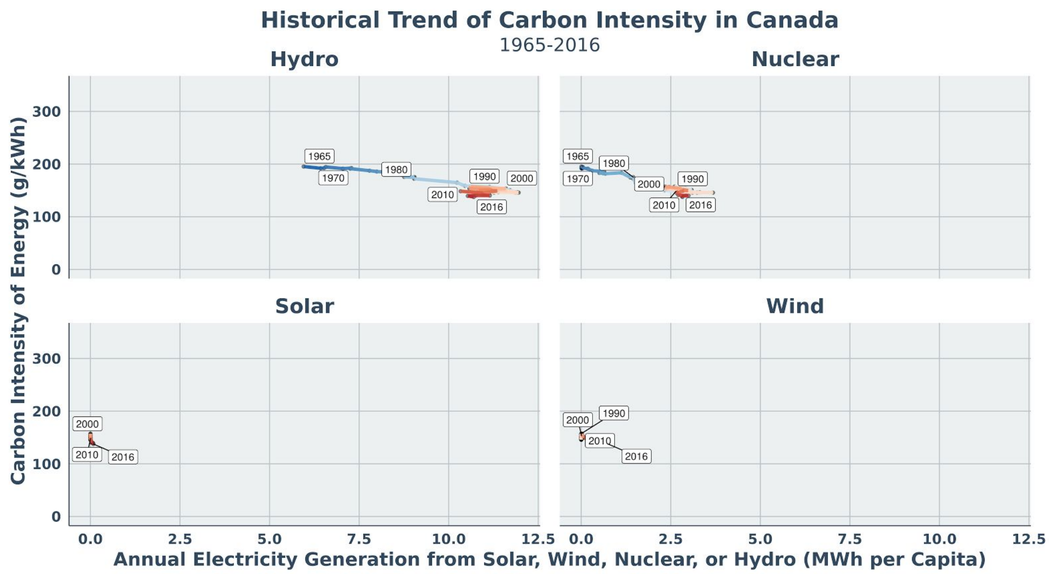


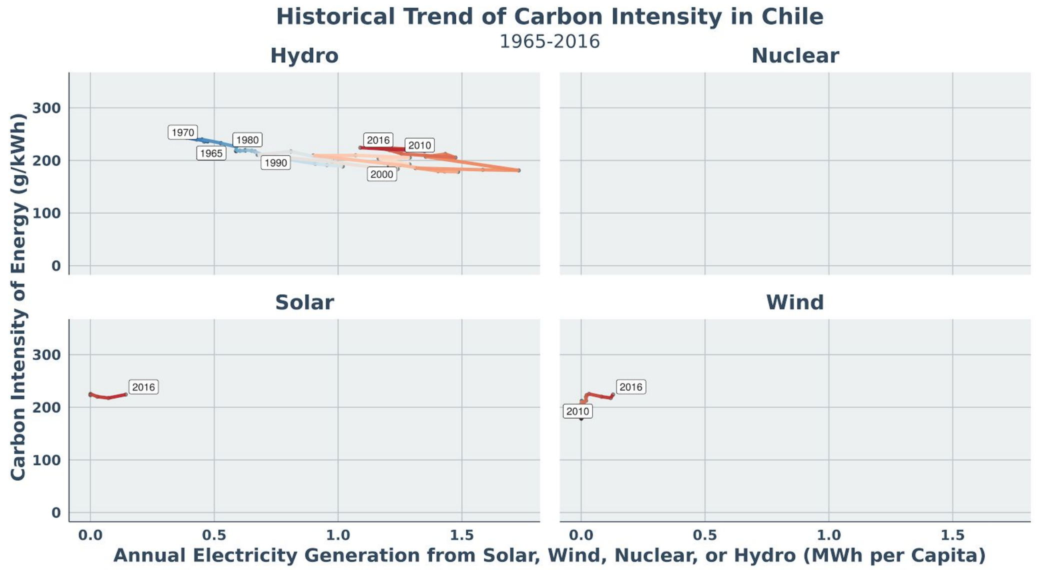
Historical Trend of Carbon Intensity in Belgium

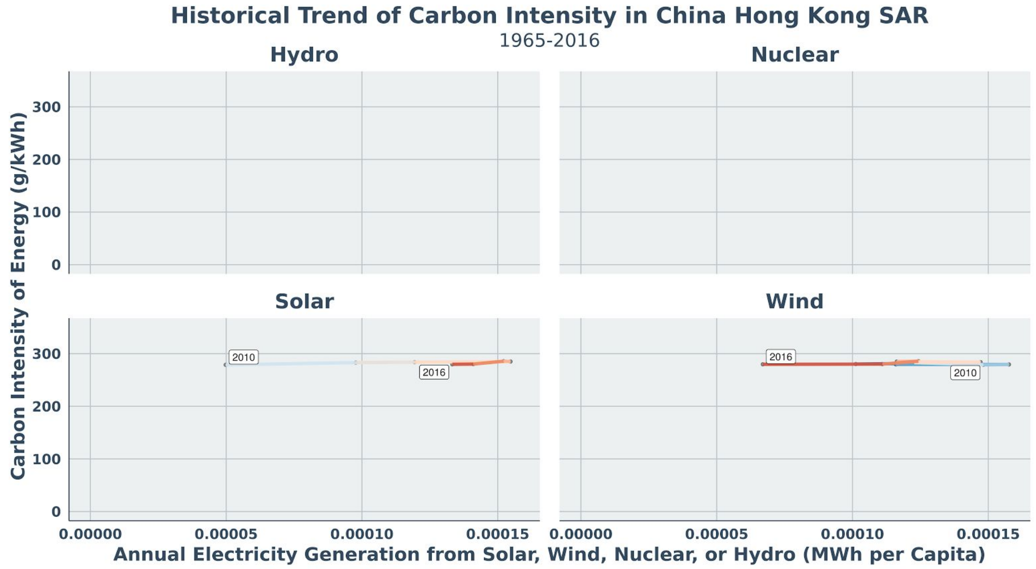
1965-2016

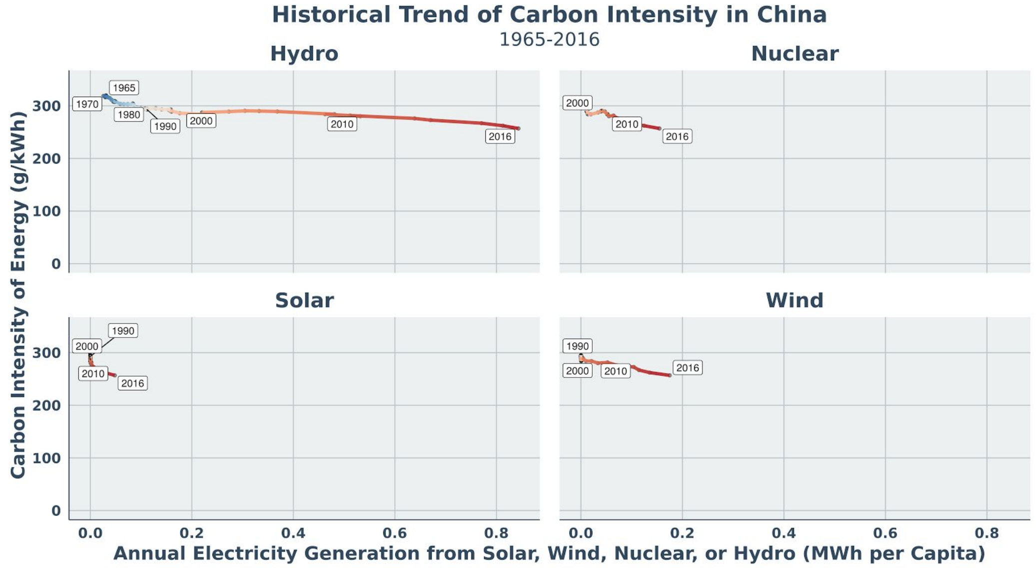

Historical Trend of Carbon Intensity in Brazil
1965-2016
Hydro
Nuclear
Solar
Wind
Carbon Intensity of Energy (g/kWh)
300
200
100
0
1965
1970
1980
1990
2000
2010
2016
0.0
0.5
1.0
1.5
2.0
Annual Electricity Generation from Solar, Wind, Nuclear, or Hydro (MWh per Capita)


Historical Trend of Carbon Intensity in Bulgaria
1965-2016
Hydro
Nuclear
Solar
Wind
Carbon Intensity of Energy (g/kWh)
300
200
100
0
1965
1970
1980
1990
2000
2010
2016
0
1
2
Annual Electricity Generation from Solar, Wind, Nuclear, or Hydro (MWh per Capita)


Historical Trend of Carbon Intensity in Canada
1965-2016
Hydro
Nuclear
Solar
Wind
Carbon Intensity of Energy (g/kWh)
Annual Electricity Generation from Solar, Wind, Nuclear, or Hydro (MWh per Capita)
0
100
200
300
0.0
2.5
5.0
7.5
10.0
12.5
1965
1970
1980
1990
2000
2010
2016


Historical Trend of Carbon Intensity in Chile
1965-2016
Hydro
Nuclear
Solar
Wind
Carbon Intensity of Energy (g/kWh)
Annual Electricity Generation from Solar, Wind, Nuclear, or Hydro (MWh per Capita)
0
100
200
300
0.0
0.5
1.0
1.5
1965
1970
1980
1990
2000
2010
2016


Historical Trend of Carbon Intensity in China Hong Kong SAR
1965-2016
Hydro
Nuclear
Solar
Wind
Carbon Intensity of Energy (g/kWh)
300
200
100
0
2010
2016
2016
2010
0.00000
0.00005
0.00010
0.00015
Annual Electricity Generation from Solar, Wind, Nuclear, or Hydro (MWh per Capita)


Historical Trend of Carbon Intensity in China
1965-2016
Hydro
Nuclear
Solar
Wind
Carbon Intensity of Energy (g/kWh)
300
200
100
0
1965
1970
1980
1990
2000
2010
2016
2000
2010
2016
1990
2000
2010
2016
1990
2000
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2016
0.0
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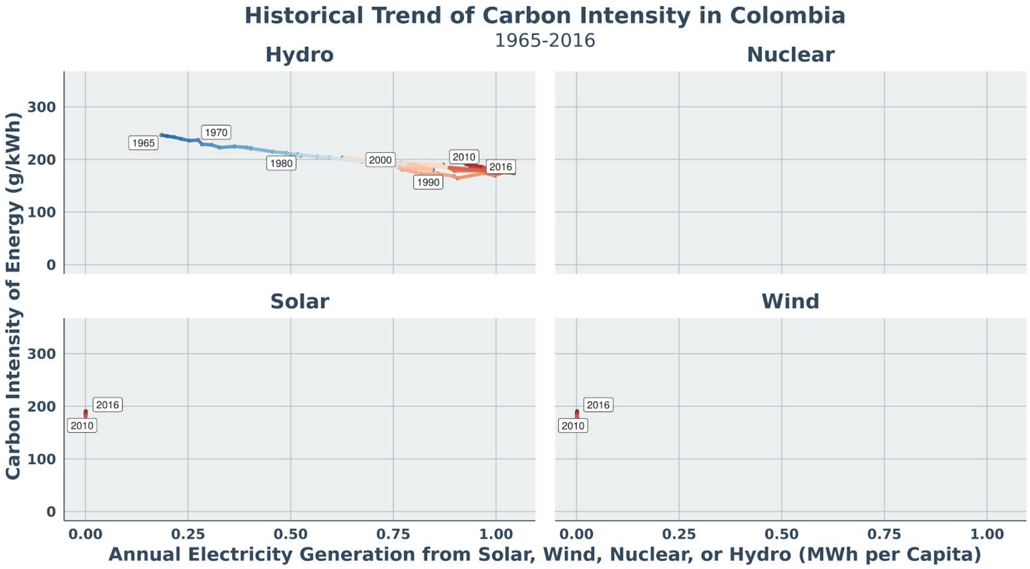
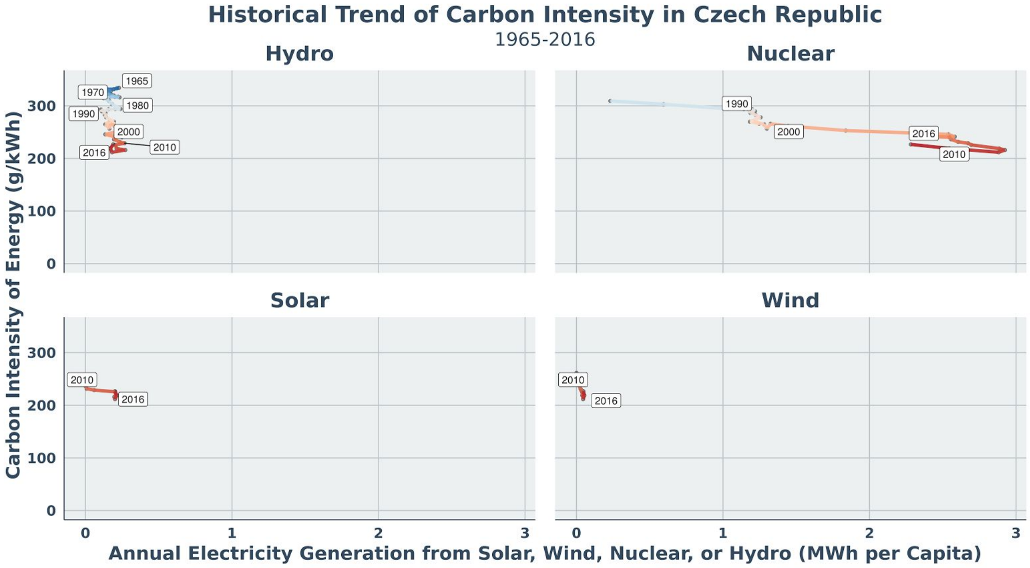
Annual Electricity Generation from Solar, Wind, Nuclear, or Hydro (MWh per Capita)



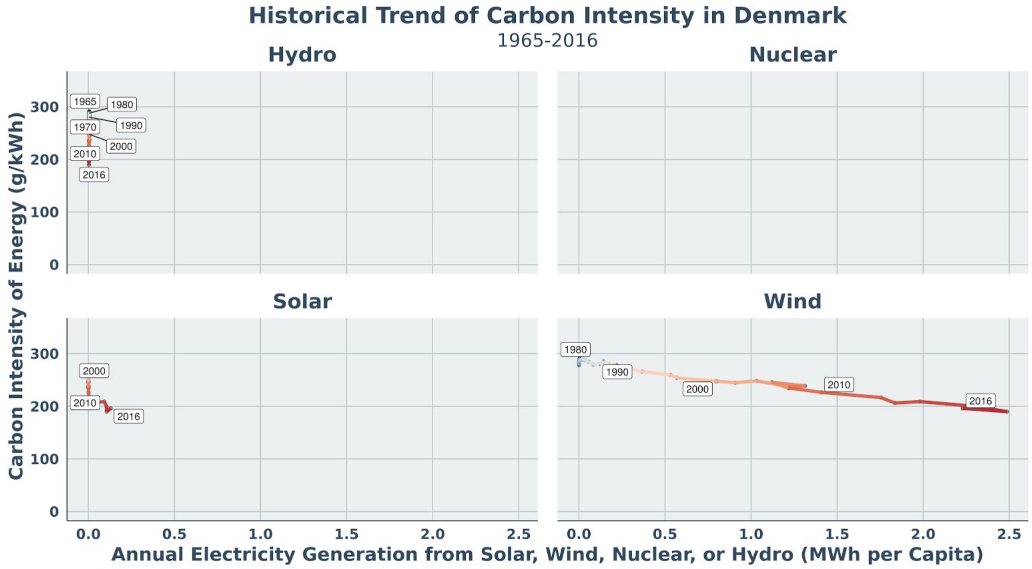
Historical Trend of Carbon Intensity in Colombia

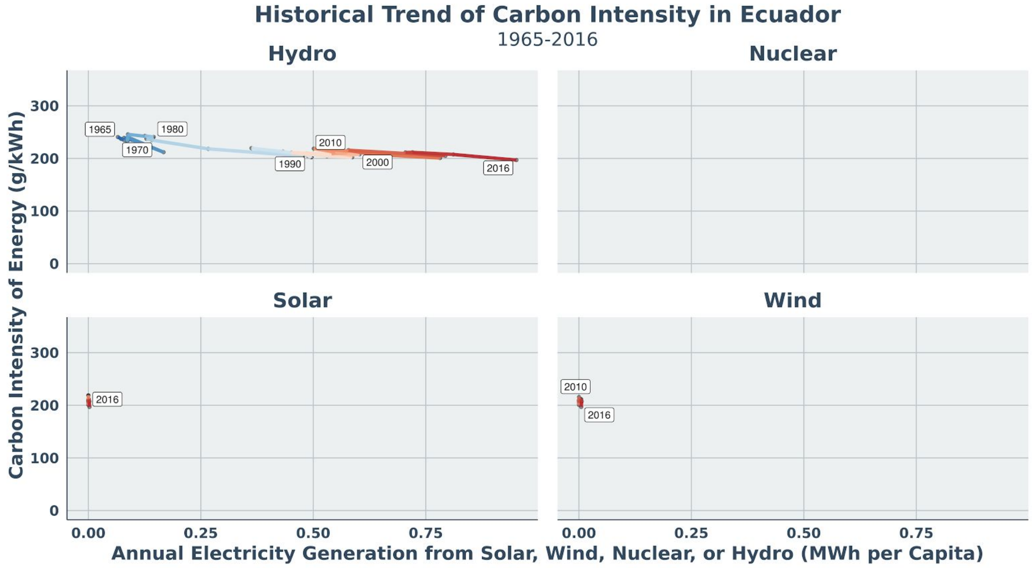
1965-2016



Historical Trend of Carbon Intensity in Czech Republic

1965-2016


Historical Trend of Carbon Intensity in Denmark
1965-2016
Hydro
Nuclear
Solar
Wind
Carbon Intensity of Energy (g/kWh)
0
100
200
300
1965
1980
1970
1990
2000
2010
2016
1980
1990
2000
2010
2016
0.0
0.5
1.0
1.5
2.0
2.5
Annual Electricity Generation from Solar, Wind, Nuclear, or Hydro (MWh per Capita)


Historical Trend of Carbon Intensity in Ecuador
1965-2016
Hydro
Nuclear
Solar
Wind
Carbon Intensity of Energy (g/kWh)
0
100
200
300
1965
1980
1970
2010
1990
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0.00
0.25
0.50
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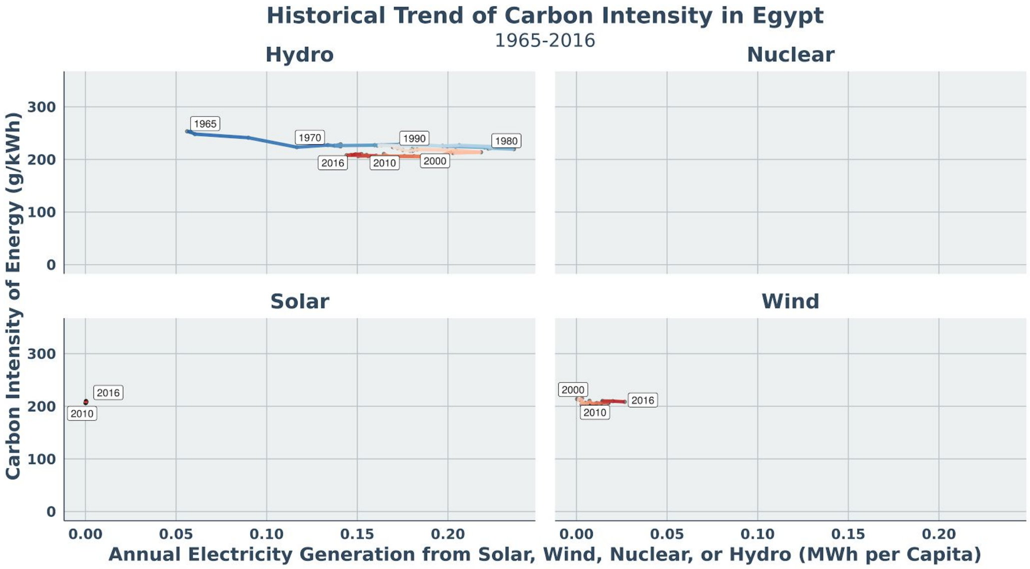
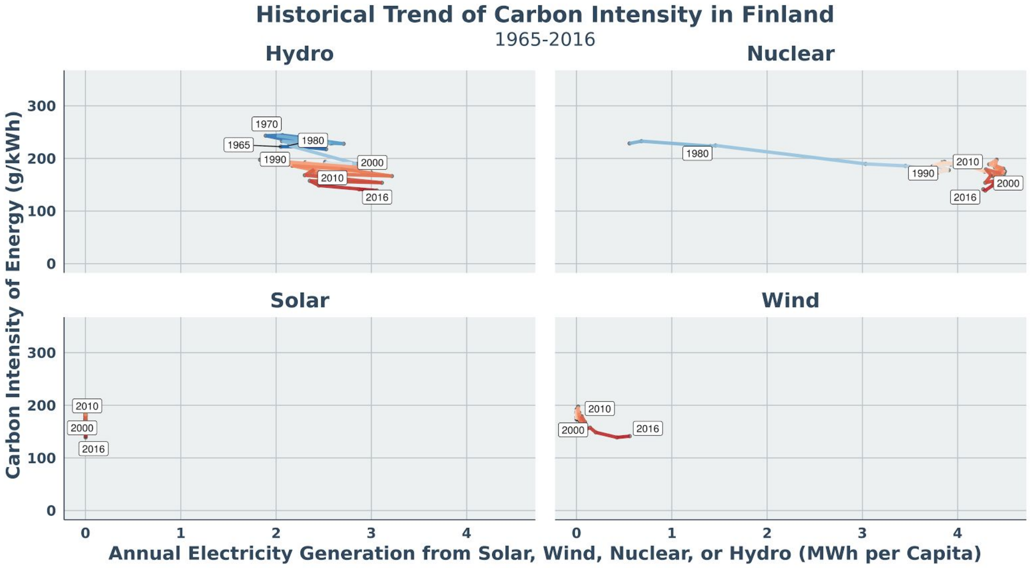
Annual Electricity Generation from Solar, Wind, Nuclear, or Hydro (MWh per Capita)



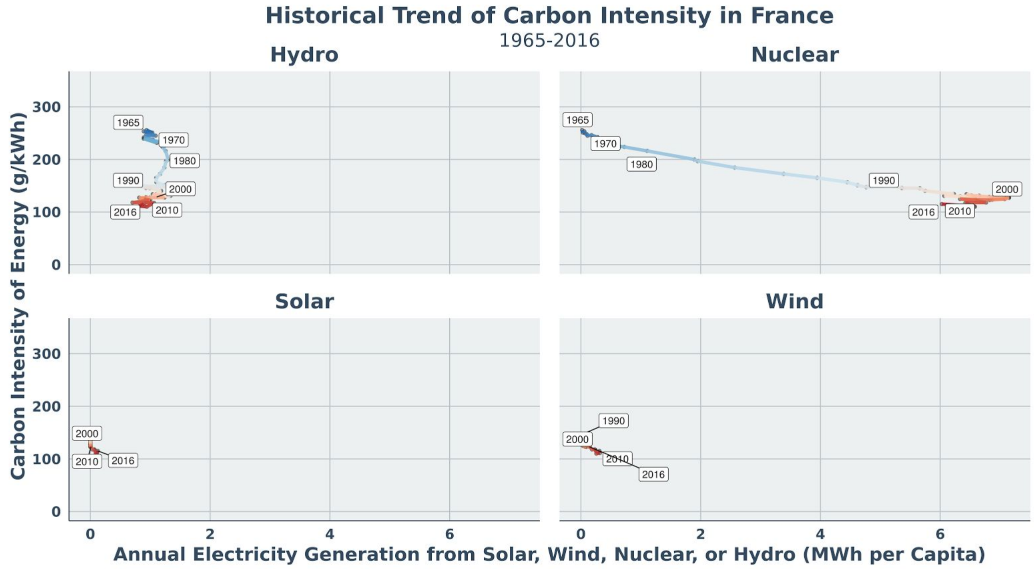
Historical Trend of Carbon Intensity in Egypt

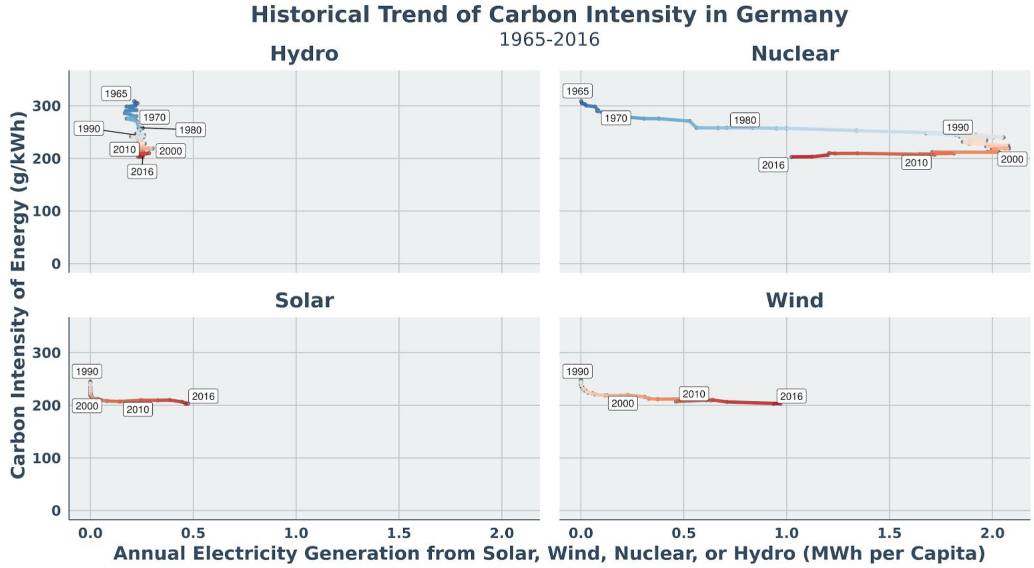
1965-2016



Historical Trend of Carbon Intensity in Finland

1965-2016


Historical Trend of Carbon Intensity in France
1965-2016
Hydro
Nuclear
Solar
Wind
Carbon Intensity of Energy (g/kWh)
Annual Electricity Generation from Solar, Wind, Nuclear, or Hydro (MWh per Capita)
0
100
200
300
0
2
4
6
1965
1970
1980
1990
2000
2010
2016


Historical Trend of Carbon Intensity in Germany
1965-2016
Hydro
Nuclear
Solar
Wind
Carbon Intensity of Energy (g/kWh)
Annual Electricity Generation from Solar, Wind, Nuclear, or Hydro (MWh per Capita)
0
100
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0.0
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1.0
1.5
2.0
1965
1970
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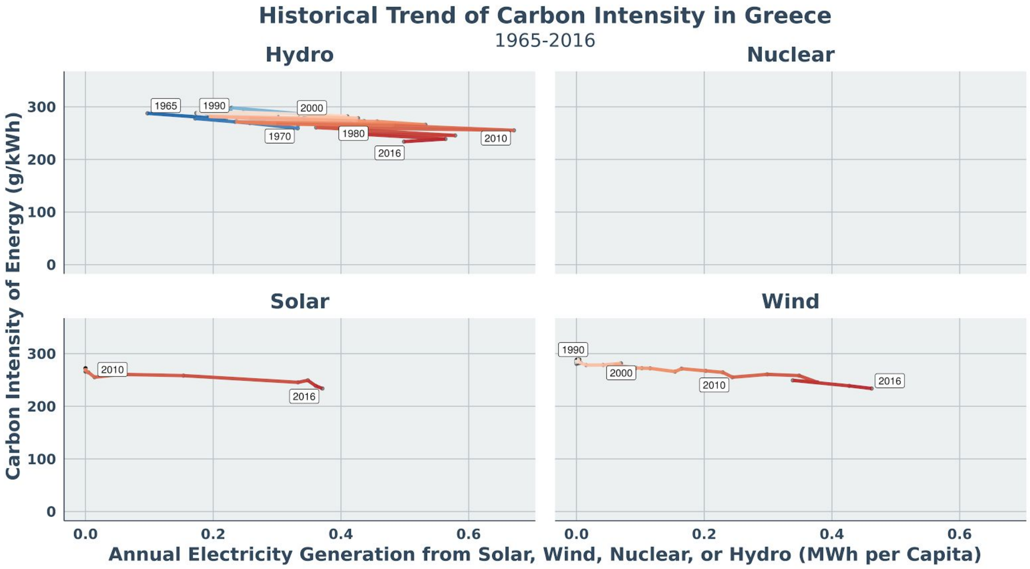
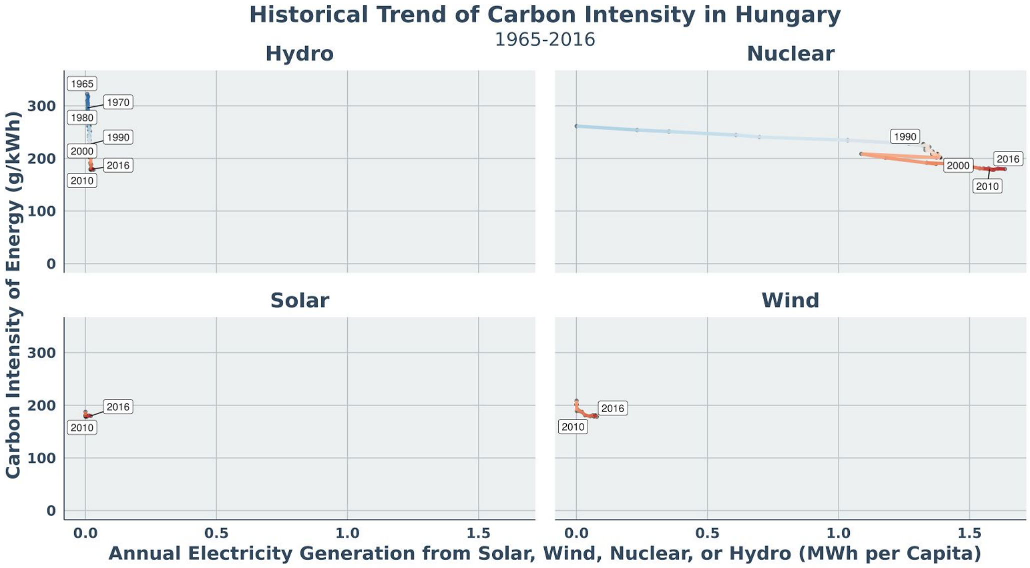
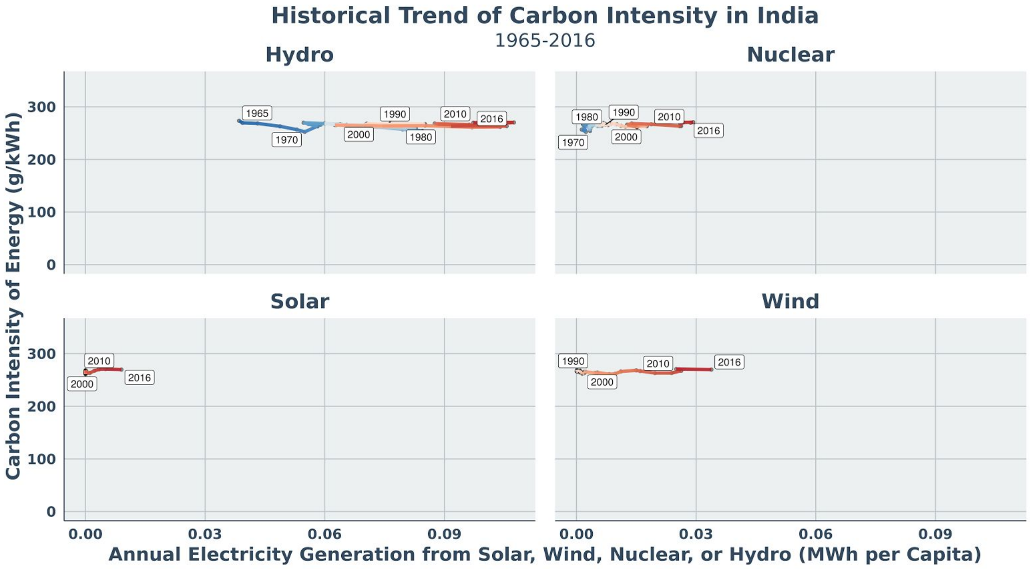
2000
2010
2016

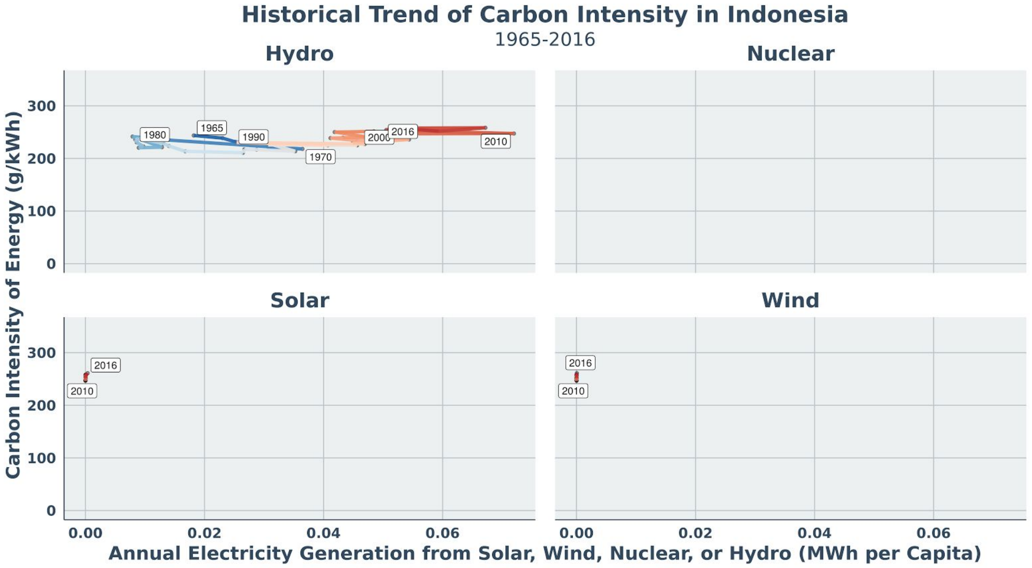

Historical Trend of Carbon Intensity in Greece
1965-2016
Hydro
Nuclear
Solar
Wind
Carbon Intensity of Energy (g/kWh)
Annual Electricity Generation from Solar, Wind, Nuclear, or Hydro (MWh per Capita)
0
100
200
300
0.0
0.2
0.4
0.6
1965
1990
2000
1970
1980
2010
2016
2010
2016
1990
2000
2010
2016


Historical Trend of Carbon Intensity in Hungary
1965-2016
Hydro
Nuclear
Solar
Wind
Carbon Intensity of Energy (g/kWh)
Annual Electricity Generation from Solar, Wind, Nuclear, or Hydro (MWh per Capita)
0
100
200
300
0.0
0.5
1.0
1.5
1965
1970
1980
1990
2000
2016
2010
1990
2000
2016
2010
2016
2010
2016
2010



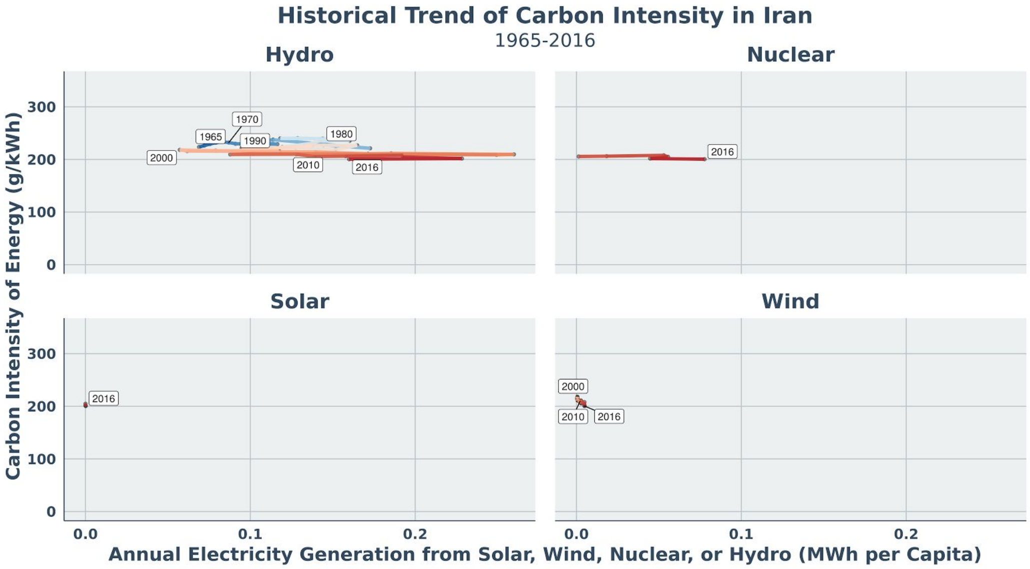
Historical Trend of Carbon Intensity in India

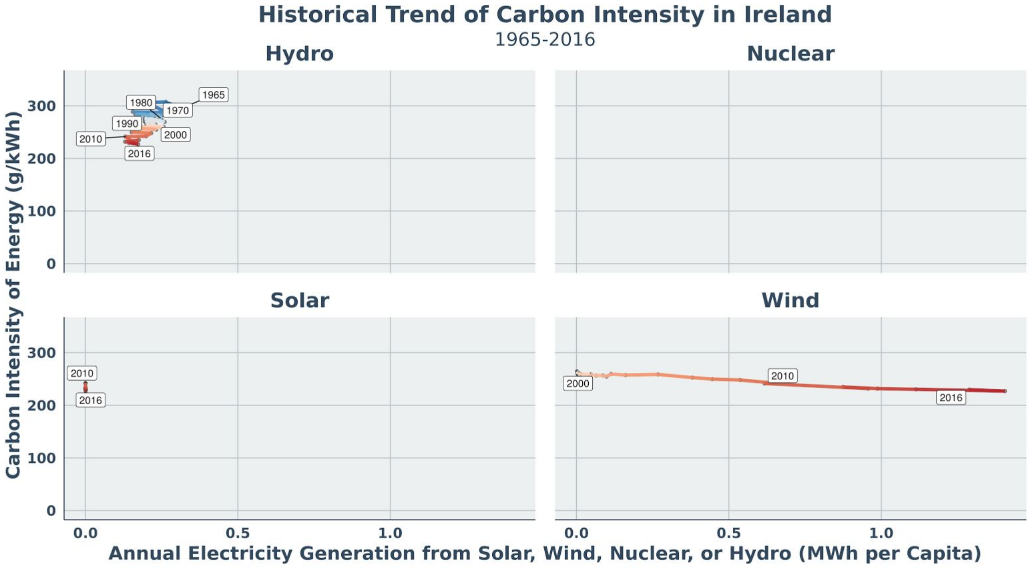
1965-2016

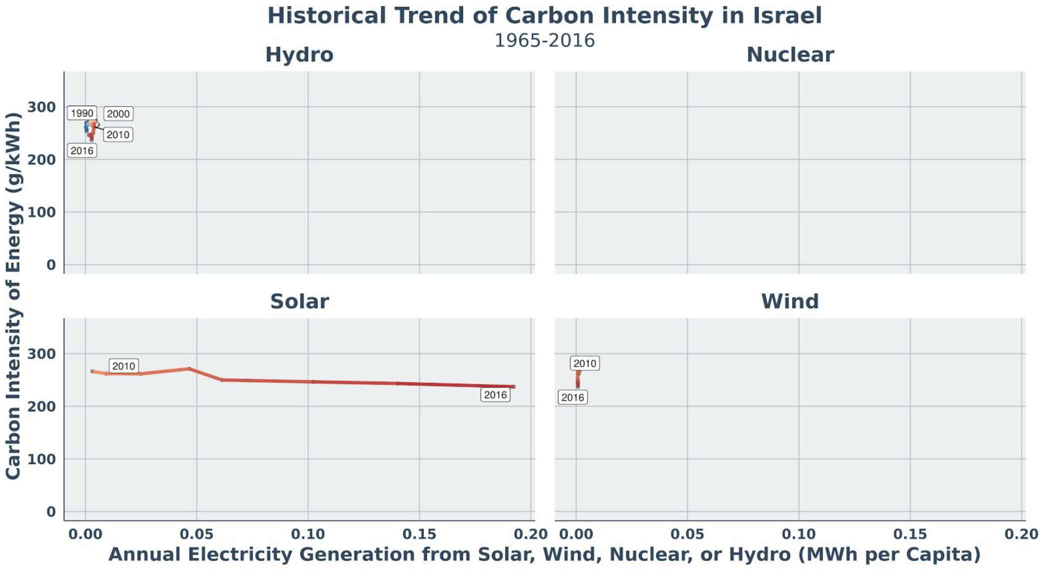


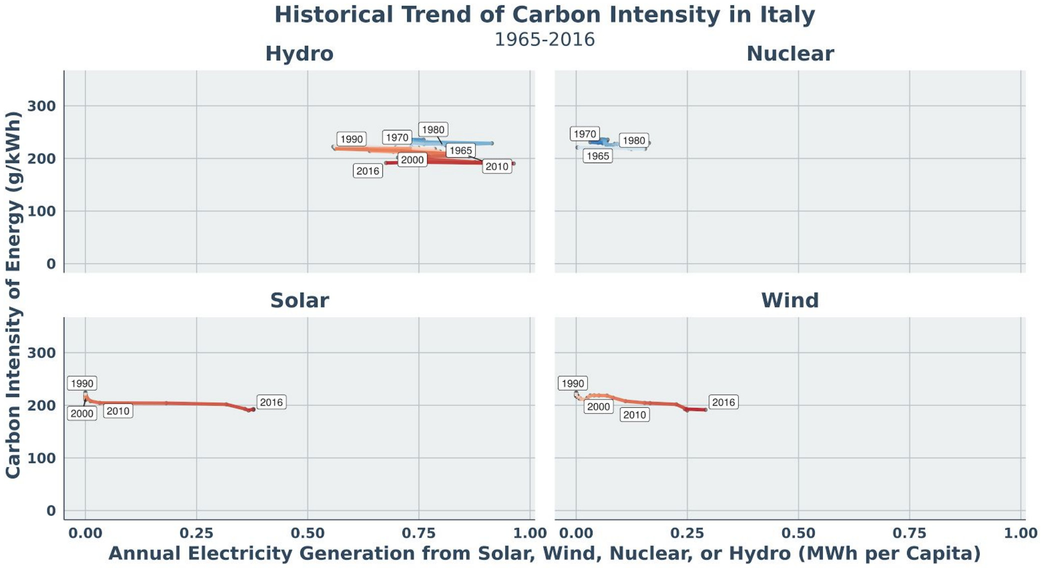
Historical Trend of Carbon Intensity in Indonesia

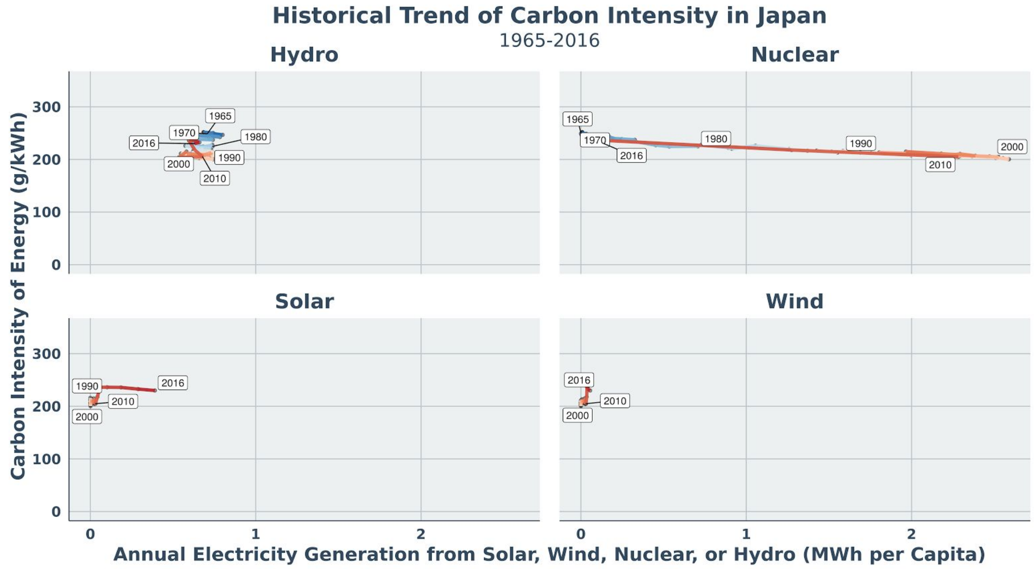
1965-2016

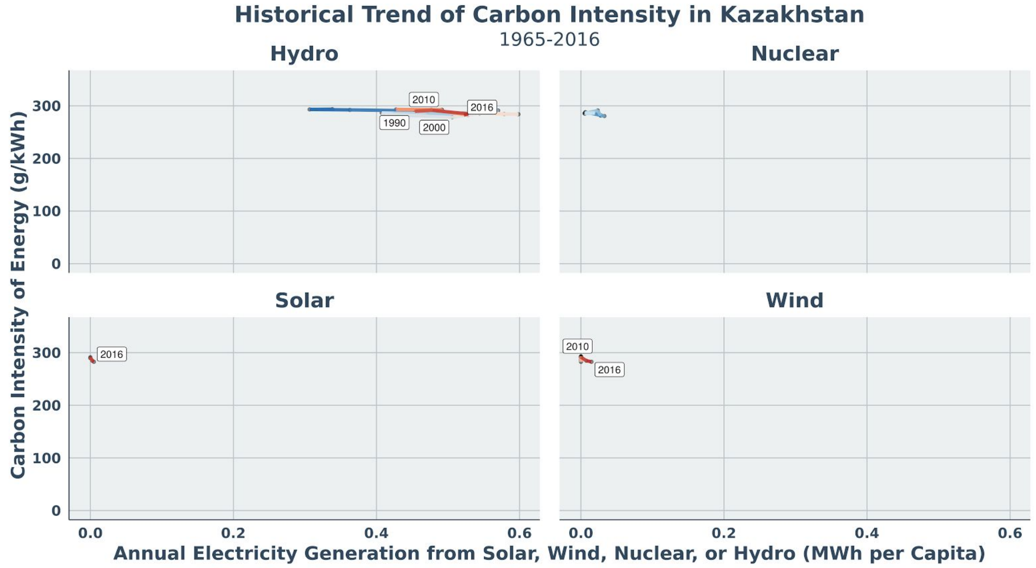

Historical Trend of Carbon Intensity in Iran
1965-2016
Hydro
Nuclear
Solar
Wind
Carbon Intensity of Energy (g/kWh)
300
200
100
0
1965
1970
1980
1990
2000
2010
2016
0.0
0.1
0.2
Annual Electricity Generation from Solar, Wind, Nuclear, or Hydro (MWh per Capita)

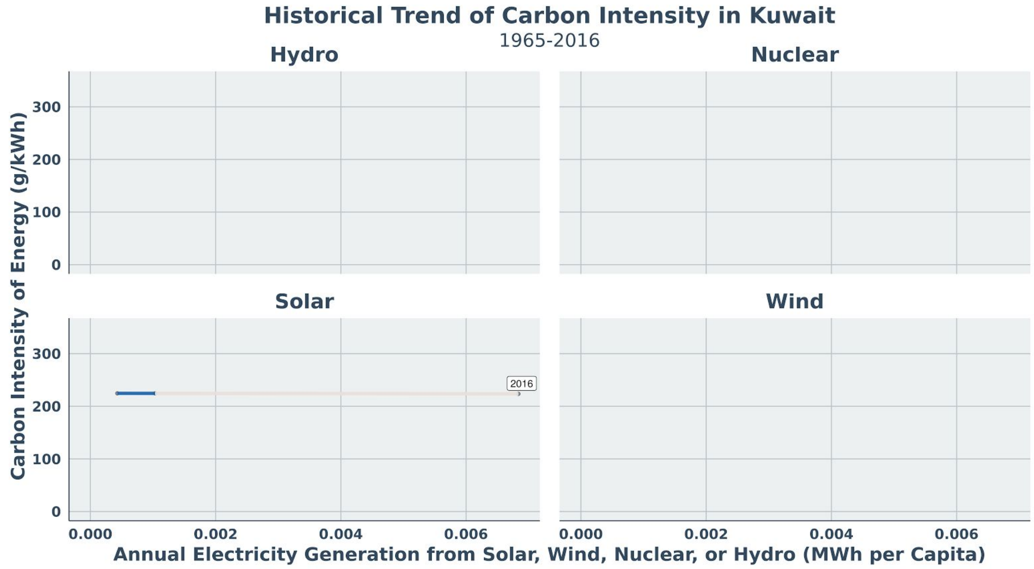

Historical Trend of Carbon Intensity in Ireland
1965-2016
Hydro
Nuclear
Solar
Wind
Carbon Intensity of Energy (g/kWh)
300
200
100
0
1965
1970
1980
1990
2000
2010
2016
0.0
0.5
1.0
Annual Electricity Generation from Solar, Wind, Nuclear, or Hydro (MWh per Capita)

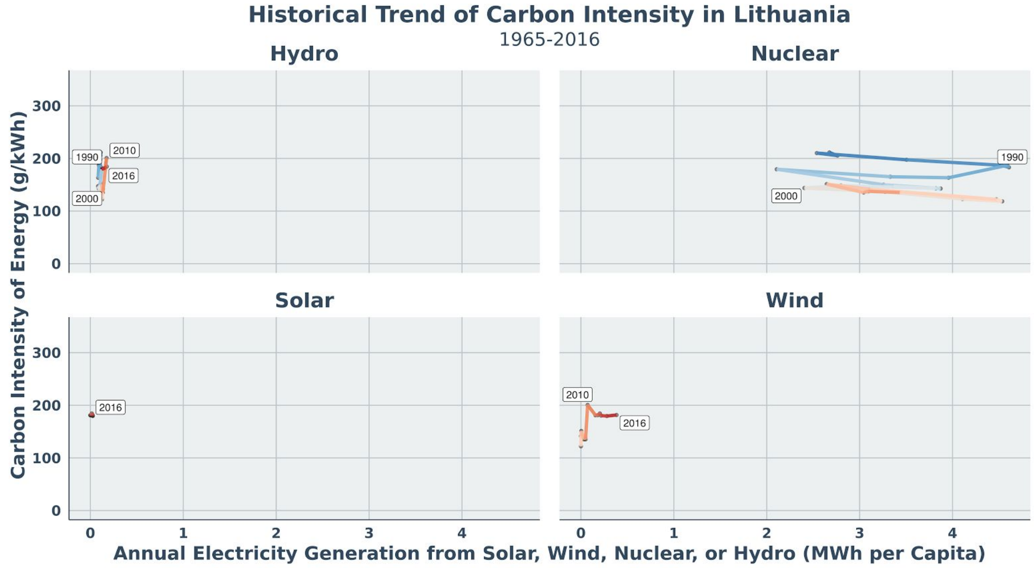

Historical Trend of Carbon Intensity in Israel
1965-2016

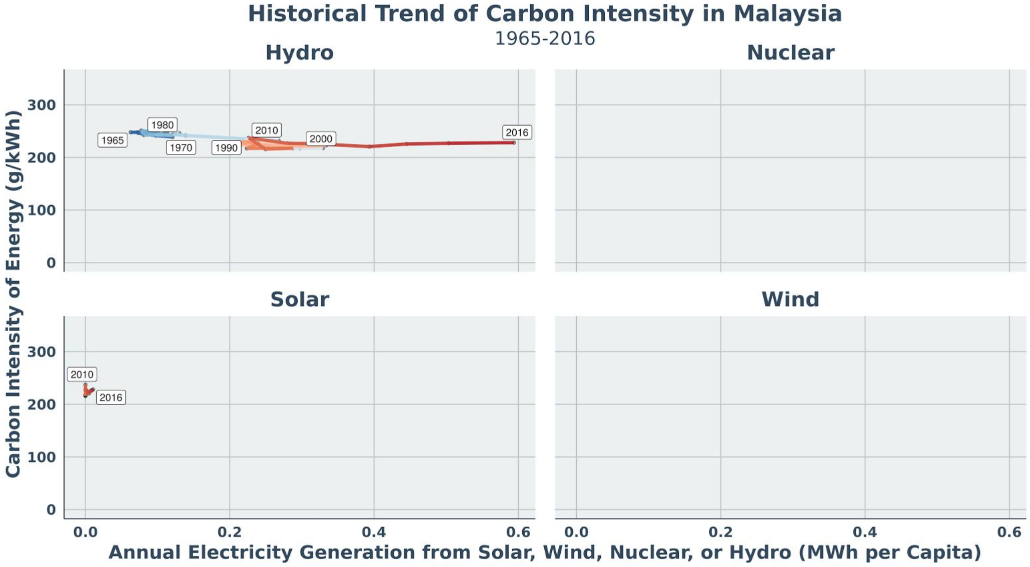

Historical Trend of Carbon Intensity in Italy
1965-2016

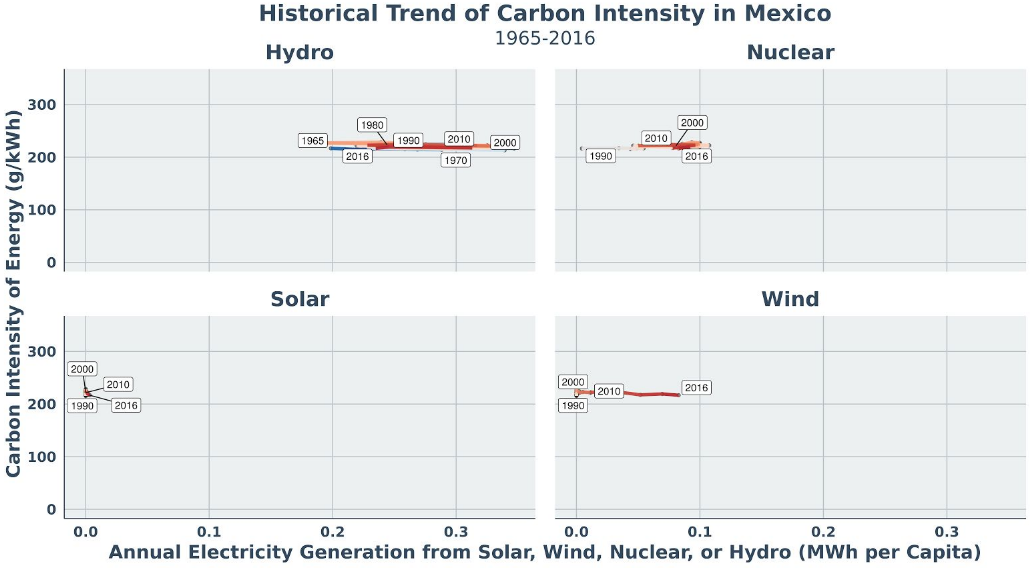

Historical Trend of Carbon Intensity in Japan
1965-2016
Hydro
Nuclear
Solar
Wind
Carbon Intensity of Energy (g/kWh)
Annual Electricity Generation from Solar, Wind, Nuclear, or Hydro (MWh per Capita)
0
100
200
300
0
1
2
1965
1970
1980
1990
2000
2010
2016

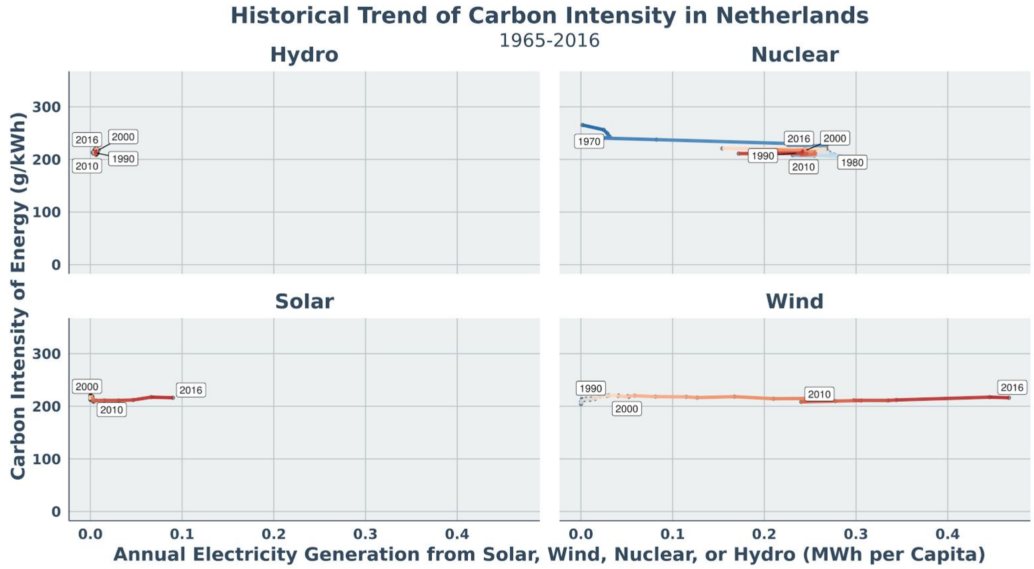

Historical Trend of Carbon Intensity in Kazakhstan
1965-2016
Hydro
Nuclear
Solar
Wind
Carbon Intensity of Energy (g/kWh)
Annual Electricity Generation from Solar, Wind, Nuclear, or Hydro (MWh per Capita)
0
100
200
300
0.0
0.2
0.4
0.6
1990
2000
2010
2016

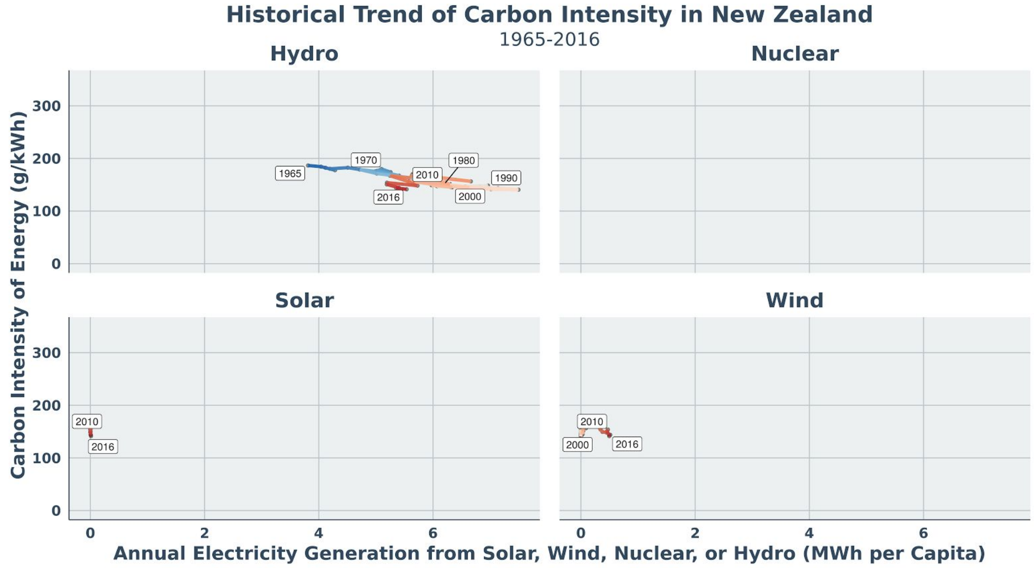

Historical Trend of Carbon Intensity in Kuwait
1965-2016
Hydro
Nuclear
Solar
Wind
Carbon Intensity of Energy (g/kWh)
300
200
100
0
2016
0.000
0.002
0.004
0.006
Annual Electricity Generation from Solar, Wind, Nuclear, or Hydro (MWh per Capita)

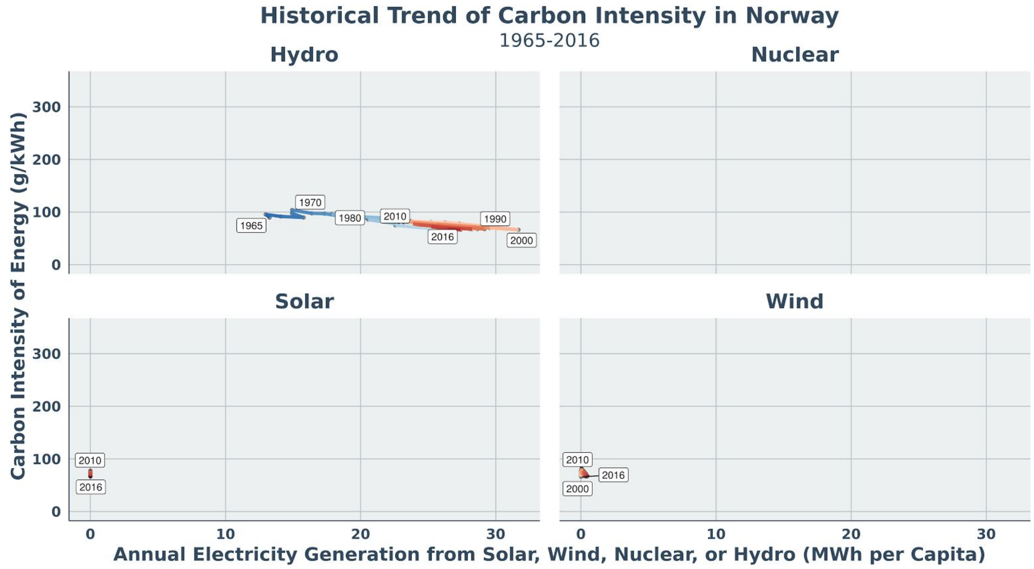

Historical Trend of Carbon Intensity in Lithuania
1965-2016
Hydro
Nuclear
Solar
Wind
Carbon Intensity of Energy (g/kWh)
300
200
100
0
1990
2010
2016
2000
1990
2000
2016
2010
2016
0
1
2
3
4
Annual Electricity Generation from Solar, Wind, Nuclear, or Hydro (MWh per Capita)


Historical Trend of Carbon Intensity in Malaysia
1965-2016
Hydro
Nuclear
Solar
Wind
Carbon Intensity of Energy (g/kWh)
300
200
100
0
1965
1980
1970
1990
2010
2000
2016
2010
2016
0.0
0.2
0.4
0.6
Annual Electricity Generation from Solar, Wind, Nuclear, or Hydro (MWh per Capita)


Historical Trend of Carbon Intensity in Mexico
1965-2016
Hydro
Nuclear
Solar
Wind
Carbon Intensity of Energy (g/kWh)
300
200
100
0
1965
1980
1990
2010
2000
2016
1970
2010
2000
1990
2016
2000
2010
1990
2016
2000
2010
1990
2016
0.0
0.1
0.2
0.3
Annual Electricity Generation from Solar, Wind, Nuclear, or Hydro (MWh per Capita)

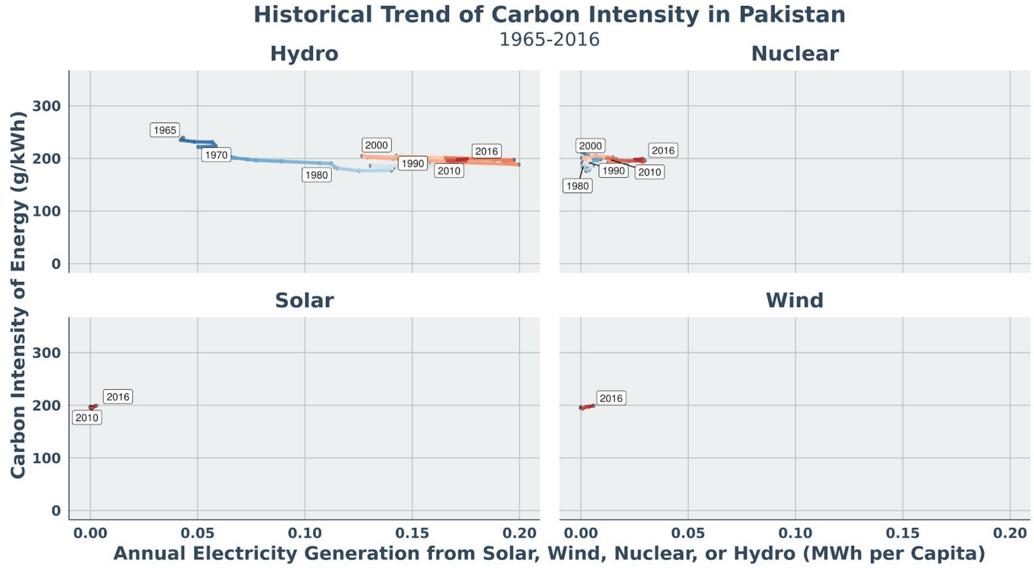

Historical Trend of Carbon Intensity in Netherlands
1965-2016
Hydro
Nuclear
Solar
Wind
Carbon Intensity of Energy (g/kWh)
0
100
200
300
2016
2000
2010
1990
1970
1980
0.0
0.1
0.2
0.3
0.4
Annual Electricity Generation from Solar, Wind, Nuclear, or Hydro (MWh per Capita)


Historical Trend of Carbon Intensity in New Zealand
1965-2016
Hydro
Nuclear
Solar
Wind
Carbon Intensity of Energy (g/kWh)
0
100
200
300
1965
1970
1980
1990
2000
2010
2016
0
2
4
6
Annual Electricity Generation from Solar, Wind, Nuclear, or Hydro (MWh per Capita)



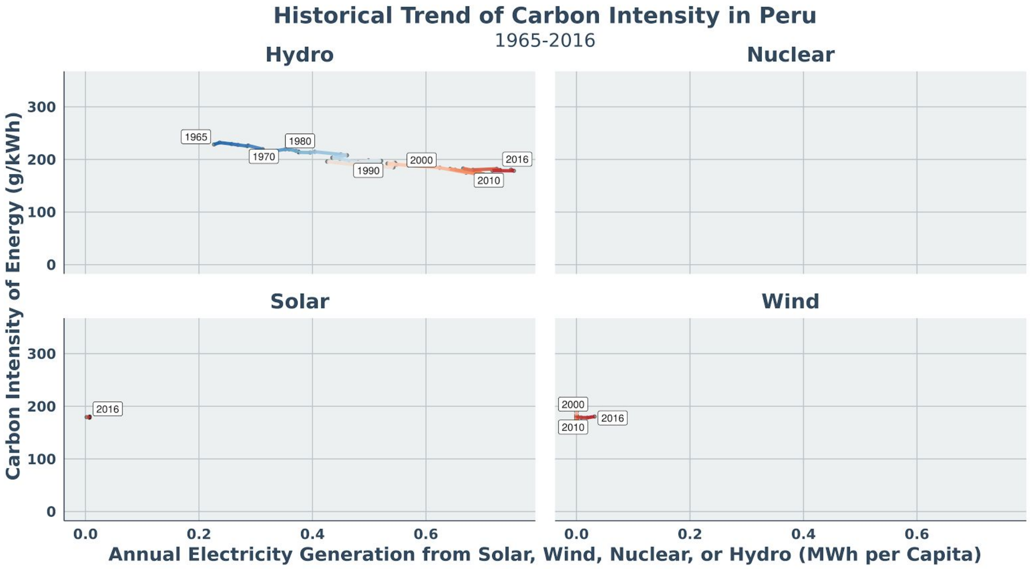
Historical Trend of Carbon Intensity in Norway

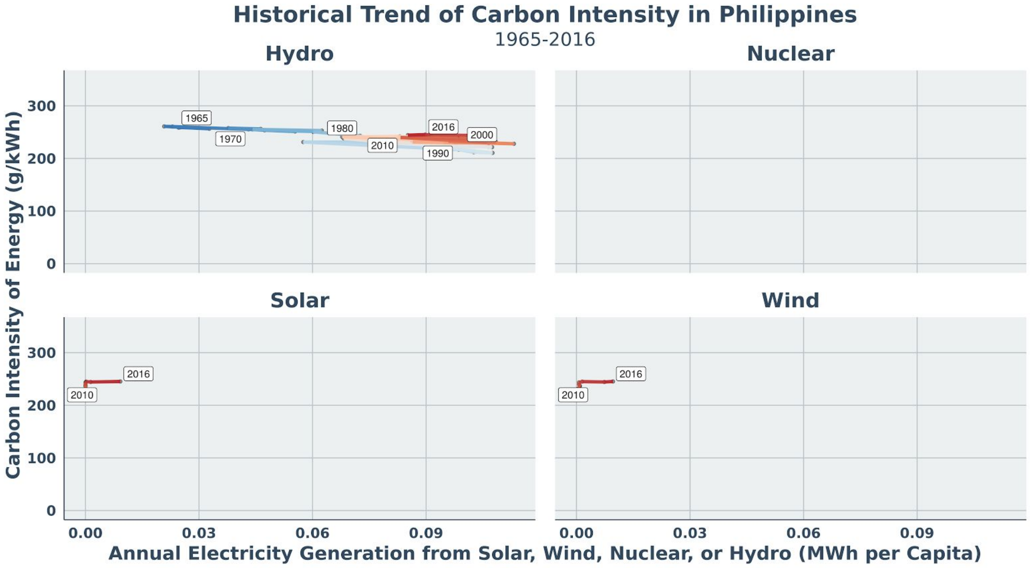
1965-2016

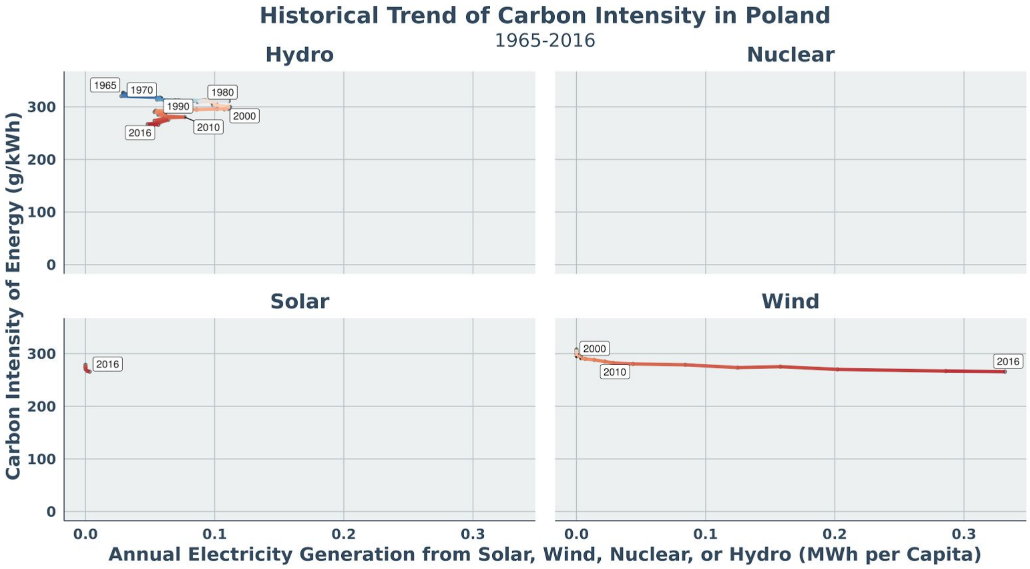


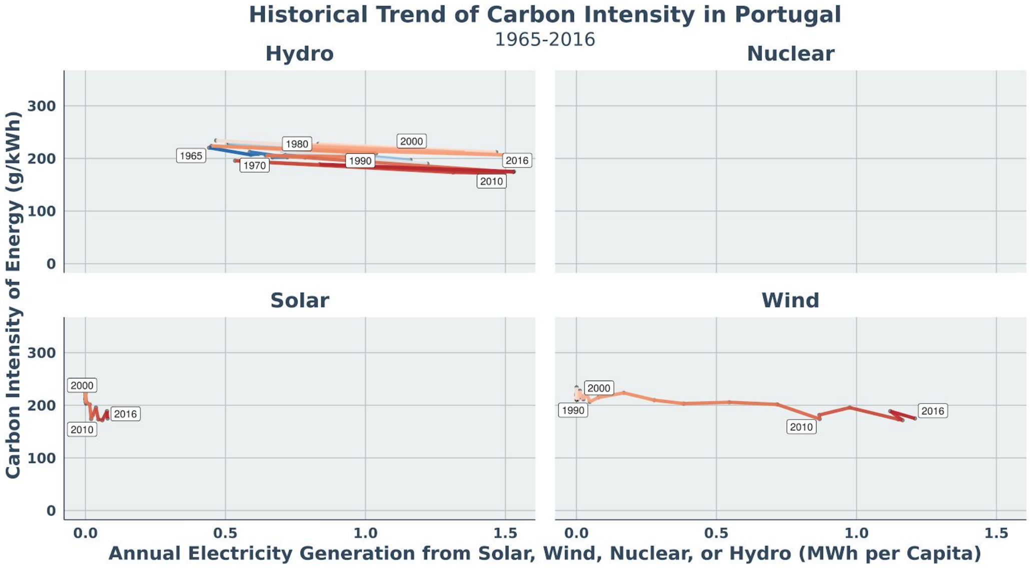
Historical Trend of Carbon Intensity in Pakistan

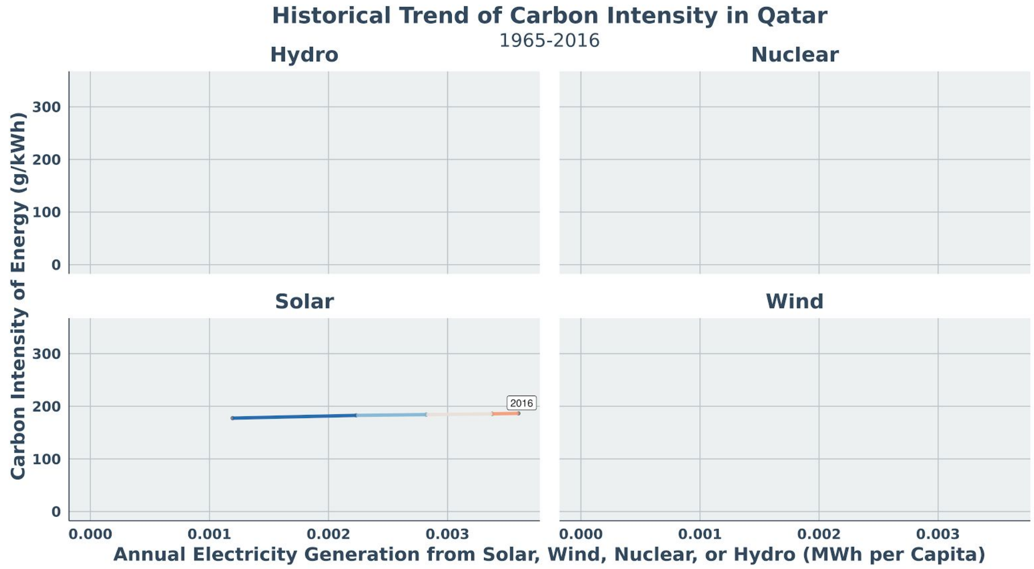
1965-2016

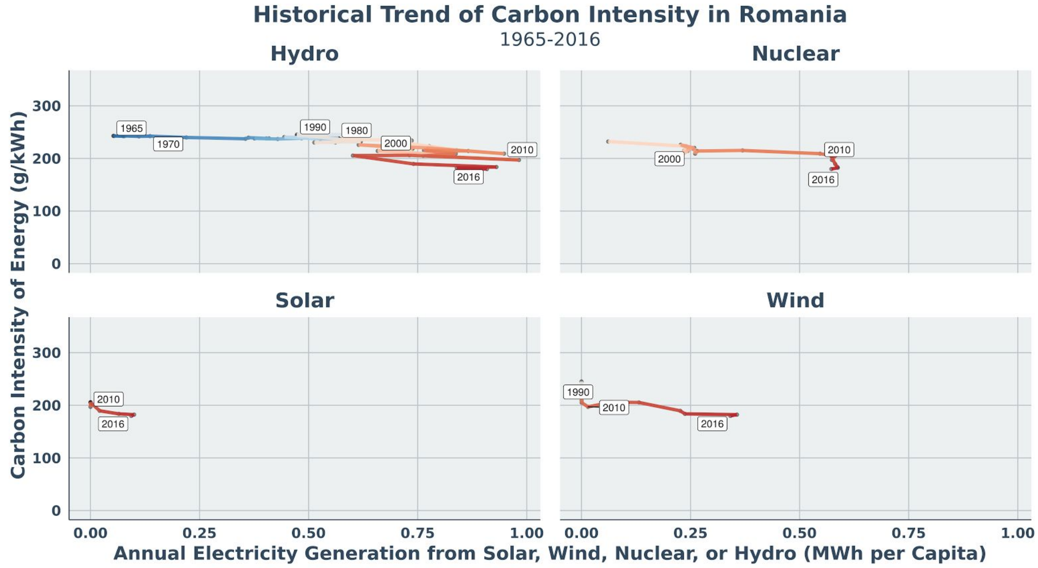

Historical Trend of Carbon Intensity in Peru
1965-2016
Hydro
Nuclear
Solar
Wind
Carbon Intensity of Energy (g/kWh)
300
200
100
0
1965
1970
1980
1990
2000
2010
2016
2016
2000
2010
2016
0.0
0.2
0.4
0.6
Annual Electricity Generation from Solar, Wind, Nuclear, or Hydro (MWh per Capita)

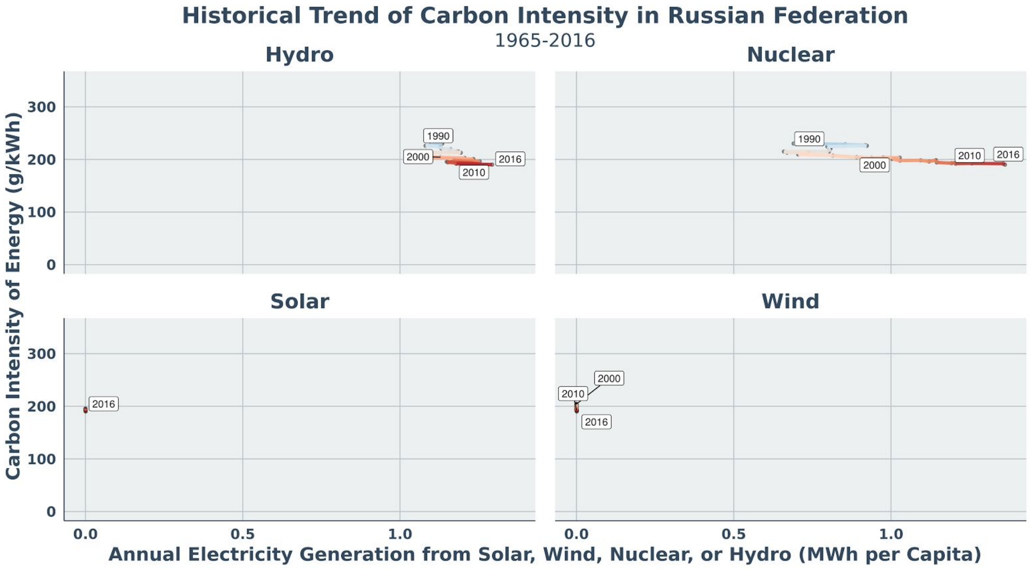

Historical Trend of Carbon Intensity in Philippines
1965-2016
Hydro
Nuclear
Solar
Wind
Carbon Intensity of Energy (g/kWh)
300
200
100
0
1965
1970
1980
2010
2016
2000
1990
2016
2010
2016
2010
0.00
0.03
0.06
0.09
Annual Electricity Generation from Solar, Wind, Nuclear, or Hydro (MWh per Capita)

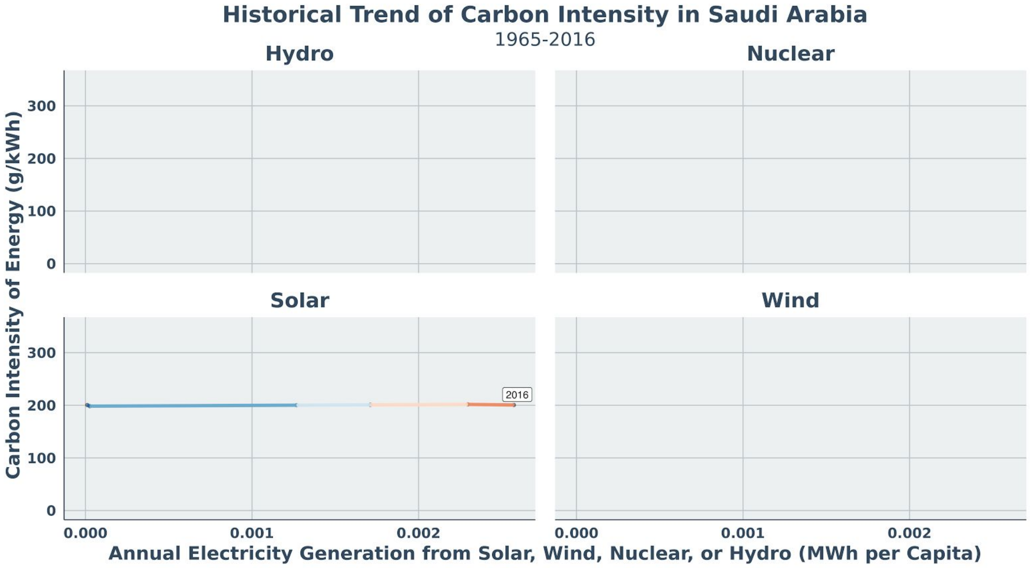

Historical Trend of Carbon Intensity in Poland
1965-2016
Hydro
Nuclear
Solar
Wind
1965
1970
1980
1990
2000
2010
2016
2016
2000
2010
2016
Carbon Intensity of Energy (g/kWh)
0
100
200
300
0.0
0.1
0.2
0.3
Annual Electricity Generation from Solar, Wind, Nuclear, or Hydro (MWh per Capita)

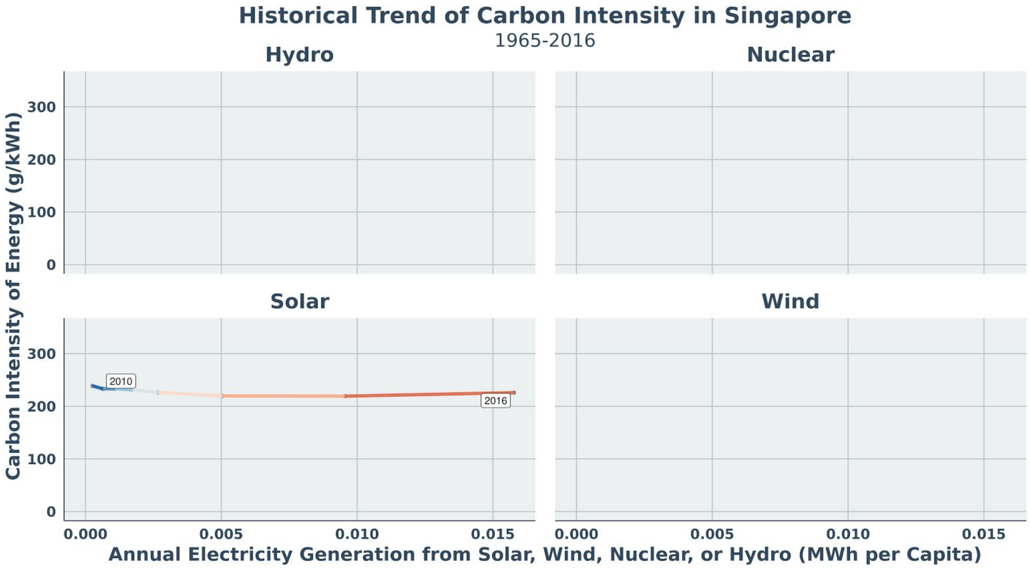

Historical Trend of Carbon Intensity in Portugal
1965-2016
Hydro
Nuclear
Solar
Wind
1965
1970
1980
1990
2000
2010
2016
2000
2010
2016
1990
2000
2010
2016
Carbon Intensity of Energy (g/kWh)
0
100
200
300
0.0
0.5
1.0
1.5
Annual Electricity Generation from Solar, Wind, Nuclear, or Hydro (MWh per Capita)

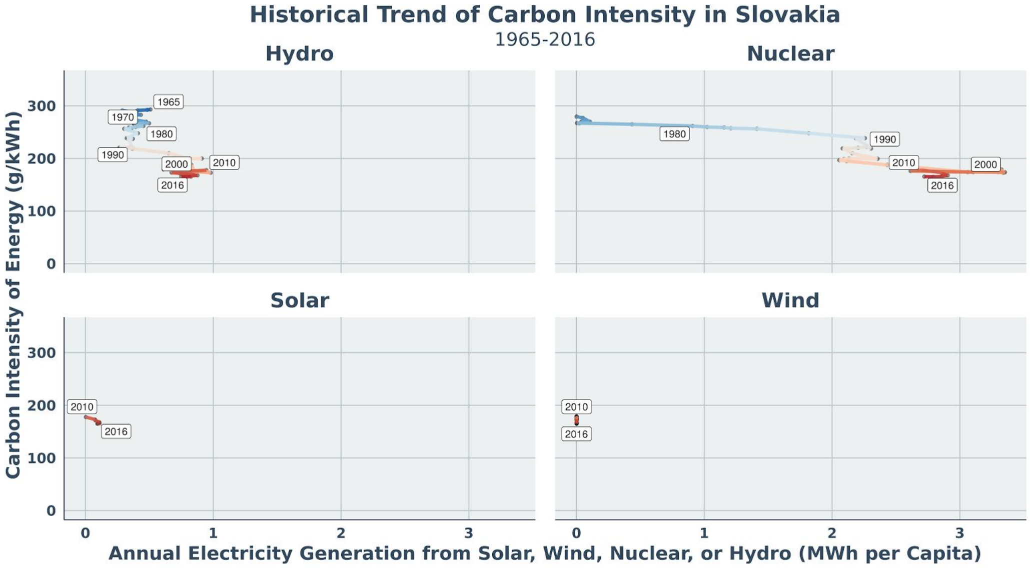

Historical Trend of Carbon Intensity in Qatar
1965-2016
Hydro
Nuclear
Solar
Wind
Carbon Intensity of Energy (g/kWh)
300
200
100
0
2016
0.000
0.001
0.002
0.003
Annual Electricity Generation from Solar, Wind, Nuclear, or Hydro (MWh per Capita)

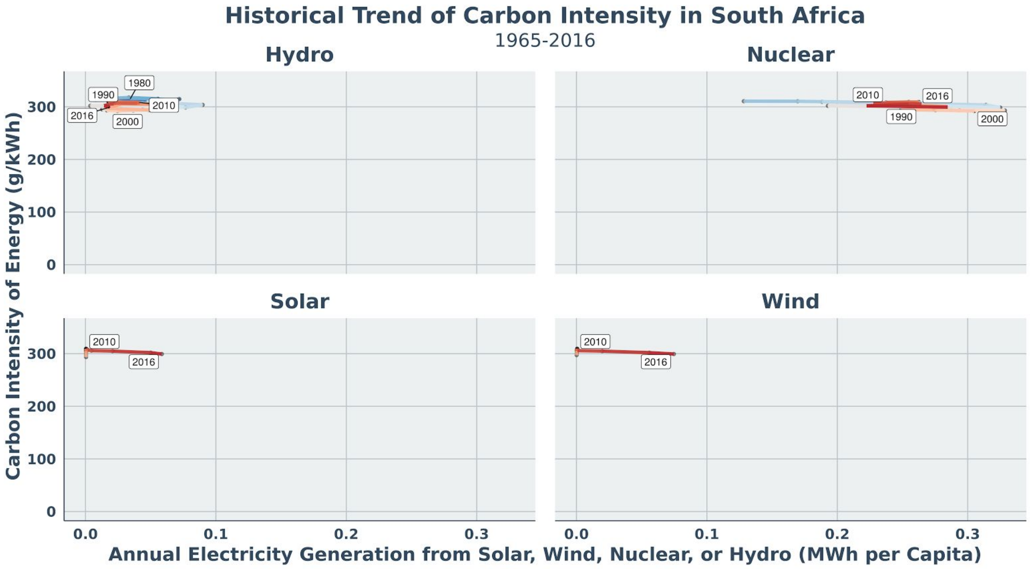

Historical Trend of Carbon Intensity in Romania
1965-2016
Hydro
Nuclear
Solar
Wind
Carbon Intensity of Energy (g/kWh)
300
200
100
0
1965
1970
1990
1980
2000
2010
2016
0.00
0.25
0.50
0.75
1.00
Annual Electricity Generation from Solar, Wind, Nuclear, or Hydro (MWh per Capita)

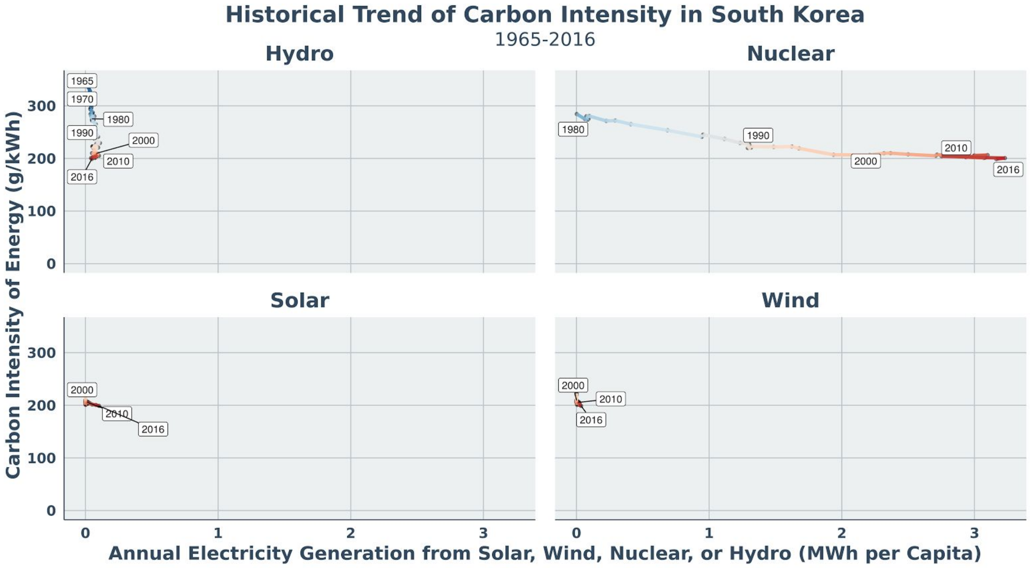

Historical Trend of Carbon Intensity in Russian Federation
1965-2016
Hydro
Nuclear
Solar
Wind
Carbon Intensity of Energy (g/kWh)
0
100
200
300
1990
2000
2010
2016
0.0
0.5
1.0
Annual Electricity Generation from Solar, Wind, Nuclear, or Hydro (MWh per Capita)

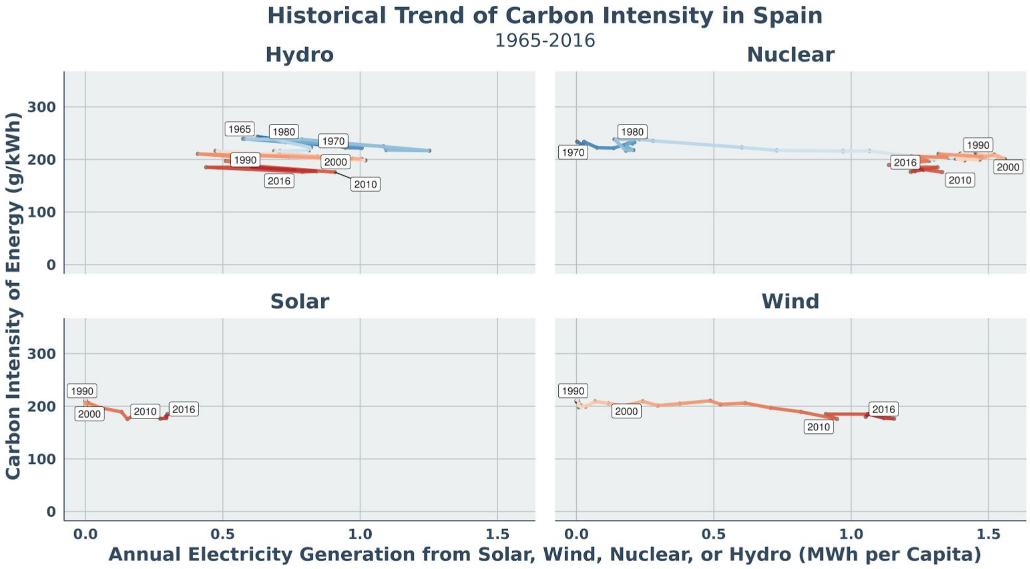

Historical Trend of Carbon Intensity in Saudi Arabia
1965-2016
Hydro
Nuclear
Solar
Wind
Carbon Intensity of Energy (g/kWh)
0
100
200
300
2016
0.000
0.001
0.002
Annual Electricity Generation from Solar, Wind, Nuclear, or Hydro (MWh per Capita)

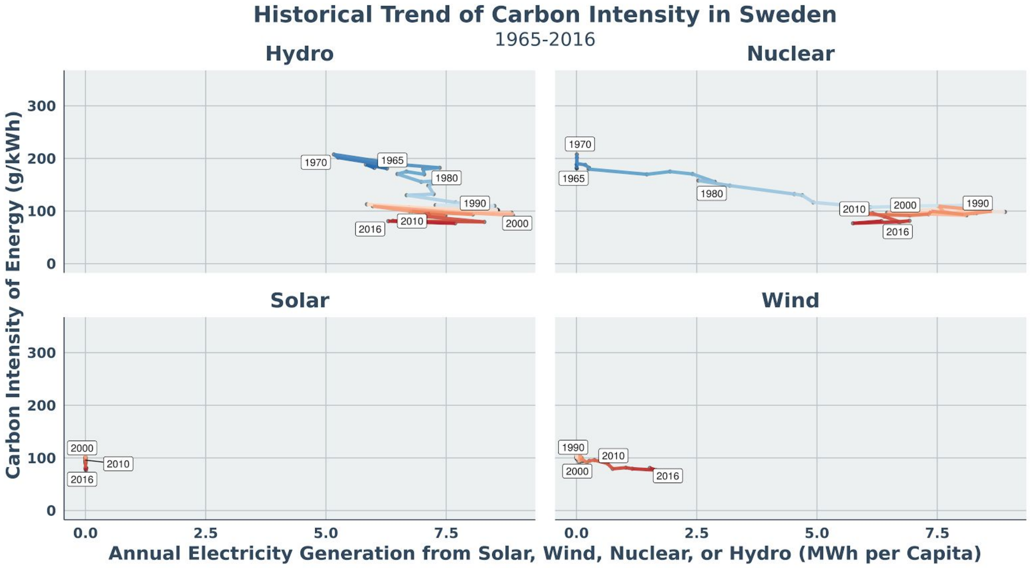

Historical Trend of Carbon Intensity in Singapore
1965-2016
Hydro
Nuclear
Solar
Wind
Carbon Intensity of Energy (g/kWh)
300
200
100
0
2010
2016
0.000
0.005
0.010
0.015
Annual Electricity Generation from Solar, Wind, Nuclear, or Hydro (MWh per Capita)

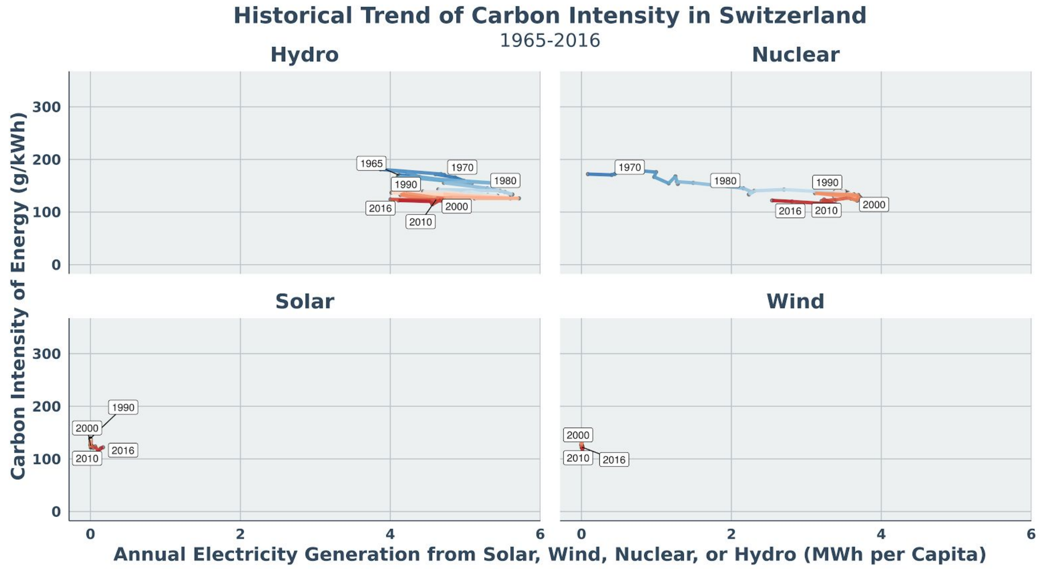

Historical Trend of Carbon Intensity in Slovakia
1965-2016
Hydro
Nuclear
Solar
Wind
Carbon Intensity of Energy (g/kWh)
300
200
100
0
1965
1970
1980
1990
2000
2010
2016
1980
1990
2010
2000
2016
2010
2016
2010
2016
0
1
2
3
Annual Electricity Generation from Solar, Wind, Nuclear, or Hydro (MWh per Capita)


Historical Trend of Carbon Intensity in South Africa
1965-2016

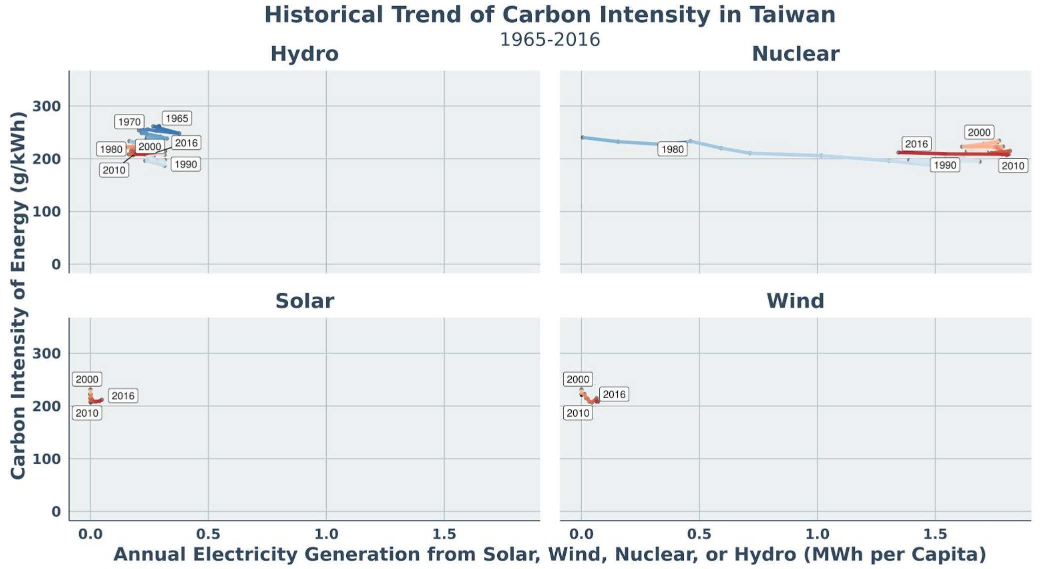

Historical Trend of Carbon Intensity in South Korea
1965-2016


Historical Trend of Carbon Intensity in Spain
1965-2016

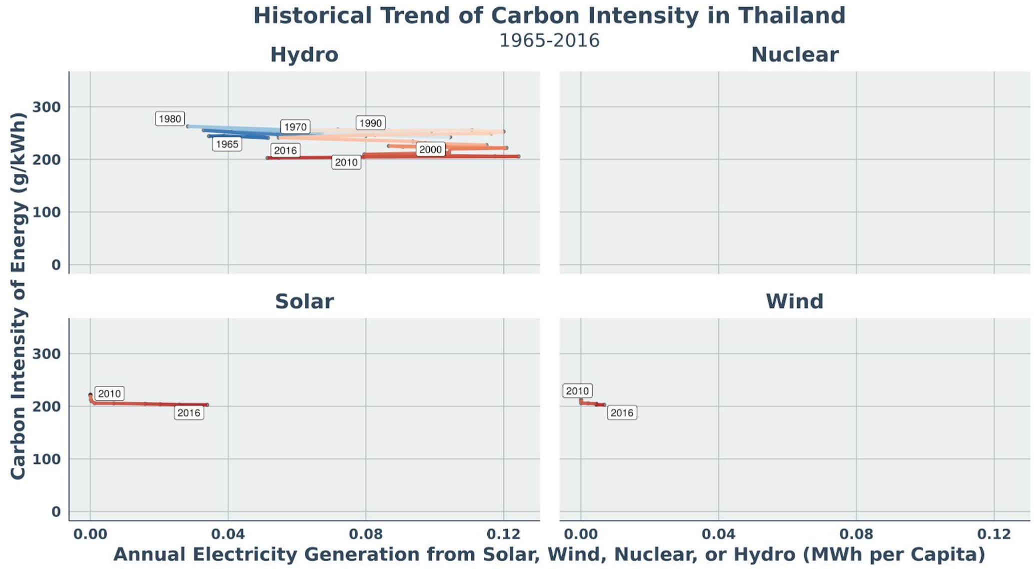

Historical Trend of Carbon Intensity in Sweden
1965-2016


Historical Trend of Carbon Intensity in Switzerland

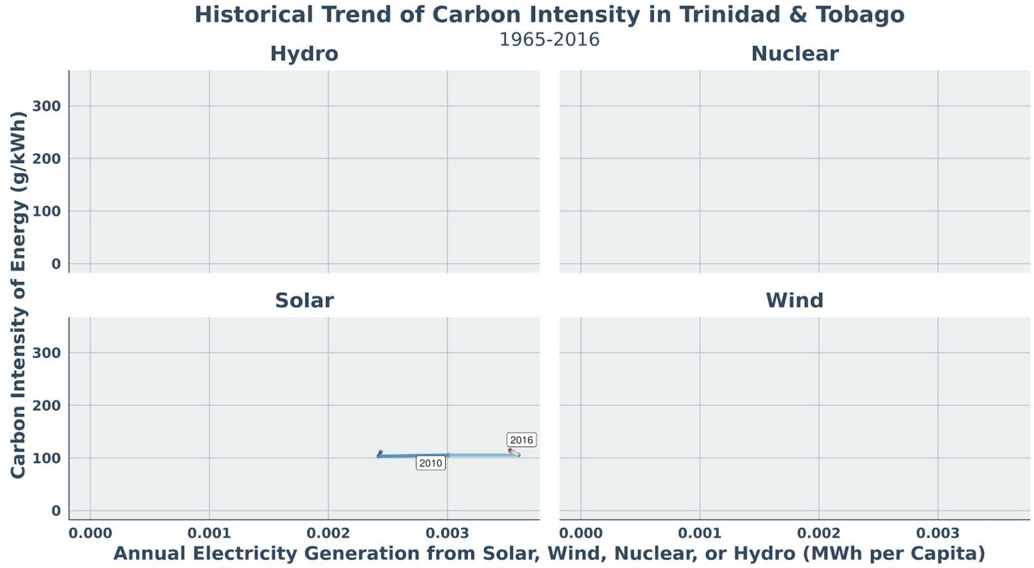
1965-2016


Historical Trend of Carbon Intensity in Taiwan

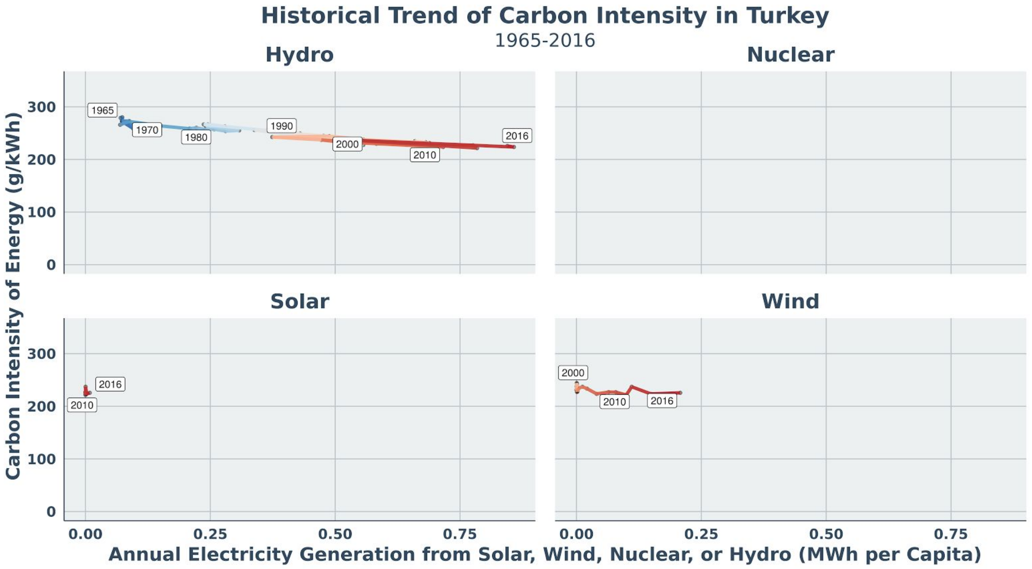
1965-2016

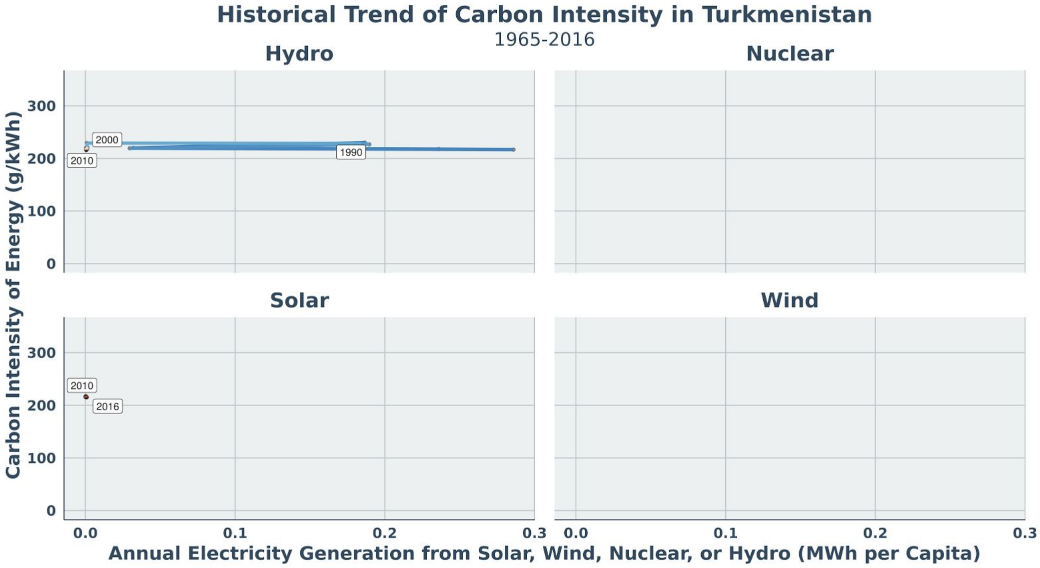

Historical Trend of Carbon Intensity in Thailand

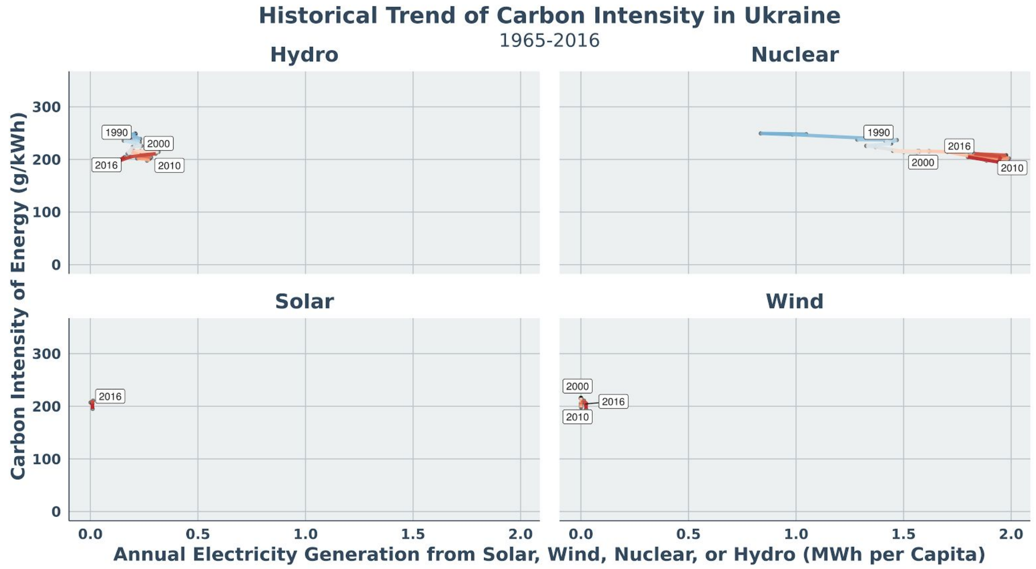
1965-2016

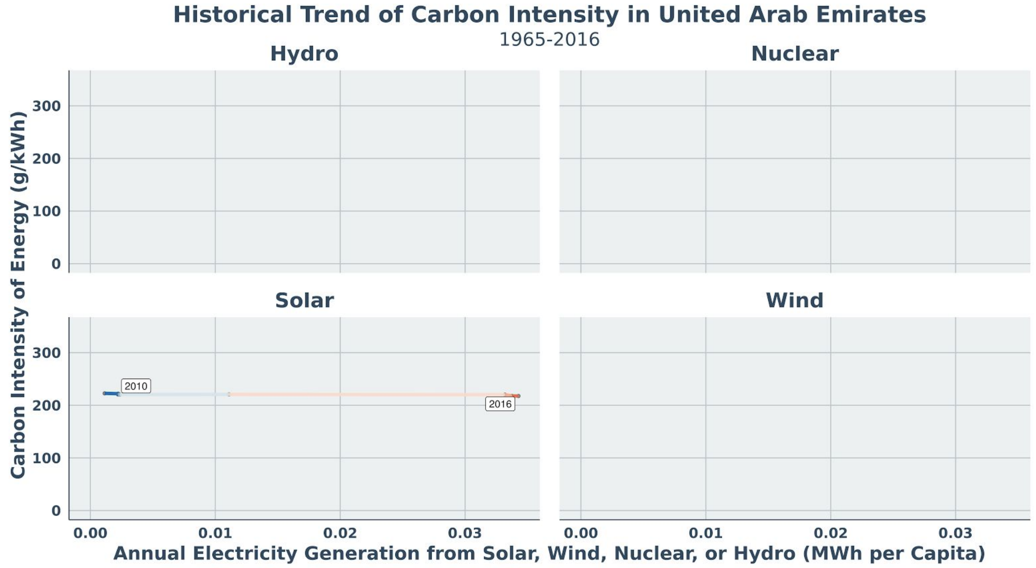

Historical Trend of Carbon Intensity in Trinidad & Tobago

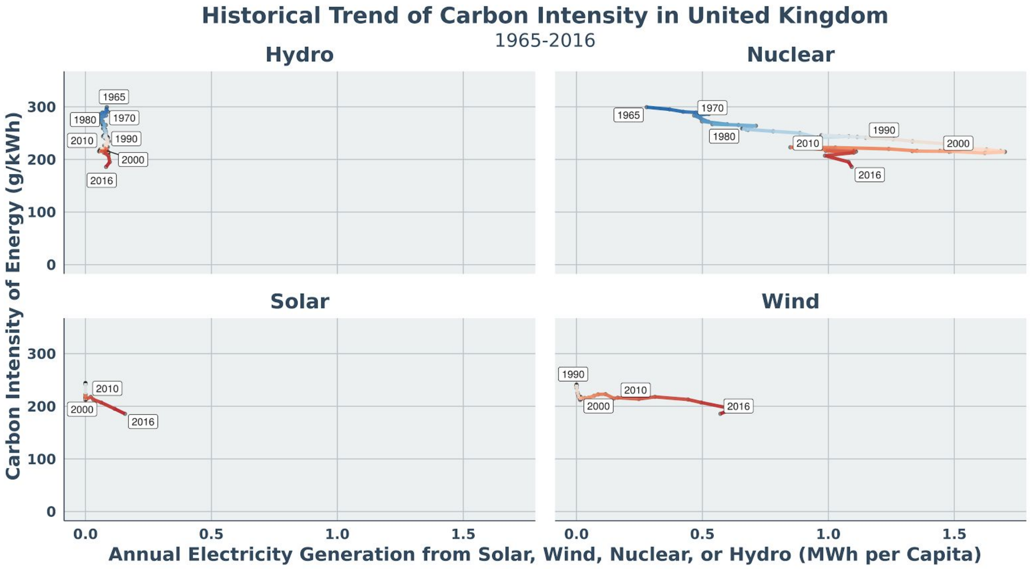
1965-2016

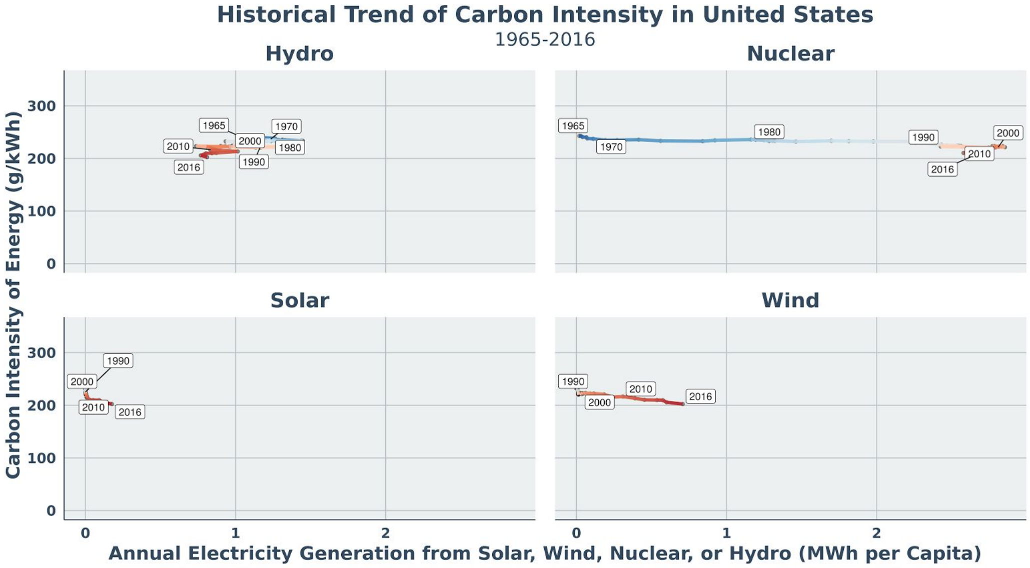

Historical Trend of Carbon Intensity in Turkey
1965-2016
Hydro
Nuclear
Solar
Wind
Carbon Intensity of Energy (g/kWh)
300
200
100
0
1965
1970
1980
1990
2000
2010
2016
2000
2010
2016
2010
2016
0.00
0.25
0.50
0.75
Annual Electricity Generation from Solar, Wind, Nuclear, or Hydro (MWh per Capita)

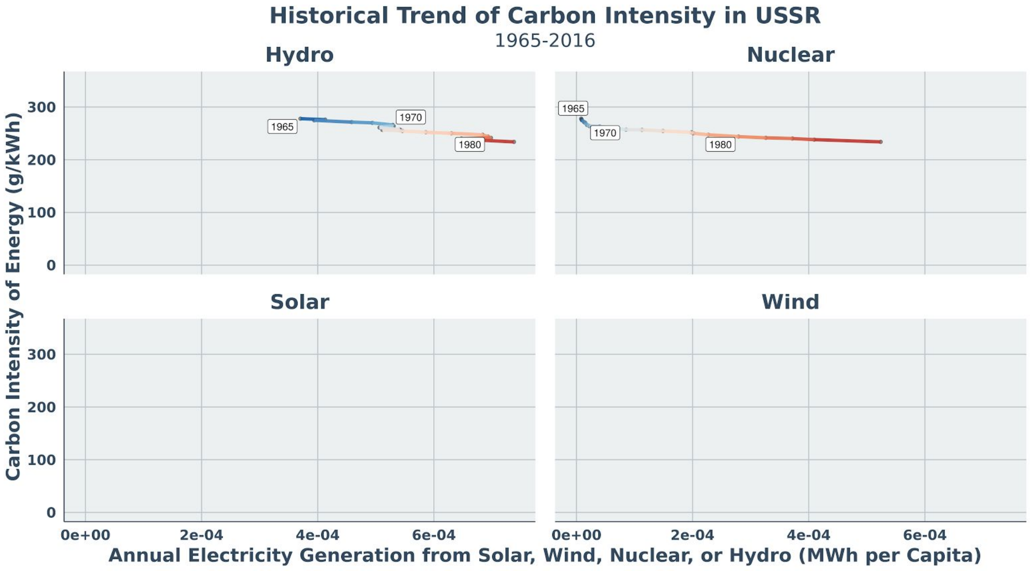

Historical Trend of Carbon Intensity in Turkmenistan
1965-2016
Hydro
Nuclear
Solar
Wind
Carbon Intensity of Energy (g/kWh)
300
200
100
0
2000
2010
1990
2010
2016
0.0
0.1
0.2
0.3
Annual Electricity Generation from Solar, Wind, Nuclear, or Hydro (MWh per Capita)

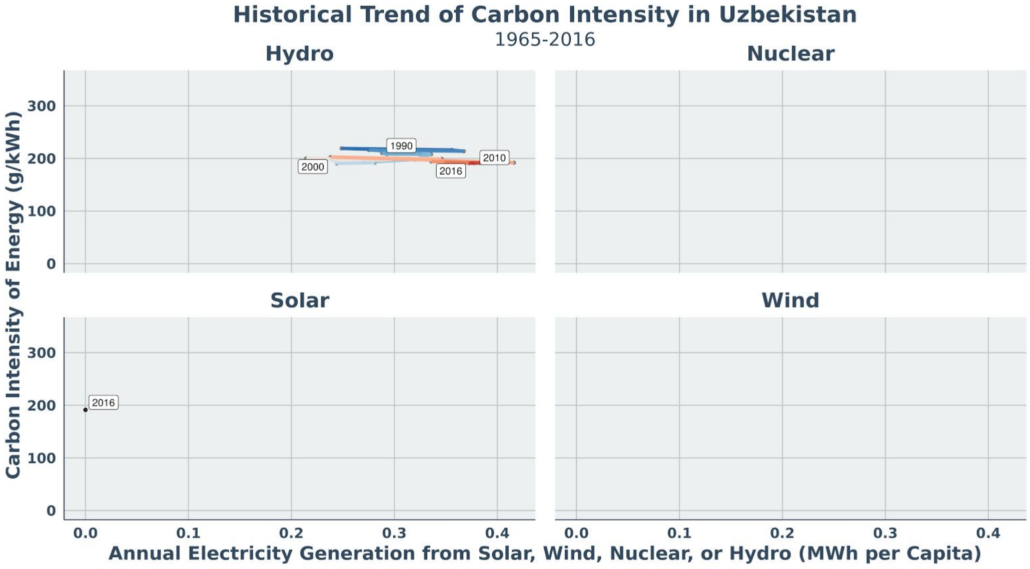

Historical Trend of Carbon Intensity in Ukraine
1965-2016
Hydro
Nuclear
Solar
Wind
Carbon Intensity of Energy (g/kWh)
300
200
100
0
1990
2000
2016
2010
2016
2000
2016
2000
2016
2010
0.0
0.5
1.0
1.5
2.0
Annual Electricity Generation from Solar, Wind, Nuclear, or Hydro (MWh per Capita)

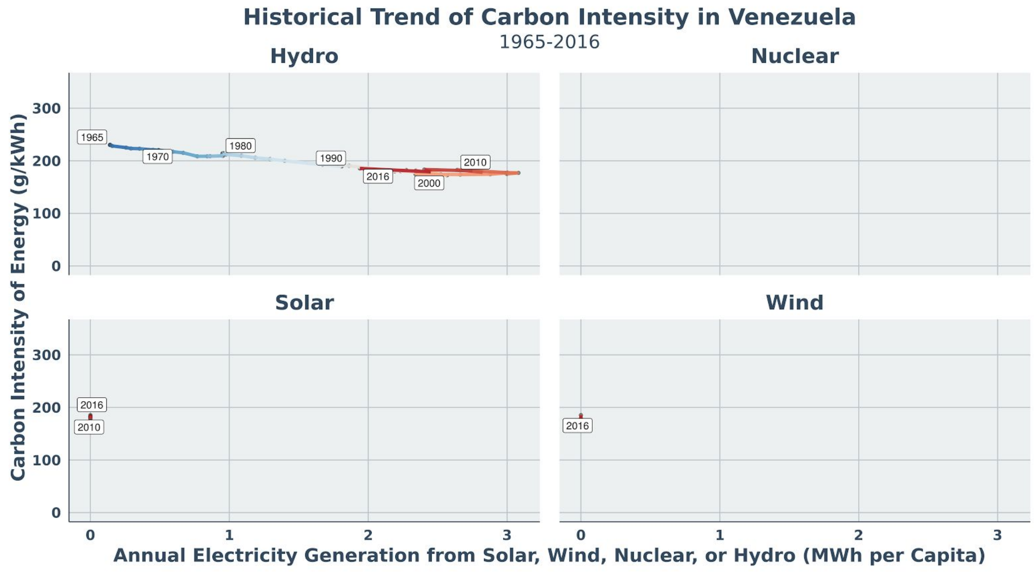

Historical Trend of Carbon Intensity in United Arab Emirates
1965-2016
Hydro
Nuclear
Solar
Wind
Carbon Intensity of Energy (g/kWh)
300
200
100
0
2010
2016
0.00
0.01
0.02
0.03
Annual Electricity Generation from Solar, Wind, Nuclear, or Hydro (MWh per Capita)

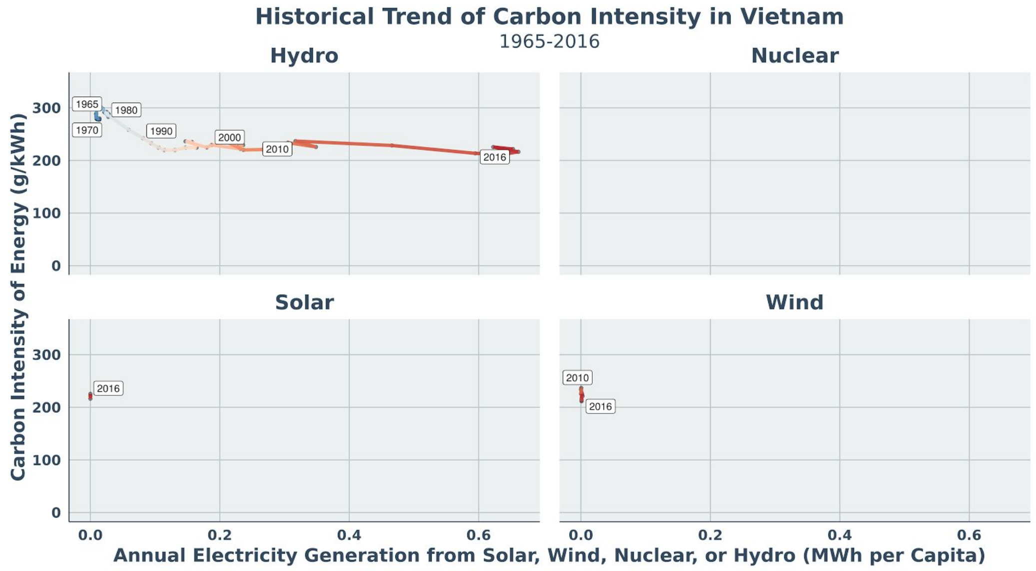

Historical Trend of Carbon Intensity in United Kingdom
1965-2016
Hydro
Nuclear
Solar
Wind
Carbon Intensity of Energy (g/kWh)
300
200
100
0
1965
1970
1980
1990
2000
2010
2016
0.0
0.5
1.0
1.5
Annual Electricity Generation from Solar, Wind, Nuclear, or Hydro (MWh per Capita)


Historical Trend of Carbon Intensity in United States
1965-2016
Hydro
Nuclear
Solar
Wind
Carbon Intensity of Energy (g/kWh)
300
200
100
0
1965
1970
1980
1990
2000
2010
2016
0
1
2
Annual Electricity Generation from Solar, Wind, Nuclear, or Hydro (MWh per Capita)


Historical Trend of Carbon Intensity in USSR
1965-2016
Hydro
Nuclear
Solar
Wind
1965
1970
1980
1965
1970
1980
300
200
100
0
0e+00
2e-04
4e-04
6e-04
Carbon Intensity of Energy (g/kWh)
Annual Electricity Generation from Solar, Wind, Nuclear, or Hydro (MWh per Capita)


Historical Trend of Carbon Intensity in Uzbekistan
1965-2016
Hydro
Nuclear
Solar
Wind
1990
2000
2010
2016
2016
300
200
100
0
0.0
0.1
0.2
0.3
0.4
Carbon Intensity of Energy (g/kWh)
Annual Electricity Generation from Solar, Wind, Nuclear, or Hydro (MWh per Capita)


Historical Trend of Carbon Intensity in Venezuela
1965-2016
Hydro
Nuclear
Solar
Wind
Carbon Intensity of Energy (g/kWh)
300
200
100
0
1965
1970
1980
1990
2016
2000
2010
2016
2010
2016
0
1
2
3
Annual Electricity Generation from Solar, Wind, Nuclear, or Hydro (MWh per Capita)


Historical Trend of Carbon Intensity in Vietnam
1965-2016
Hydro
Nuclear
Solar
Wind
Carbon Intensity of Energy (g/kWh)
300
200
100
0
1965
1970
1980
1990
2000
2010
2016
2016
2010
2016
0.0
0.2
0.4
0.6
Annual Electricity Generation from Solar, Wind, Nuclear, or Hydro (MWh per Capita)

Appendix C: Frequently Asked Questions

Why did you do this analysis?

We did this analysis in order to understand which energy technologies and policies have the largest impact on the decarbonization of energy.

What does your analysis show?

Our analysis shows that while the deployment of hydroelectricity and nuclear have been correlated with reductions in the carbon intensity of energy supplies at aggregated national levels, the deployment of solar and wind have not been.

Why is this analysis important?

This analysis is important because the Intergovernmental Panel on Climate Change, the International Energy Agency, and most other official sources operate under the assumption that solar and wind have equal decarbonizing power as hydro and nuclear. Partly in response, policymakers around the world have invested significant funds — about $2 trillion — into deploying solar and wind for climate mitigation purposes over the last decade and a-half.

How did you do your analysis?

We looked for changes to the carbon intensity of individual nations' energy supplies following the deployment of four different low-carbon energy sources. We produced 68 individual nation analyses, and then aggregated them. We then fit a generalized additive model regressing annual carbon intensity of energy on annual per-capita deployment for each of nuclear, hydro, solar, and wind power, and compared the models.

What does each colored dot in Figures IV, V, VII, and VIII show?

Each country is represented by a different color. Each dot signifies a nation's carbon intensity of energy and per-capita electricity consumption in a particular year. The effect of the deployment of electricity from a clean energy source on carbon intensity of a nation's energy supply is indicated by whether the dots of the same color move in a downward, upward, or flat trend.

What is new about this analysis?

This is the first analysis that looks at correlations between the deployment of specific clean energy sources and the carbon intensity of energy in such a large number of nations and such a large span of time.

Why does your analysis look at per-capita electricity consumption rather than national electricity consumption?

We look at per-capita electricity consumptions in order to control for large differences in population between nations.

Aren't you mixing apples and oranges by looking at the carbon intensity of energy and the per-capita consumption of electricity?

On the contrary. Solar, wind, nuclear, and hydro almost exclusively produce electricity and not other kinds of energy.

Haven't past analyses already identified changes to the carbon intensity of energy from, say, the addition of nuclear in France and the phase-out of nuclear in Japan?

Yes. All we are doing here is aggregating these country-specific analyses so we can see if there is a pattern that emerges from the planet as a whole.

Hasn't the decarbonizing impact of clean energy sources like nuclear already been shown in the past?

Yes, but only nation-by-nation, not aggregated. Aggregating the data allows for the visualization of a global pattern.

What insights does your analysis offer that simply looking at national cases doesn't offer?

Our analysis captures the relationship between thousands of cases of clean energy deployment on carbon intensity. Our much larger sample allows us to visualize correlations between clean energy sources and carbon intensity of energy.

You say correlation, but can't causal claims be made at national levels?

Yes, the claim can be made that, for example, the deployment of wind and nuclear energy in Denmark and France, respectively, caused the reduction in the carbon intensity of energy supplies in those two countries. And the claim can be made that the closure of nuclear plants in Japan caused the increase in carbon intensity of energy supply in Japan.

How can it be that wind energy reduced the carbon intensity of energy in Denmark but wind energy did not reduce carbon intensity at global levels?

While the deployment of wind energy in Denmark was significant enough to reduce the carbon intensity of energy, it was not significant enough for Denmark's success alone to make up for other national cases where wind increases were not correlated to decreasing carbon intensity of energy. By contrast, the decarbonization of energy supplies while hydro and nuclear was deployed occurred frequently and firmly across many nations, and therefore aggregated national data for hydro and nuclear clearly correlates with decreasing carbon intensity of energy.

But couldn't wind (and solar) still reduce the carbon intensity of energy supplies in the future?

While that is a possibility, this analysis suggests that there may be factors intrinsic to these four different energy sources which allows for the decarbonizing effect of nuclear and hydro to emerge when national data is aggregated, but not for wind or solar.

Why do you focus on evaluating the impact of solar, wind, hydro, and nuclear energy deployment on the carbon intensity of energy rather than the carbon intensity of the economy or the carbon intensity of electricity?

Most energy analysts believe that decarbonizing global energy supplies requires replacing liquid fuels like petroleum and heating fuels like coal and natural gas with electricity. Additionally, the energy policies of individual nations have direct impacts on carbon intensity of energy, and carbon intensity of energy stratifies nations with differing energy mixes.

Isn't this analysis just another way of expressing the fact that solar and wind do not generate significant quantities of energy relative to their cost?

In a sense, yes.