

Mapping data centre energy consumption to carbon-dioxide emissions

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Abstract—Regulatory frameworks push data centre operators towards renewable energy usage. The available energy in the energy grid is a mix of different energy sources, both fossil and renewable. The rapid growth of data centres has led to a significant increase in energy consumption and, thus, emissions. The operation of data centres can be adjusted depending on the current emissions of the energy mix. This paper presents an analysis of multiple studies to develop a comprehensive estimate of the emission intensity of different energy sources. It introduces a mapping of each data source to its emissions based on the studies. Furthermore, a Digital Twin is used to integrate energy production data from the energy grid and live energy usage data from the data centre. The Digital Twin allows transparent and real-time emissions tracking and provides a foundation for carbon-aware data centre operation.

I. INTRODUCTION

THE energy market is in the transformation process towards renewable energy sources. The energy grid contains a mix of different energy sources at all times. Energy production needs to meet demand by businesses and consumers. Renewable sources are also dependent on weather and daytime, thus the energy mix is constantly changing. With it, the associated emissions are changing as well. Businesses need to know these emissions to determine their own emissions when using electric energy.

The emissions are of particular interest to businesses with high energy consumption. One such example is data centres. Countries with many data centres already face a challenge. Ireland predicts that by 2031 31% of its energy consumption will stem from data centres [1]. From 2017 to 2023, the data centre energy usage in the USA doubled [2]. Fuelled by the advent of AI technologies, data centres experience an exponential growth of their energy demand. Generally, carbon-aware computing is on the rise but computing and data centres as a whole are not yet fully carbon-aware [3]. The TOP500 list of the fastest supercomputers gives a good indication on the rising energy demand: Figure 1 shows that both the number 1 system and the average power consumption rise continuously. In order to compute the current CO₂-intensity, a mechanism is required that calculates the carbon intensity from the current energy production and mix.

This paper makes the following contributions:

- A survey of studies establishes a representation of the carbon dioxide emissions from different energy sources.
- Based on the survey results, a single CO₂ intensity value is established for each energy source.
- A mechanism based on Digital Twins is presented that calculates the actual CO₂ emissions based on the current energy mix in the power grid.

The remainder of this paper is structured as follows: Section II introduces relevant related work. In Section III, relevant studies are analysed in order to find the carbon-dioxide emissions per energy source. With these values, a method is developed in Section IV that automatically provides the CO₂-intensity of the energy grid and the emissions of a data centre. Finally, a conclusion is given in Section V.

II. RELATED WORK

The 2030 agenda for sustainable development [4] is also relevant for the data centre industry. Goal 7 (Affordable and Clean Energy) is directly linked to rising energy demands of data centres and a conscious decision by operators where they source their energy from. The goals 9 (Industry, Innovation and Infrastructure) and 12 (Responsible Production and Consumption) also demand a conscious energy consumption.

There are stark differences between low emission energy sources and renewable energy sources. While the European Union focusses more on actual renewable energy, US companies plan to rely on small nuclear power plants to satisfy their energy needs [5]. Historic data is also available [6], however, for data centre operation live data are necessary.

Carbon dioxide is only one green house gas of many. However, to make the impact comparable, all gases are converted into their carbon dioxide equivalent. For example, the effect of releasing 1 kg of methane is equivalent to the effect of 25 kg of carbon dioxide. In the context of this paper, only the carbon dioxide equivalent is used.

The current carbon intensity of the energy grid can be integrated into the operation of data centres. The carbon emissions have been identified as an issue by the High-Performance Computing community and are already considered in the manufacturing phase of HPC systems [7]. Different approaches exist for the operational phase. A first approach [8], [9] uses a Digital Twin and the emissions directly to move workloads to

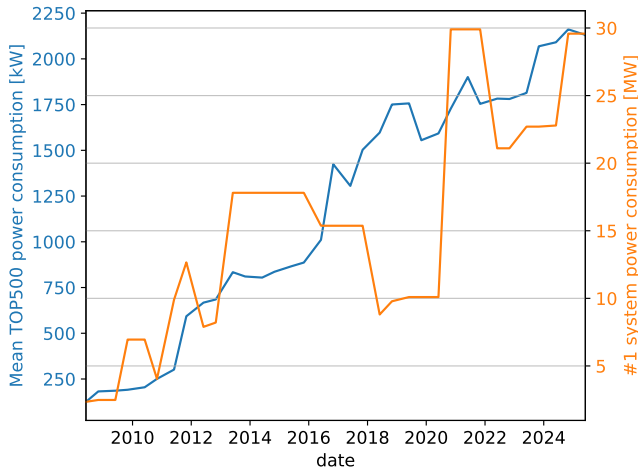


Figure 1: Mean and #1 system power consumption of the TOP500 HPC systems [23].

times with lower emissions allowing a reduction of the CO₂ emissions of approximately 7%. Alternatively, the processor frequency can be adjusted dynamically according to the current emissions [10]. Both approaches identify a reduction of the processor frequency as a viable approach to reduce the overall energy consumption. Similarly to the HPC approach, Google is scheduling flexible workloads depending on the CO₂ intensity in their data centres [11].

The use of renewable energy sources is demanded by more and more regulatory frameworks and certifications. These certifications include the German Blue Angel certificate for data centre [12], the Singapore's Green Mark for data centres [13], Japan's Green Growth Strategy [14], UK's climate change umbrella agreement [15] and the EU's best practice guidelines [16] in conjunction with the energy efficiency directive [17] and renewable energy directive [18]. Other frameworks demand at least improved energy usage, e.g. the Energy Star in the US [19].

Besides the aforementioned standards and certifications, policy and law makers have identified the growth of energy consumption by data centres as an issue. The EU already has many measures in place but the growth of AI and the associated energy demand create new challenges [20]. Policies have not yet caught up to the exponential growth of AI data centres [21]. Even the US, where the transformation towards renewable energy sources has slowed, might be influenced by the policies made elsewhere in the world [22].

III. SURVEYING CARBON DIOXIDE INTENSITY OF ENERGY SOURCES

The energy in the energy grid comes from different energy sources. Each individual source releases a different amount of emissions while generating electric energy. These emissions can come directly from chemical processes, e.g. burning coal or gas. Another source are so-called lifetime costs that also take emissions into account which come from the construction

of the power plant or the sourcing of the fuel. This paper only considers emissions that include the lifetime costs in the emissions.

Determining these values for the different sources for a general energy mix can never be exact. The exact lifetime emissions can only be determined for each power plant individually since different products all slightly differ, depend on the location of the power plant and many other factors [24]. One example is the enrichment of uranium for nuclear power plants. This is an energy intensive process and the energy used has a direct influence on the lifetime emissions of the nuclear power plant [25].

Hence, this paper relies on a number of studies that report lifetime emissions for different energy sources to get a reliable reporting on these values and to base the carbon dioxide calculation upon these studies. They are in particular:

- The *Intergovernmental Panel on Climate Change (IPCC)* is an organisation of the United Nations tasked with providing information and reviews on climate information and climate research. This allows governments to make informed decisions regarding climate [26].
- The *National Laboratory of the Rockies*, formerly known as *National Renewable Energy Laboratory (NREL)*, is a US research organisation funded by the US Department of Energy. Their research focusses on renewable energies and energy efficient technologies [27].
- The Swiss *Federal Office for the Environment (BAFU)* has commissioned the company *treeze Ltd.* to determine the carbon emission factors for the Swiss energy mix [28].
- The *United Nations Economic Commission for Europe (UNECE)* conducted a study on different energy sources focussing on their sustainability [29].
- *Electricity Maps (EM)* [30] is a software company located in Copenhagen, offering a product with the same name [31]. They chose specific emission values and list them in their repository [32]. However, the sources of these values are not clear in all cases.

These studies analyse the lifetime emissions of different energy sources. The individual values for each source are summarized in Table I. When reporting values for individual studies, the mean values have been used. The following sections discuss the individual energy sources. However, the goal of the paper is not to debate the benefits of different energy sources. The discussion section is used to explain differences between the sources.

The first row of Table I shows biomass. Although biomass is a renewable energy source, the burning of biomass emits large amounts of carbon dioxide. However, compared to fossil fuels, the cycle between binding the CO₂ and releasing it is much shorter than with fossil fuels. Additionally, many machines in agriculture rely on fossil fuels.

Energy from hydropower is clean. Most of the lifetime emissions stem from the construction of the plant and composting of flora due to the hydropower plant.

Wind turbines can be built on land and on water. Thus, offshore wind turbines have slightly higher lifetime emissions

Table I: Emissions per energy source for each study and the average value in gCO₂eq/kWh.

Source	IPCC	NREL	BAFU	UNECE	EM	Chosen
Biomass	230	42	154	-	230	164
Hydropower	24	21	17	10.7	11	17
Wind offshore	12	19	11.3	14	13	14
Wind onshore	11	12	11.3	12.4	13	12
Photovoltaics	41	43	44.1	37.2	35	40
Other renew.	-	-	-	-	-	30
Nuclear	12	13	14.20	5.13	5	10
Lignite	-	-	1220	-	-	1113
Hard coal	820	1001	1108	1023	1152	1067
Fossil gas	490	486	664	434	593	533
PHES	-	7.4	85.3	-	419	419
Other conv.	-	-	-	-	-	700

because their construction is more complex. During their operation, they have no direct emissions themselves. All in all, their lifetime emissions are low.

Similar to wind turbines, solar panels do not cause emissions during their operation. Their emissions mostly come from their production.

Other renewable energy sources include geothermal energy and other gases, e.g. from sewage gas. Although some have high emissions, they contribute very little to the energy production.

Differences in the value for nuclear energy mainly stem from uranium enrichment. The process is energy intensive and the energy used for the enrichment has a direct influence on the lifetime emissions of the nuclear fuel.

Burning coal for electric energy generation emits a lot of emissions. Most studies only report values for lignite (brown or soft coal). The BAFU source is one of the few to include hard coal. Their difference is approximately 10%. Hence, this relation is also used in this paper.

Fossil gas is burned similarly to coal. Some of the emissions stem from leakages of gas directly into the atmosphere. A benefit of gas power plants compared to coal, is that they can be easily turned on and off to cover spikes in energy demand.

Pumped hydroelectric energy storage (PHES) can store excess energy as potential energy by pumping water to a higher elevation. By releasing the water, the energy can be converted into electric energy. Therefore, their emissions depend on the energy used for pumping the water. If the energy at the time of storage come from fossil fuels, PHES also have high emissions and vice versa. Thus, these values are highly dependent on the region of the PHES and energy used.

Finally, other conventional sources include other gas and solid products from fossil origin that are sourced as side products from other processes and used for energy generation.

For each energy source, the carbon intensity is given by the function $f_{\text{intensity}}^{\text{source}}$. It returns the chosen value from Table I in gCO₂eq/kWh.

IV. COMPUTING CURRENT CARBON DIOXIDE EMISSIONS WITH A DIGITAL TWIN

The previous section introduced the specific carbon dioxide equivalent emissions per energy source. This section presents

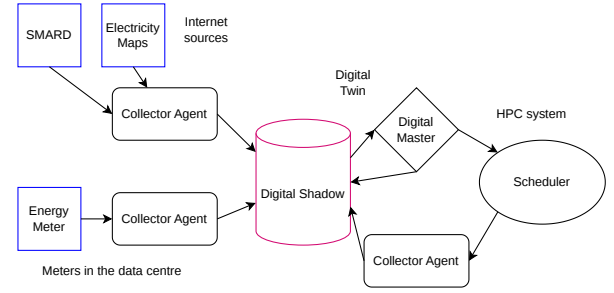


Figure 2: Schema of the Digital Twin

a method using the numbers from the previous Section III to calculate the live carbon dioxide emissions of a data centre.

The relevant components of the Digital Twin for an HPC data centre are shown in Figure 2. A comprehensive definition of Digital Twins can be found in [33]. At its core, a Digital Twin consists of a Digital Shadow, responsible for collecting data about the real world, and a Digital Master, that models the system behaviour. The solution presented here uses so-called *Collector Agents* that connect to different data sources. A first agent is responsible for external data sources, such as information from the energy grid. This paper uses the German SMARD service [34]. For Europe, one could also use ENTSO-E. This approach can be adapted for other regions as well, if data is available. For Germany, the energy production data is updated every 15 minutes. Germany only has one zone, sharing all productions. Other countries use a more fine grained approach. The collector agent can also collect data from Electricity Maps as an alternative, which is used here as a comparison to the values in Table I. A second collector agent collects information from internal sensors and meters of the data centre, e.g. energy meters. A third and final collector agent interfaces with the actual compute cluster and collects information from the HPC hardware.

With the current energy production data, namely the percentage of production per energy source contributing to the overall energy mix $c_{\text{mix}}^{\text{source}}$, and the carbon intensity values for each source from Section III, the current carbon intensity can be computed with the following formula:

$$f_{\text{CO}_2}(t) = \sum_{i \in \text{sources}} f_{\text{intensity}}^i * c_{\text{mix}}^i(t) \quad (1)$$

The Digital Twin stores the energy production from the energy grid. An exemplary month can be found in Figure 3 with the mapping from Section III and the values from Electricity Maps. Additionally, Figure 4 includes the energy production, showing some base load from coal and gas, a day and night cycle in solar power and changing contributions of wind energy, depending on the weather. With the function for the emissions, the Digital Twin can calculate the carbon dioxide emissions in real time. This is shown in the orange

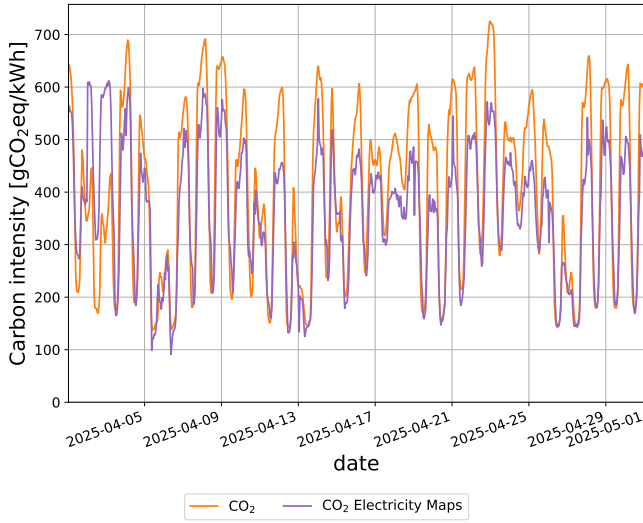


Figure 3: Carbon intensity as computed with values from Table I and values from Electricity Maps.

line. For reference, the figure also includes the emissions from Electricity Maps.

Since the Digital Twin also collects energy usage information from the energy meter, it can calculate the CO₂ emissions of the data centre. Given the current power consumption of the data centre $P_{DC}(t)$ in kW between a start point t_i and end point t_f , the CO₂ emission total $T_{CO_2,DC}$ can be calculated by the Digital Twin as:

$$T_{CO_2,DC}(t_i, t_f) = \int_{t_i}^{t_f} f_{CO_2}(t) * P_{DC}(t) dt \quad (2)$$

Figure 5 shows the difference between the mapping presented in this paper and the mapping used by Electricity Maps. The mapping presented in this paper differentiates between Wind onshore and offshore as well as hard coal and lignite. The differences are largest when the energy production comes mostly from fossil sources. This indicates a different report in the emissions of these sources. During phases of high contribution from renewable energies, the two mappings behave very similar.

Comparing the slopes of the two mappings shows that the biggest differences again arise in times of low renewable energy contribution, as shown in Figure 6. Because of the design, the mapping of this paper follows directly the energy production. The values from Electricity Maps seem to take additional factors into account or use different information such as energy imports and exports from/to other countries. However, the data from SMARD is the official energy production information for Germany.

V. CONCLUSION

This paper introduced a carbon dioxide mapping based upon many scientific studies accounting also for lifetime emissions. It has been compared against another source for carbon dioxide

emissions. The findings from this paper have been integrated into a Digital Twin for energy-aware High-Performance Computing [9]. The Digital Twin collects information about the energy grid, uses the formula defined in this paper and offers the current CO₂ emissions through its API. For a data centre, the emissions can be computed in real-time. This allows the Digital Twin to control the data centre based on the current emissions and improve the carbon footprint. A scheduling approach using this method can be found in [8].

As future work, an extension of the kind of energy sources to data centre specific sources could be achieved. Data centres are often equipped with backup generators, either with diesel or unleaded fuel. Batteries are also becoming more common. Their emissions depend on their production and the energy sources used while charging. Additionally, since technology is evolving and older power plants go offline, the concrete values for the individual sources need to be updated from time to time.

Finally, this work only covered historic and current emissions data. For planning purposes, a look into the future is required. A forecast could be made with statistical models designed for time-series analysis, e.g. SARIMAX [35], [36], [37], or machine learning ones like Lag-Llama [38].

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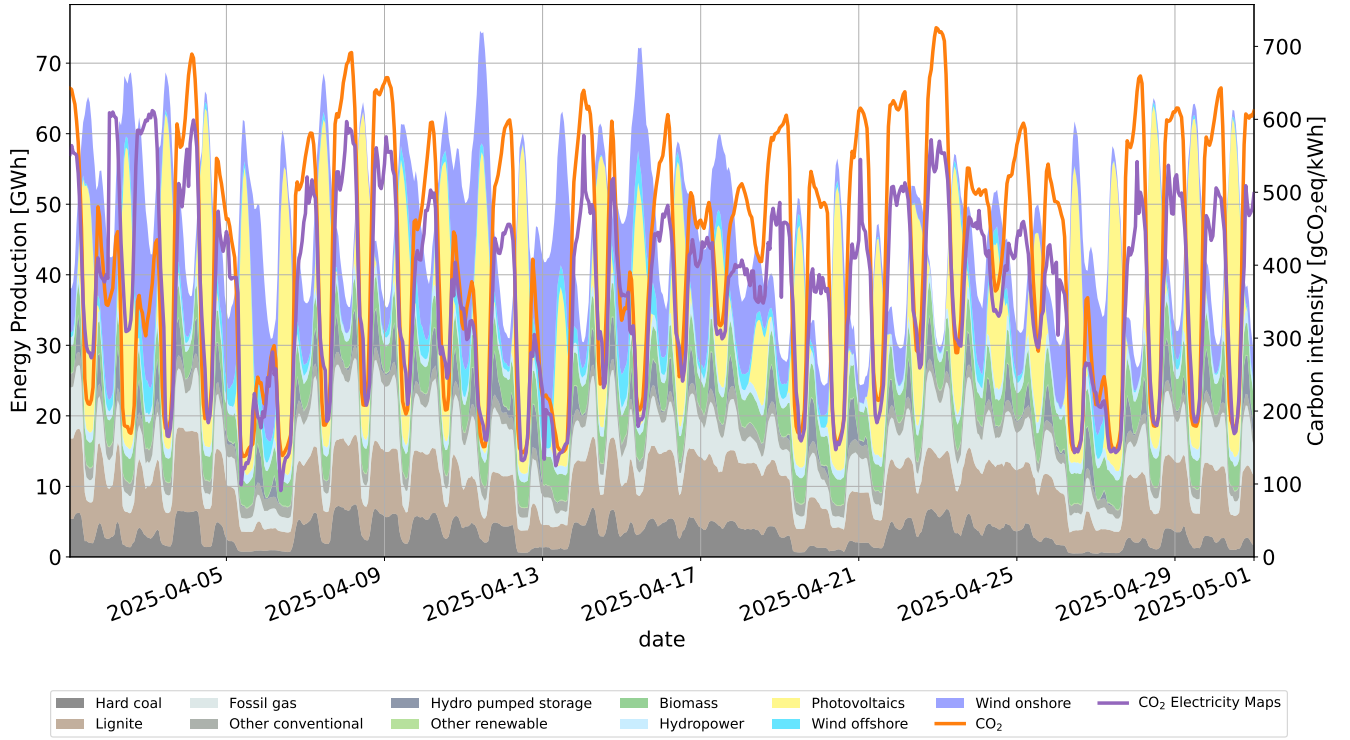


Figure 4: Energy production in Germany layered with carbon intensity as computed with values from Table I and values from Electricity Maps.

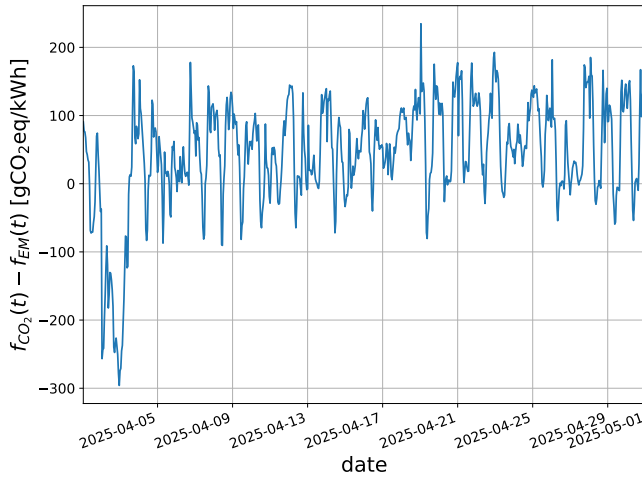


Figure 5: Difference between carbon intensity as found in Table I and Electricity Maps.

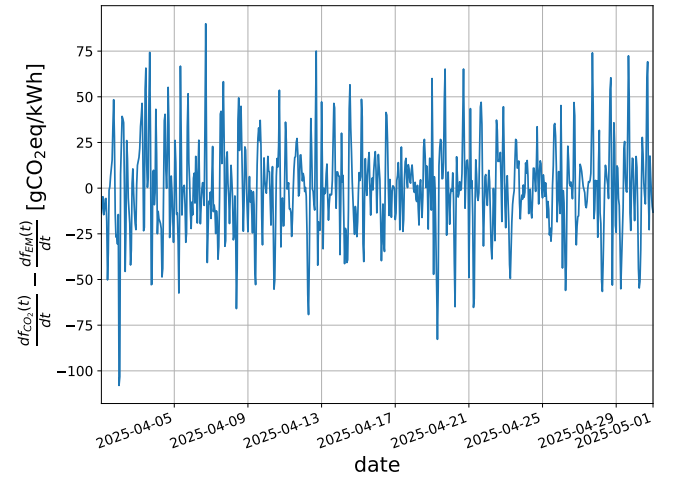


Figure 6: Difference of the first derivative of this CO₂ and Electricity Maps.

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