A four-step approach to estimate avoided emissions from renewables

White paper

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Summary

This paper introduces a more accurate methodology than widely spread approaches to estimate the avoided emissions from renewable energy sources, given a country's energy mix, its historic development, and a potentially increasing electricity demand.

It distinguishes between “Serving New Demand” (SND) and “Replacing Existing Demand” (RED):

- SND: Even though renewables make new electricity cleaner (relative decarbonisation), an increasing electricity demand represents a rebound effect, which does not lead to a reduction in societal emissions.
- RED: If renewables replace existing energy sources, they effectively reduce emissions, leading to a real reduction in emissions. This is because most countries' current electricity mix still contains fossil energy sources, which need to be replaced at the end of their life.

The four-step approach consists of:

1. Estimate generated energy: If the actual annual generated electricity is unknown, this paper proposes to work with country averages.
2. Split energy into SND and RED: Determine the amount of newly installed energy required to replace existing energy sources and the amount that serves new demand.
3. Determine the carbon intensity of SND and RED: Calculate the emissions associated with each kilowatt-hour of SND and RED.
4. Calculate avoided emissions: Leveraging the calculated carbon intensities of SND and RED, and considering the carbon intensity of the installed renewables, the avoided emissions can be derived.

The proposed methodology has several advantages over conventional approaches:

- It considers that, in most countries, the mix of newly-added energy sources is cleaner than the grid.
- Since the average lifetime of fossil power plants is often longer than for renewables, newly-added wind and solar power more often replace existing wind and solar (“repowering”) than fossils.
- It assumes non-zero emissions for renewables, allowing for honest decision-making.
- Taking into account rebound effects, it can differentiate between a real reduction and a lesser increase in emissions.

All the above-mentioned effects reduce the avoided emissions from renewables.

The proposed methodology, therefore, provides a more realistic estimation of avoided emissions, giving carbon credit buyers more confidence and providing politicians and managers with a basis for informed decision-making.

The following Chapters offer detailed calculation rules.
An example compares the effect of adding wind and solar capacity to the grid in China, the EU, and the US.

What are Avoided Emissions?

Wind energy produces fewer emissions than electricity from a coal-fired power plant. Hence, replacing coal power plants with wind turbines avoids emissions.

Avoided emissions describe the emissions reduction caused by a solution. This can be a product, a service, a technology, or a project. They quantify a solution’s impact relative to a hypothetical reference scenario, often the status quo before introducing the solution.

Contrary to a company’s carbon footprint, which represents the burden of company operations on the environment, avoided emissions quantify the positive impact of a company’s portfolio.

Why it matters

As the world faces the urgent challenge of climate change, industries are under immense pressure to accelerate decarbonisation efforts. Manufacturing, automotive, aerospace, and other sectors play a crucial role in reducing greenhouse gas emissions and transitioning towards a net-zero future. The energy sector takes a leading role since many other sectors build on electrification to achieve this ambitious goal. However, decarbonisation requires a comprehensive approach that leverages a company’s impact beyond reducing its carbon footprint.

Quantifying avoided emissions is critical in supporting corporate accountability, driving innovation, and prioritising solutions contributing to net-zero targets. Without accurate quantification, it becomes challenging for companies to assess the impact of decarbonisation initiatives and make strategic decisions that align with sustainability goals.

The same applies to countries taking steps to decarbonise specific sectors: Accurately quantifying the avoided emissions from installing renewables, for example, enables informed decision-making and trustworthy carbon markets.

The problem with existing approaches

Existing approaches for quantifying the carbon-positive impact of renewables often come with multiple inaccuracies:

- They assume zero emissions associated with renewables.
- They do not consider repowering, the effect of renewables replacing existing renewables that have approached the end of their lifecycle.
- They do not consider growing energy demand. When thinking of climate change, it’s all about reducing the absolute amount of CO_2 in the air. Achieving relative decarbonisation is simply insufficient.

These oversimplifications tend to overestimate the avoided emissions from renewables. This can mislead political and corporate decision-makers into thinking they have already done enough, when, in fact, they would need to accelerate the green transition to meet their sustainability goals.

The four-step approach

This paper describes a method that implicitly considers the three shortcomings of existing approaches: assigning a non-zero carbon intensity to renewables, considering repowering, and changing energy demand.

The starting point is the installed capacity in a given country, which allows for an estimate of the annually generated energy.

Based on a country's energy split by source (see Figure 3 as an example), the energy generated can be divided into energy that satisfies an increasing electricity demand (Serving New Demand, SND), and energy that replaces existing energy sources at their end-of-life (Replacing Existing Demand, RED).

The energy split by source allows for deriving the country-specific carbon intensity of SND and RED. Leveraging the previously determined energy split, avoided emissions can be calculated.

This paper describes a methodology for calculating avoided emissions from installing renewables. It requires only a country's electricity split by source and its carbon intensity of electricity, and assumptions on the carbon intensity of energy sources and power plant lifetimes. It corrects the calculated avoided emissions for energy that satisfies additional demand, and energy that replaces other renewables.

The methodology, therefore, provides more accurate data than other known approaches, which is essential for informed decision-making and carbon credit trading.

The following subchapters provide a high-level description of the calculation process using the example of installing new wind and solar power.

Step 1: Estimate generated energy

In a first step, the energy E_i generated in a given year i is determined. If measured data is available, this step can be omitted.

Figure 1 and Figure 2 visualise a country's installed wind and solar capacity and the electricity generated. The data is available for multiple years. It allows for the quick estimation of the average energy yield in a country, given the installed capacity.

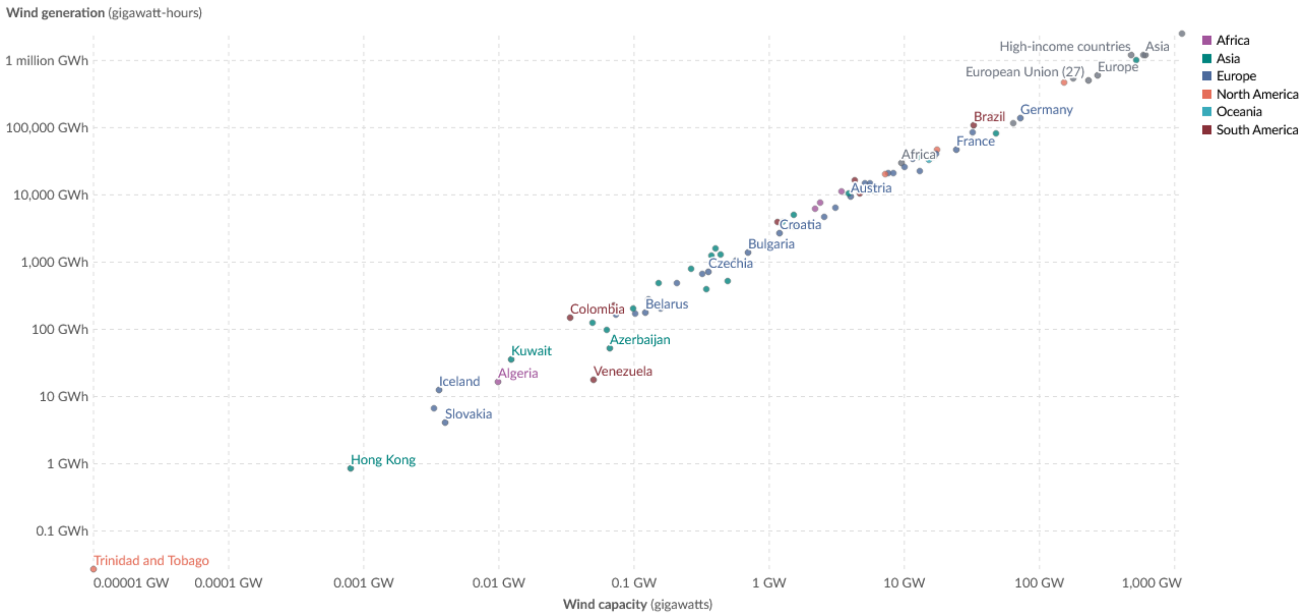

Figure 1: Wind energy generation vs. installed capacity in 2024, source: https://ourworldindata.org/grapher/wind-energy-consumption-vs-installed-wind-energy-capacity

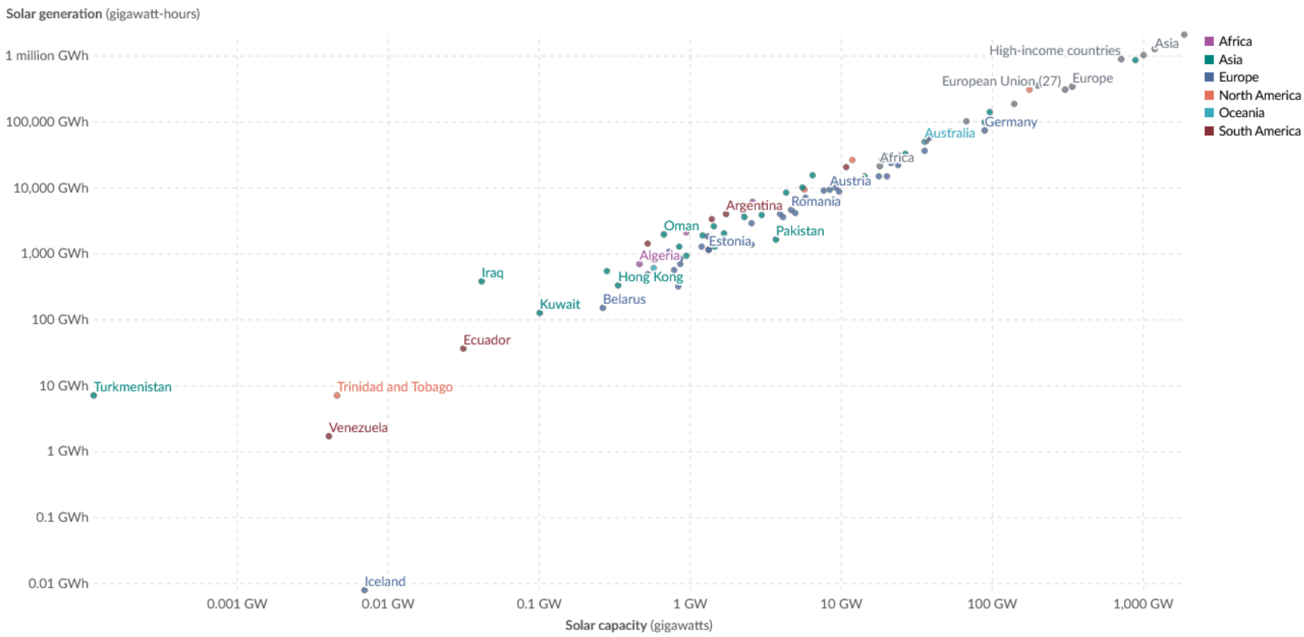

Figure 2: Solar energy generation vs. installed capacity in 2024, source: https://ourworldindata.org/grapher/solar-pv-energy-consumption-vs-solar-pv-capacity

In 2024, the worldwide average yield for solar energy was 1,131 GWh/GWp, for wind energy 2,216 GWh/GW.

Step 2: Split energy into “Serving New Demand” (SND) and “Replacing Existing Demand” (RED)

This study differentiates between “Serving New Demand” (SND) and “Replacing Existing Demand" (RED). The former category refers to renewables, which satisfy an increasing electricity demand. The latter refers to capacity, which replaces already existing energy sources; it does not distinguish whether they are renewable or fossil.

The energy generated by newly installed renewables can be divided into SND and RED, assuming it reflects the country-wide share. The allocation is based on the country-specific electricity generation by source and year.

Equation 1 calculates the absolute annual increase in generated electricity by source and year.

If a given source's electricity generation has decreased year-on-year, its “increase” is set to zero to avoid compensation between energy sources. This means that any decrease in energy generation of a given source is considered retired energy that has not been replaced.

Equation 1: For each energy source, calculate the absolute annual increase in generated electricity

$$\forall s: SND_{s,i} = \max\left(E_{s,i} - E_{s,i-1}, 0\right)$$

Abbreviations:

- E: Total energy generated by a source s in a year i
- Index s = energy source; index i = year

The energy required to replace recently retired power plants can be derived from the total generated energy by source and an assumed average power plant lifetime L. To keep energy generation stable, $\frac{E_{s,i}}{L_s}$ needs to be replaced in any given year i. There are three cases to distinguish:

1. $E_{s,i} - E_{s,i-1} > 0$: The generated electricity increased year-on-year. Hence, all retired energy must be replaced: $RED_{s,i} = \frac{E_{s,i}}{L_s}$
2. $-\frac{E_{s,i}}{L_s} < E_{s,i} - E_{s,i-1} < 0$: The decrease in generated electricity is smaller than the retired energy. Hence, the retired energy must be partially replaced: $RED_{s,i} = \frac{E_{s,i}}{L_s} + E_{s,i} - E_{s,i-1}$
3. $E_{s,i} - E_{s,i-1} < -\frac{E_{s,i}}{L_s}$: The year-on-year decrease is bigger than the retired energy. Hence, no replacement: $RED_{s,i} = 0$

Equation 2 covers all three cases.

Equation 2: For each energy source, calculate the absolute annual required electricity to replace recently retired power plants

$$\forall s\colon RED_{s,i} = \max\left(\min\left(\frac{E_{s,i}}{L_s}, \frac{E_{s,i}}{L_s} + E_{s,i} - E_{s,i-1}\right), 0\right)$$

Equation 3 calculates the share of SND and RED.

Equation 3: Calculate the share of SND and RED in a given year

$$S_{SND,i} = \frac{SND_i}{SND_i + RED_i}, \qquad S_{RED,i} = \frac{RED_i}{SND_i + RED_i} = 1 - S_{SND,i}$$

$$\text{with } SND_i = \textstyle\sum_s SND_{s,i} \text{ and } RED_i = \sum_s RED_{s,i}$$

The generated energy E_i from Step 1 can now be allocated according to the country-wide split between SND and RED; see Equation 4.

Equation 4: Split the generated electricity into SND and RED

$$E_{SND,i} = E_i\, S_{SND,i}, \qquad E_{RED,i} = E_i\, S_{RED,i}$$

Step 3: Determine the carbon intensity of SND and RED

The carbon intensity of SND and RED can be calculated from the electricity mix and the assumed carbon intensity by source; see Equation 5. The energy mix is specific to SND and RED, and changes annually.

Equation 5: Calculate the carbon intensity of SND and RED in a given year

$$CI_{SND,i} = \textstyle\sum_s S_{SND,s,i}\, CI_{s,i} \text{ and } CI_{RED,i} = \sum_s S_{RED,s,i}\, CI_{s,i}$$

$$\text{with } S_{SND,s,i} = \frac{SND_{s,i}}{SND_i} \text{ and } S_{RED,s,i} = \frac{RED_{s,i}}{RED_i}$$

The weighted average in Equation 5 requires the carbon intensity for each source and year under consideration. Typically, this data is not available, especially not on an annual basis. A pragmatic way to solve this issue is the following:

1. Assume a constant carbon intensity for all energy sources, except for one. This study proposes to select the most prevalent one; named p in Equation 6: Leverage the carbon intensity of electricity to calculate the carbon intensity of one selected energy source p.

2. Leverage the overall carbon intensity of electricity in a country to calculate the carbon intensity of the most dominant energy source; see Equation 6.

Why choose the most prevalent energy source? Small changes have a huge impact on the overall carbon intensity of electricity. It's the easiest way to compensate for small variations while keeping the carbon intensity of all energy sources within a realistic range.

Equation 6: Leverage the carbon intensity of electricity to calculate the carbon intensity of one selected energy source p

$$CI_i = \sum_s CI_{s,i}\, S_{s,i} \;\leftrightarrow\; CI_{p,i} = \frac{CI_i - \sum_{s \setminus \{p\}} CI_s\, S_{s,i}}{S_{p,i}}$$

$$\text{with } \forall s\colon S_{s,i} = \frac{E_{s,i}}{\sum_s E_{s,i}}$$

Now that the carbon intensity of all sources is determined, the carbon intensity of SND and RED can be calculated according to Equation 5.

Step 4: Calculate avoided emissions

The last step determines the avoided emissions as the sum of avoided emissions from "Serving New Demand" (SND) and "Replacing Existing Demand" (RED); see Equation 7.

Equation 7: Calculate avoided emissions

$$AE_i = AE_{SND,i} + AE_{RED,i}$$

$$\text{with } AE_{SND,i} = \left(CI_{SND,i} - CI_r\right) E_{SND,i} \text{ and } AE_{RED,i} = \left(CI_{RED,i} - CI_r\right) E_{RED,i}$$

The carbon intensity of SND and RED is corrected by the carbon intensity of the newly installed renewable energy source r, e.g., wind or solar.

Following WBCSD's Guidance on Avoided Emissions, AE_{SND} represents a lesser increase in emissions while AE_{RED} represents a real reduction.

Comparison to known approaches

The most widely used method to determine avoided emissions from renewables would stop after Step 1. The estimated generated electricity would be multiplied by the average carbon intensity of electricity in a country.

It would not consider the emissions associated with the renewable energy source. Even more importantly, it would neither consider that parts of the renewable energy would replace existing renewable energy sources nor reflect higher-order effects like the growing energy demand most countries experience.

As a result, it overestimates avoided emissions, possibly misleading carbon credit buyers and giving politicians a false sense of progress.

Example: Comparing China, the EU, and the US

This section leverages the described methodology to estimate the avoided emissions from adding one Gigawatt of wind power and one Gigawatt-peak of solar power to the grid. Using 2023, the latest year of available data, it compares the carbon benefits of renewable energy in China, the EU, and the US.

Step 1: Estimate generated energy

The amount of electricity generated by the newly added wind and solar power is assumed to represent the country-average in 2023; see Table 2, rows 7 and 12. Figure 1 and Figure 2 depict the source data.

Step 2: Calculate the SND/RED-split

This step divides the previously estimated generated electricity into SND, satisfying increasing demand, and RED, replacing existing energy sources at their end-of-life. The calculations according to Equation 1, Equation 2, and Equation 3 require the following inputs:

- Assumptions on the average power plant lifetime by energy source (see Table 1, column 2), and
- The country-specific electricity stack by source; see Figure 3.

Table 1: Assumptions on average power plant lifetime and average carbon intensity by energy source; the values in brackets indicate typical ranges; "Other Renewables" is assumed to largely represent geothermal energy

Energy Source	Average Power Plant Lifetime [years]	Average Carbon Intensity [gCO2e/kWh]
Other Renewables	25 [20, 30]	100 [20, 170]
Bioenergy	30 [20, 40]	50 [10, 90]
Solar	25 [20, 30]	45 [20, 70]
Wind	25 [20, 30]	25 [15, 35]
Hydro	75 [50, 100]	10 [0, 20]
Nuclear	50 [40, 60]	7.5 [0, 15]
Oil	30 [20, 40]	780 [660, 900]
Gas	35 [30, 40]	450 [400, 500]
Coal	45 [40, 50]	1,000 [820, 1180]

Step 3: Calculate the carbon intensity of SND and RED

Informed by the electricity generation depicted in Figure 3, this example chooses the energy source p in Equation 6 as:

- Coal for China and the EU
- Gas for the US

Table 2, row 6 shows the carbon intensities, calculated to match the 2023 carbon intensity of electricity in row 5. It uses assumptions on the average carbon intensities of energy sources depicted in Table 1, column 3.

Equation 5 can now be used to determine the carbon intensity of SND and RED; see Table 2, rows 3-4.

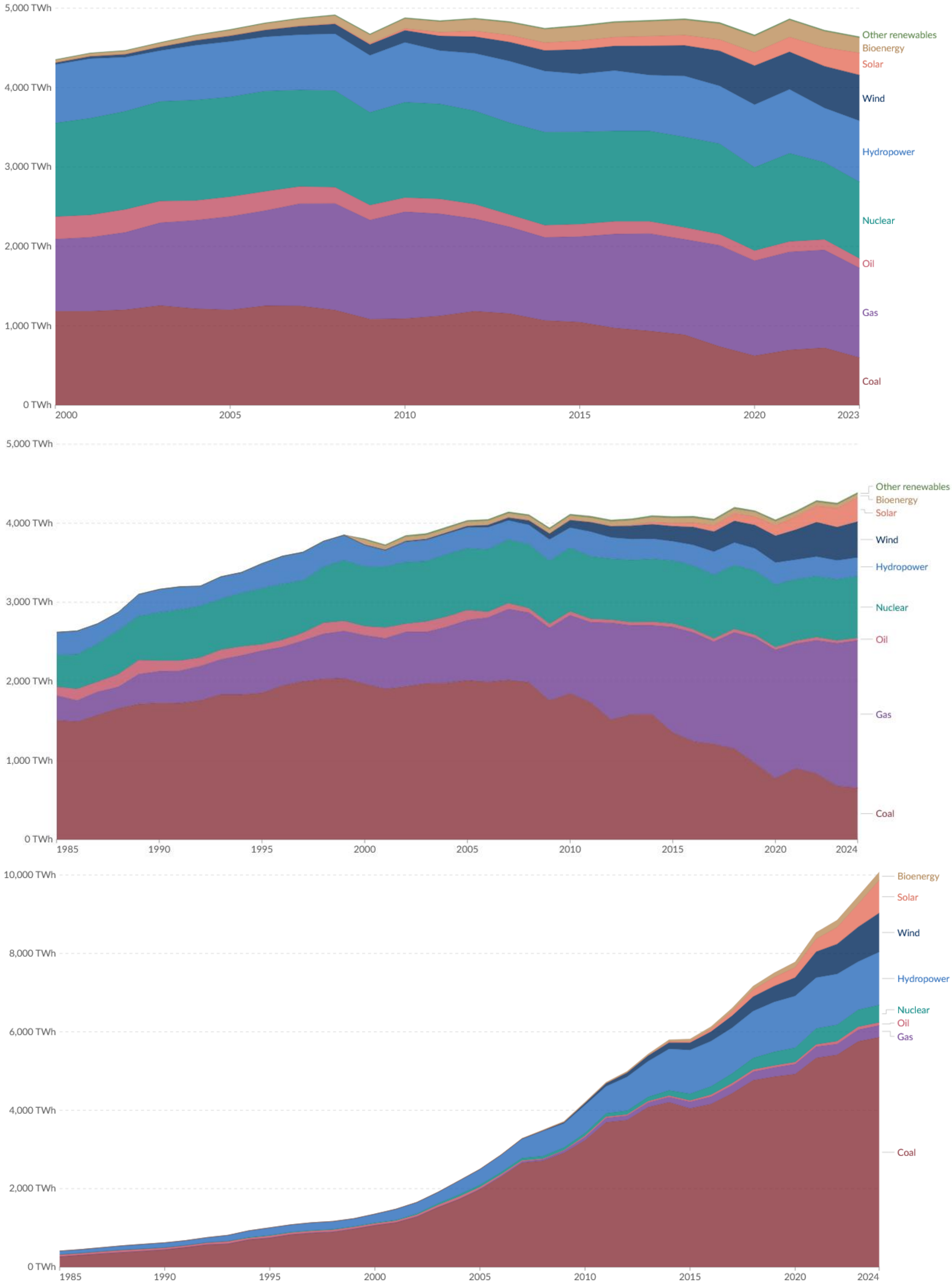

Figure 3: Electricity generation by source in the US (top), the EU (middle), and China (bottom); source: https://ourworldindata.org/grapher/electricity-prod-source-stacked

Step 4: Calculate avoided emissions

Taking into account the carbon intensity associated with wind and solar, respectively (see Table 1, column 3), Equation 7 calculates

- AE_{SND}, the avoided emissions representing a lesser increase in emissions,
- AE_{RED}, the avoided emissions representing a real reduction in emissions, and
- AE_{tot}, the sum of both.

Table 2, rows 8-10 and 13-15 display the results.

In addition, AE_{conv} allows for comparing this paper's methodology to the simplified conventional approach of multiplying the estimated generated energy according to Step 1 by the carbon intensity of electricity.

Table 2: Avoided emissions from installing 1 GW wind and 1 GWp solar in 2023 in China, the EU, and the US

		China	EU27	USA
	S_{SND} [%]	76%	77%	66%
	CI_{SND} [gCO2e/kWh]	492	24	366
	CI_{RED} [gCO2e/kWh]	584	23	366
	CI_{el} [gCO2e/kWh]	584	237	393
	CI_{coal} / CI_{gas} [gCO2e/kWh]	909	670	468
Wind	E [GWh]	2,005	2,195	2,874
	AE_{SND} [tCO2e]	712,222	-2,058	645,589
	AE_{RED} [tCO2e]	267,288	-859	334,492
	AE_{tot} [tCO2e]	979,510	-2,917	980,081
	AE_{conv} [tCO2e]	1,169,963	521,346	1,129,009
Solar	E [GWh]	958	982	1,734
	AE_{SND} [tCO2e]	325,678	-16,086	366,631
	AE_{RED} [tCO2e]	123,127	-4,857	189,958
	AE_{tot} [tCO2e]	448,805	-20,943	556,589
	AE_{conv} [tCO2e]	558,949	233,193	681,110

Interpretation of results

If optimising for overall avoided emissions A_{tot}, one Gigawatt of wind power is best installed in the US, so is one Gigawatt-peak of solar.

In this example, the same holds true if prioritising a real reduction in emissions (A_{RED}): Both wind and solar power are best placed in the US.

In general, one Gigawatt of wind power can avoid roughly double the amount of emissions of one Gigawatt-peak of solar.

In the EU, installing additional wind or solar power in 2023 would have led to additional emissions. The reason is that the carbon intensities of SND and RED are both lower than the carbon intensities of wind and solar, due to a ~20% increase in hydropower compared to 2022. In 2023, more than 40% of the bloc's newly installed energy sources were hydro and nuclear, the remaining almost 60% being wind and solar.

Historic data prove that 2023 is an exception. In 2022, Europe’s situation would have been quite different: one Gigawatt of wind power would have avoided 696,000 tCO2e, one Gigawatt-peak of solar power 321,000 tCO2e.

If this variability is undesired, it is suggested to work with averages over several years. For example, compare the average electricity mix of the last five years with that of the five years before.

Conventional approaches to estimating avoided emissions assume that renewables replace the average grid mix. They neglect that in most countries, the mix of newly-added energy sources is cleaner than the grid.

In addition, since the lifetime of fossil fuel power plants is often longer than that of wind and solar, repowering can consume a significant portion of newly-added renewable capacity.

Last but not least, conventional approaches cannot correct for an increase in electricity generation. Therefore, differentiating between a real reduction and a lesser increase in emissions is impossible.

All three above-mentioned reasons result in conventional approaches overestimating avoided emissions. In the example above, they overestimated 2023 avoided emissions by 15-25% in China and the US. In the EU, conventional approaches did not fully recognise that additional wind and solar would have caused additional emissions.

The example outlines the importance of reliably quantifying avoided emissions for informed decision-making. The proposed methodology solves all known issues experienced with commonly used approaches.