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Carbon footprinting of universities worldwide: Part I—objective comparison by standardized metrics

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Abstract

Background: Universities, as innovation drivers in science and technology worldwide, should be leading the Great Transformation towards a carbon–neutral society and many have indeed picked up the challenge. However, only a small number of universities worldwide are collecting and publishing their carbon footprints, and some of them have defined zero emission targets. Unfortunately, there is limited consistency between the reported carbon footprints (CFs) because of different analysis methods, different impact measures, and different target definitions by the respective universities.

Results: Comprehensive CF data of 20 universities from around the globe were collected and analysed. Essential factors contributing to the university CF were identified. For the first time, CF data from universities were not only compared. The CF data were also evaluated, partly corrected, and augmented by missing contributions, to improve the consistency and comparability. The CF performance of each university in the respective year is thus homogenized, and measured by means of two metrics: CO_2e emissions per capita and per m^2 of constructed area. Both metrics vary by one order of magnitude across the different universities in this study. However, we identified ten universities reaching a per capita carbon footprint of lower than or close to 1.0 Mt (metric tons) CO_2e/person and year (normalized by the number of people associated with the university), independent from the university's size. In addition to the aforementioned two metrics, we suggested a new metric expressing the economic efficiency in terms of the CF per $ expenditures and year. We next aggregated the results for all three impact measures, arriving at an overall carbon performance for the respective universities, which we found to be independent of geographical latitude. Instead the per capita measure correlates with the national per capita CFs, and it reaches on average 23% of the national impacts per capita. The three top performing universities are located in Switzerland, Chile, and Germany.

Conclusion: The usual reporting of CO_2 emissions is categorized into Scopes 1–3 following the GHG Protocol Corporate Accounting Standard which makes comparison across universities challenging. In this study, we attempted to standardize the CF metrics, allowing us to objectively compare the CF at several universities. From this study, we observed that, almost 30 years after the Earth Summit in Rio de Janeiro (1992), the results are still limited. Only one zero emission university was identified, and hence, the transformation should speed up globally.

Keywords: Carbon footprinting, University sustainability, University carbon footprint, Higher education institutions, Per capita carbon footprint, Zero emission university, Carbon offsetting, Greenhouse gas emissions, GHG accounting and reporting, Energy impacts, Mobility impacts

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Introduction

This contribution discusses and evaluates the sustainability of the institutions that are the origin of sciences: the universities. We like to hypothesize that particularly universities emphasizing sustainability actions might inspire scientists engaged in sustainability research, and will qualify engineers engaged in seeking sustainable practise. Hence, it should be essential to develop sustainable universities from every point of view. The institutional sustainability of a university has been quantified and evaluated by a variety of research attempts, like as, e.g., sustainability contents in university education [1]. In this article, however, we understand and analyse university sustainability as a technical term, with respect to CO_2-equivalent emissions of campuses.

Universities began to pick up sustainability problems early: The COPERNICUS University Charter for Sustainable Development in 1993 is seen as "a response to the Earth Summit in Rio de Janeiro (in 1992) and marked a breakthrough in raising consciousness within the European universities" [2]. Following this, several international networks were founded to foster sustainable development at higher education institutions (HEI) by conferences, awards, etc. (e.g., the ISCN International sustainable campus network, [3]. Often sustainability in higher education institutions (HEI) has been interpreted as a management attempt (e.g., [4]) rather than a quantitative effect.

Analysing the ecological footprint of higher education institutions (HEI)

Quantifying the environmental impact of a university often suffers from the problem that consumption and impact data are not recorded regularly and/or without sufficient depth of data. This problem has been alleviated by the method of Environmentally Extended Input Output Analysis (EEIOA) operating with financial data provided by the universities purchasing departments (e.g., [5]). Financial data are then converted by certain factors resulting in land footprints (for six different land types available, see [6]). Emissions such as CO_2 are converted into a certain value of land consumption. EEIOA requires much recalculation, and accordingly, it comes with an additional uncertainty [7]. We stay away from this method and quantify a direct consumption-based CF. Although the CF is just one metric, it is the most discussed aspect of a university's ecological footprint. Less commonly, other footprints have been quantified like the nitrogen impact of a campus [8].

University carbon footprinting: global status quo

In the scientific community, there is a broad discussion about the necessity and the potential of universities to become "carbon–neutral" (e.g., [9]). Nevertheless, only a small minority of universities are currently recording and publishing comprehensive carbon inventories, while those published in local languages may not be easily available for international comparison (e.g., the one from the University of Potsdam [10], is published in German). Clearly, university carbon footprinting is most institutionalized in USA, where almost 1,000 HEIs have registered to use the Stars Reporting Tool [11]. Around half of these institutions are being rated based on their performance in emissions and documentation. Stars [11] is listing just one university from outside North America with a gold award, the university college of Cork (Ireland), which has been included in this investigation. The gold award in this grading system indicates that all data necessary to compile a full GHG (greenhouse gas) emission inventory have been submitted. The biggest advantage of reporting systems such as Stars [11] certainly is the attempt to make data internationally comparable, transparent, and available which is essentially needed when transforming and tracking the global economy towards a more climate friendly situation or preferably towards zero carbon emissions, while this target so far may miss a commonly agreed definition [12]. To enable a transparent international inter-comparison, Stars [11] is for example reporting basic specifications of university campuses (CO_2e emissions by sector, no. of students and staff, the energy intensive space of a campus, etc.). Because the system is "self-reporting", no critical evaluation may be expected. The publication of standardized raw emission data, however, generates an important kind of transparency.

Outside such carbon reporting schemes, there are plenty of sustainability initiatives established among HEIs worldwide, some of them institutionalized like university rankings. However, many of these initiatives mainly focus on management aspects, climate action in general, and scientific activity around sustainability subjects, thus serving as advertisement and marketing platforms within the global competition for students and projects (e.g. [13, 14]).

In Europe, most universities that publish complete carbon footprints seem to be located in Great Britain. In fact, the British government encourages HEIs to report CFs [15]. In Germany, there seems to be a few universities only quantifying their institutional CO_2 emissions in detail like the University of Potsdam [10] and the dedicated zero carbon emission Leuphana University Lüneburg [16], which describes itself as being the "first climate-neutral university worldwide without purchasing certificates" [17]. Umwelt-Campus Birkenfeld (UCB), although marketed as a "Zero emission university" [18], did not publish a complete carbon balance so far, this is presented here for the first time.

A literature search for universities publishing CFs from Scandinavia and France failed, as also, for example, in the "motherland" of the Kyoto protocol, Japan.

This investigation is not meant as a quantitative report on universities publishing CFs worldwide; however, it aims to deliver an overview on activities, current methodology, and the magnitude of CFs caused by universities worldwide. Nevertheless, we believe that the map in Fig. 1 delivers a representation of university activities worldwide. Presently, there is an agglomeration of such activities in western Europe and particularly in North America, besides these two regions, there are a few universities scattered worldwide that are particularly engaged on this field.

GHG protocol corporate accounting and reporting standard

Almost all universities who report CO_2 emissions are following a scheme given by the "GHG Protocol Corporate Accounting and Reporting Standard" [19]. Although the allocation of impacts due to this scheme is simple (Scope 1: impacts caused by internal infrastructure, Scope 2: purchased energy; Scope 3: everything other, usually upstream activity impacts), many universities partly deviate from this scheme and apply individual allocations. On top of that, the single most important impact (energy consumption) usually belongs to Scope 2; however, big universities are running their own power plants (here: University College of Cork, Monash University,

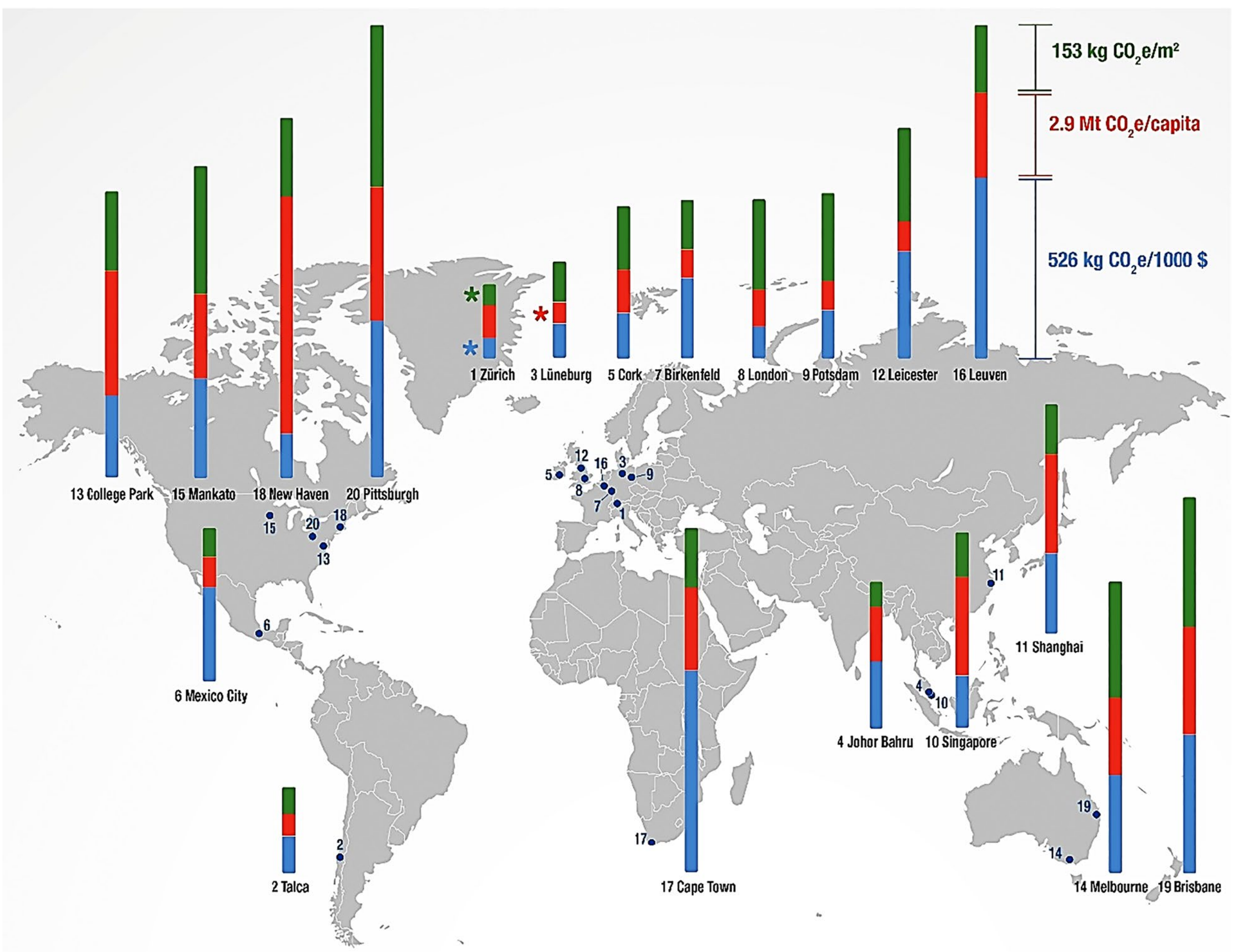

Fig. 1 Locations and carbon footprint (CF) performances of 20 universities fully rated allowing a relative comparison and ranking 1–20 in total CF performance Table 1. The lowest CF/best performance each found for constructed area (green), per capita (red), and per expenditures (blue) is given the same column height, these three minimum CFs are marked by an asterisk (ETH Zürich, University of Lüneburg). In each category, the relative column heights correspond to the absolute values, as shown in Fig. 3. For calculation of the CF performances, see Appendix: Table 3 and Fig. 7. Carbon offsets specified for three universities (see Fig. 3a–c) not considered here. The absolute CFs of Leuven University are shown numerically as an example. Mt = metric tons

University of Cape Town, and Yale University) shifting energy production impacts to Scope 1. Many universities today have photovoltaic (PV) installations, such as the Nanyang Technological University (NTU), Umwelt-Campus Birkenfeld, and the Leuphana University Lüneburg, respectively, which is relocating a part of their energy production impact from Scope 2 to Scope 1. Additionally, if the university operates its own car vehicle fleet, these impacts as well belong to Scope 1. When using external vehicles on business trips; however, it is a Scope 3 impact. As a whole, it is challenging to compare university carbon impacts based on separation into Scopes 1–3 due to the GHG Protocol Corporate Accounting and Reporting Standard. Therefore, we base our comparison on impact categories instead of Scopes.

In this way, we were able to quantify the CFs of 20 universities worldwide more precisely than known before with three independent CF parameters, identifying some of the most carbon-efficient universities. Such objective and detailed comparison had not yet been conducted in the literature, and is the main contribution of this study. Kennedy and Sgouridis [12] suggested a more rigorous emission classification scheme which would more precisely allow defining (zero) emission targets, however, the structure of publicly available data does not allow the application of such schemes here.

The rest of the paper is organized as follows. In "Materials, methods and purpose" section, we first describe the strategy of data collection, evaluation and completion. In "Results and discussion" section, we compile an overview of worldwide university CFs using three independent metrics, next, we analyse inter-correlations between the metrics, and compare the significance of university CFs relative to the national CFs. Finally, we present options to approach net zero carbon emissions, and offer concluding remarks.

Materials, methods, and purpose

This survey started by analysing scientific papers published on university CFs worldwide. It turned out; however, that the scientific literature contains only a limited number of studies with often very different methodology in data collection and interpretation. As a result, a valid quantitative description of the status quo in university carbon footprinting is difficult to conduct. Accordingly, for this study, next to scientific sources, university reports were additionally consulted. Many universities, however, only published (small) parts of their impacts or just total amounts, so we had to limit ourselves to the most detailed reports. From those universities periodically publishing CO_2 emissions, the most recent reports were analysed, in addition to the most recent reports providing detailed data about the university operations, such as budget information. Finally, this analysis yielded CF data of 22 universities worldwide, 18 of them reporting a detailed impact record (Fig. 2). It was impossible to collect data from just 1 year: Some universities report yearly, some publish every few years, while others only published their CO_2 emissions once. The period of collected data is between 2008 and 2018 (see Table 1). While it is easy to identify more US and British universities publishing carbon emission data, this is not the case for universities in other regions of the world. We scanned the literature and internet resources until we were able to cover all continents.

We directly adopted CO_2e emissions as they were reported by the universities. In contrast, we calculated all CO_2e emissions from Umwelt-Campus Birkenfeld (Germany) based on the collected energy and material consumption data. Also, we quantified the mobility impacts of Umwelt-Campus Birkenfeld from commuting and travelling data. Following the same method, we quantified mobility data for 5 universities which did not report them (see Table 1). For the University of Potsdam, we quantified the CO_2e emissions by freshwater consumption (extrapolated from the wastewater impact). The CO_2e factors for all consumptions and activities considered this way are reported in the Appendix.

It is an essential focus of this study to estimate the performance of universities worldwide in reducing their CF. In this context, the question arose which impacts comprehensively describe university performance in CO_2 emission limitation/reduction, and, respectively, which essential impacts are to be considered. Even after filtering those universities with satisfying documentation, it turned out that often different impacts had been measured (Fig. 2). Several scientific studies deliver statistics on which impacts were quantified how often (e.g., [20, 21]), however, without a critical quantitative assessment. This study intends to investigate the main contributing impacts towards a university's CF, and, on the other hand, to identify impacts that may be dropped as such impacts are negligible or are similar across all universities.

The 18 universities reporting a detailed carbon impact record quantified 28 single impact categories that we decided to consider (others were removed, see Table 1 and below). For better clarity, we condensed the 28 impact categories into 16 impacts areas (Fig. 2), from which we can infer those emission impacts mostly relevant for a university's CF. After collecting, sorting, revising, and complementing the impacts, in the next step, we relate the CO_2e emissions to the size of a university. In this way, we obtained size-normalized CFs, allowing us to compare universities independent from their size.

University CFs have been evaluated in the scientific literature so far in two ways: in terms of per constructed/

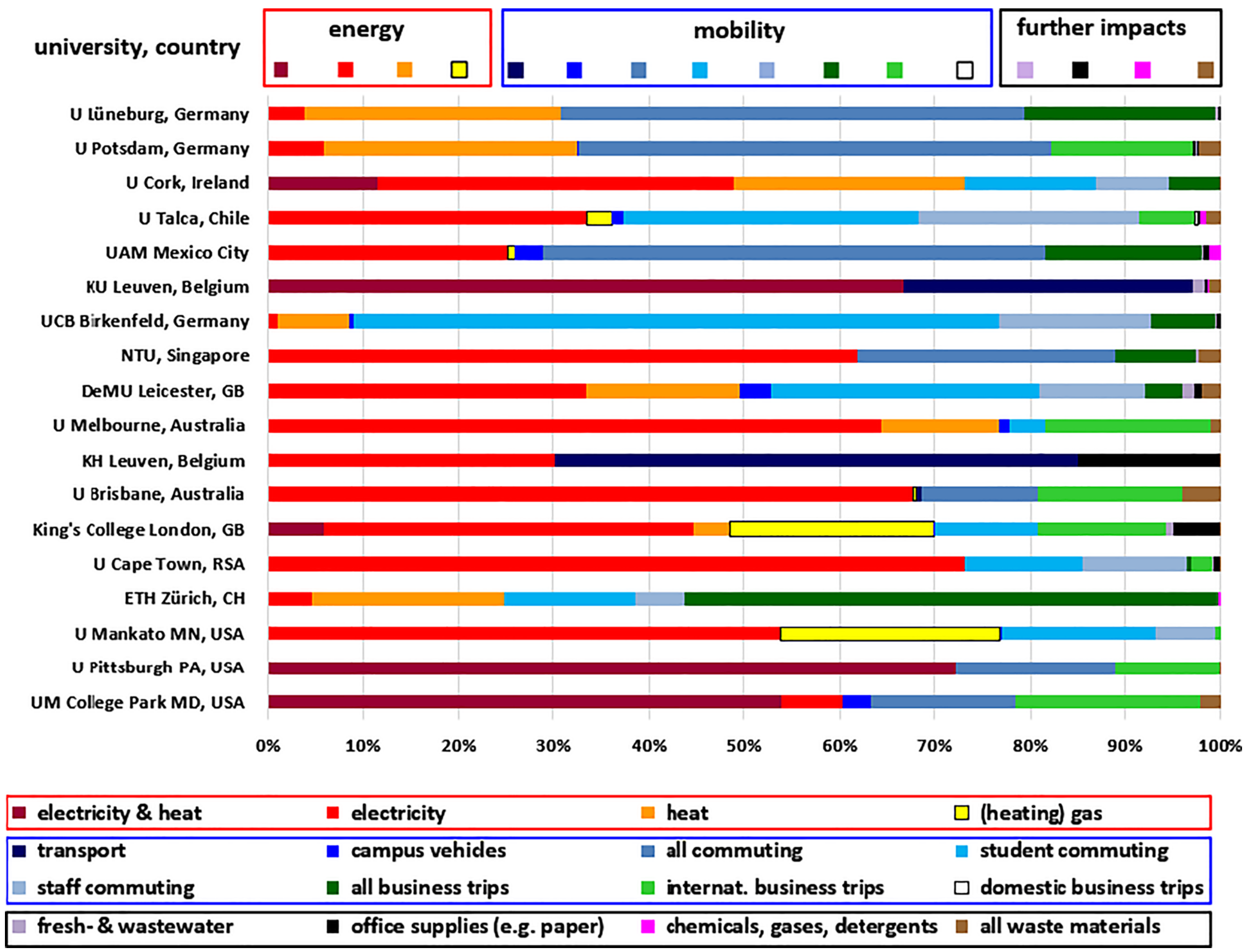

Fig. 2 Distribution pattern of partial carbon emission impacts at 18 universities worldwide: energy consumption (red/orange/yellow), mobility impacts (blue/green/white), and other impacts. University (U) specifications and full names are listed in Table 1, abbreviations listed in Fig. 3 caption. Note: electricity and heat may be listed twice in case the university received it from internal plus external sources. Results in numerical form are available in Appendix: Table 2

built area and per capita. We apply the term "constructed enclosure area" (or, simplified, "floor") in this publication as an umbrella term to cover the different terms and definitions of the building floor area found in the respective countries (see explanations below Table 1). King's College seems to be the first university additionally relating its CF to an economic factor, the university income, reporting a decrease from 140 to 30 kg CO_2e/1,000 British Pounds between 2005 and 2019 [22]. We follow this idea, but suggest to modify the quantification method. We believe that university expenditures have a stronger impact on the CF than university income, since most expenditures directly impact the CF, while parts of the income may be saved. A linear relationship between household carbon footprints and total household expenditure has been reported in [23]. Consequently, we collected data on university expenditures of 20 universities in this study. After subtracting the respective salary payments, we related the resulting expenditures (the procurement related spending) to the respective amount of emitted CO_2e. We converted expenditures to US $, consequently, we are able to apply purchasing power parity (PPP) and currency fluctuation correction with factors provided by [24], we refer to the Appendix for more details.

Results and discussion

Emission impacts to consider

Energy impacts

Undoubtedly, the biggest part of a university's carbon impact is the energy consumption in terms of electricity and heat production (red and yellow colours in Fig. 2).

Table 1 Specifications, data sources and structure, and performance of universities covered

Overall carbon performance rank	University, country	No. of staff	No. of students	Constructed enclosure area[A] [m^2]	years of impacts recorded	Impacts missing (IM), Impacts removed (IR), impacts added[B] (IA)	Mt CO_2e emitted/y[C]	Overall normalized carbon footprint performance[D]	Main data sources
1	ETH Zürich, CH	8,620	20,607	691,000	2017	IM: waste; IA: 4481 Mt CO_2 students commuting*	32,869	3.53	[41]
2	University of Talca, Chile	928	6,941	98,000	2016	–	5,920	4.14	[100]
3	Leuphana University Lüneburg, Germany	1,100	9,239	83,300	2015	Water and paper not separated (50 t CO_2e). For the detailed calculation see Appendix	7,593	4.55	[16]
4	Universiti Teknologi Johor Bahru, Malaysia	4,894	19,433	813,352	2011	IM: business trips (flights), office material, water, waste missing. Result just for orientation	45,991	6.99	[78]
5	University College of Cork, Ireland	2,697	18,464	193,781	2016/17	–	31,425	7.23	[101]
6	Universidad Autonoma Metropolitana-Cuajimalpa (UAM), Mexico City, Mexico	549	2,202	44,350	2016	IR: 109 Mt CO_2e for food	2,848	7.29	[40]
7	Umwelt-Campus (UCB) Birkenfeld, Germany	281	2,450	24,268	2015–2017	see Appendix	2,696	7.51	data were collected for this study
8	King's College London, GB	8,500	31,377	251,154	2018/19	IR: 83,218 Mt CO_2e supply chain (not specified or long-term investment into buildings and equipment); 2,461 Mt CO_2e for paper products kept. IA: 5,386 Mt CO_2e for student commuting*	50,556	7.53	[22]
9	University of Potsdam, Germany	2,753	20,878	120,772	2018	IR: 105 Mt CO_2e IT infrastructure, IA: 14.3 Mt CO_2e for freshwater (extrapolated from wastewater impact)	23,727	7.86	[102]

Table 1 (continued)

Overall carbon performance rank	University, country	No. of staff	No. of students	Constructed enclosure area[A] [m^2]	years of impacts recorded	Impacts missing (IM), Impacts removed (IR), impacts added[B] (IA)	Mt CO_2e emitted/y[C]	Overall normalized carbon footprint performance[D]	Main data sources
10	Nanyang Technological University (NTU), Singapore	8,923	31,827	1,382,388	2017	–	138,402	9.27	[64]
11	Tongji University, Shanghai, China	6,000	47,000	1,600,000	2014?	All impacts related to students. Total impact: 47,000 students × 3.84 Mt CO_2e/student	180,480	10.87	[30] [year of data collection not specified]
12	De Montfort University, Leicester, GB	3,995	21,585	128,215	2008/09	IR: business services (consulting), construction, visitors travel, food	26,692	10.93	[26]
13	University of Maryland, College Park MD, USA	14,000	40,521	1,300,000	2018	–	232,000	13.56	[58]
14	Monash University, Melbourne, Australia	7,678	63,246	728,193	2015	IA: 7,190 Mt CO_2 for student commuting*	188,416	13.81	[59]
15	Minnesota State University Mankato MN, USA	855	14,712	157,930	2017	IM: business trips and waste; IA: 456 Profs × 1 flight with 4000 km each*	44,831	14.78	[63]
16	University of Leuven (KU), Belgium	13,457	39,383	1,000,000	2010	Waste and water not separated (2%); IR: 11,482 Mt CO_2e IT infrastructure; 7,734 t CO_2e unspecified "fixed assets"	153,436	15.81	[103]
17	University of Cape Town, RSA	5,041	26,000	668,165	2013	IR: 6,485 Mt CO_2e for food supply; IA: 7,797 Mt CO_2e for student commuting*	88,752	16.30	[27]
18	Yale University, New Haven CT, USA	16,184	12,458	1,342,297	2016	Very few numbers published only: total emissions, campus fleet emissions, purchased electricity. All students live on-campus	234,024	17.06	[104]

Table 1 (continued)

Overall carbon performance rank	University, country	No. of staff	No. of students	Constructed enclosure area[A] [m^2]	years of impacts recorded	Impacts missing (IM), Impacts removed (IR), impacts added[B] (IA)	Mt CO_2e emitted/y[C]	Overall normalized carbon footprint performance[D]	Main data sources
19	University of Queensland, Brisbane, Australia	6,791	50,830	747,523	2014/15	–	214,249	17.80	[60]
20	Duquesne University Pittsburgh PA, USA	2,078	9,214	145,011	2018	–	51,883	21.44	[105]
not rated	KH Leuven, Belgium	704	6,914	N/K	2010	IR: 972 Mt CO_2e infrastructure	6,113	–	[6]
	South East European University, Tetovo, Macedonia	370	6000	N/K	2009	–	5,100	–	[106]

N/K not known, *Mt* metric tons

*See the Appendix for details on the calculations

[A] In USA/Singapore/Malaysia/Australia: GFA (Gross floor area), in Great Britain: NIA Net internal area, in South Africa: total floor area, in Belgium: built surface area, in Chile: total constructed area, in Switzerland: energy-consuming area, in Germany: Netto-Raumfläche.

[B] These impacts were not reported but additionally estimated and considered here.

[C] Without carbon offsets. Note: CO_2 vs. CO_2e follows the specifications in the respective data sources. Unfortunately, the differentiation of both emissions are not precise in literature, often resulting in deviations. As an example, 77.7% to 81.7% of the total GHG emissions in the EU28 over the 1990–2015 period are from fossil CO_2 emissions [42].

[D] The best performing university is set to 1.0 in each of the three CFs according to Fig. 3a−c, see details in Appendix: Table 3 and Fig. 7.

The percentages of energy consumption (the four related impacts taken together) ranges from 8.6% (Umwelt-Campus Birkenfeld) to 76.8% (Minnesota State University Mankato), with an average of 52.1% (Fig. 2). Umwelt-Campus Birkenfeld has the lowest percentage of energy consumption in its overall CO_2 emissions due to access to 100% renewable energy production. As an analogy, a university campus behaves similarly to the Life Cycle impact of an electric car, which is largely influenced by the availability of renewable electricity to charge the car in the use phase [25].

The fact that all universities report different groups of (energy-related) impact statistics prevents a more in-depth analysis of the energy sector. Some differentiate energy sources and/or fuels; others only report summarized units. We do not know exactly the purpose of the energy sources, e.g., gas might be consumed for either heating, cooling, or even cooking. Ultimately, the university ends up with a total amount of CO_2 emission computed by aggregating all energy consumptions. The university may consider how the mixture of energy sources can be optimized with respect to costs and emissions. The absolute CO_2 emissions of every single impact can be calculated by multiplying the percentages reported in Appendix: Table 2 with the overall CO_2 impact of the university listed in Table 1.

Mobility

The second set of impacts of relatively high importance is found in the area of mobility. Similar to the energy sector (see above), the reporting method of mobility-related impacts is very heterogenous among the universities considered in this study: two universities (KH Leuven and KU Leuven, Belgium) only report the total emissions due to transport activities (see Fig. 2), while the other universities specified up to five different emission impacts due to mobility (see Appendix: Table 2).

The 18 universities that are providing the most detailed data (see Fig. 2) exhibited between 22.2% (University of Melbourne) and 90.8% (Umwelt-Campus Birkenfeld) mobility impacts. With an average of 45.3%, mobility impacts are almost as important as the energy consumption for the overall CO_2 emissions. Within mobility impacts, an average 27.7% of the overall university carbon impacts is due to commuting. Umwelt-Campus Birkenfeld with its remote campus location reaches the highest percentage with 83.8% commuting impact within the overall campus impact. As there are a lot of more students than staff (Table 1), student commuting alone makes up 67.8% of the overall campus CF at Umwelt-Campus Birkenfeld (Fig. 2). Given the relative importance of this impact, it is surprising that 4 of the 18 universities did not consider student commuting in CF quantification which is why we had to estimate and add it (for details, see the Appendix). Without these added impacts, it would not have been a fair CF inter-comparison within our set of universities. Only questionnaires among students and staff can derive detailed traffic mode statistics for a precise commuting impact estimation. When calculating the missing commuting impacts of four universities, we could partly resort to questionnaire results we found in the reports, alternatively, we analysed the specific traffic situation around a campus. The city of Zürich, as for example, is operating an excellent public transportation system and there are almost not parking spots available near ETH Zürich campus. Accordingly, we assumed 100% arrival by public transportation to ETH campus (for details, see Appendix). Universities in a very remote location (like Umwelt-Campus Birkenfeld) will always have to struggle with relatively high commuting impacts. In the future, politicians should take this location factor into account when deciding for certain locations to establish or enlarge a university. Those decisions are very important to impact the way towards a climate-neutral society.

Next to commuting, there is a lot of business transportation at and caused by university campus activities: The universities covered in this investigation quantified the impacts of campus vehicles (can be buses, business cars, or trucks), and domestic and international business trips (some report them condensed in one impact). Between 2.7% (University of Cape Town) and 55.9% (ETH Zürich) of the overall campus CF was caused by business transportation alone. Universities reporting detailed transportation impact data revealed a particularly high impact of international business travelling, caused by flying (up to 17.4% of the overall campus CF at Monash University, Melbourne). Accordingly, it is essential to consider the impact of air travelling, which is why we estimated and added this impact to that of Minnesota State University Mankato. Due to lack of data availability (number of professors), we could not estimate the air travelling impact at Tongji university (Shanghai) and Universiti Teknologi (Johor Bahru, see Table 1).

Smaller impacts

All further recorded impacts (freshwater and wastewater consumption, office supplies like paper, chemicals, gases, and detergent consumption, and waste disposal) result in just 0.14–14.9% (average: 2.6%) of the overall university CF (Fig. 2 and Appendix: Table 2). We condensed several impact subcategories reported by the universities. Paper and offices supplies' consumption is the most important factor here, whereas the variation between the universities is substantial: Duquesne University (Pittsburgh) is reporting that 0.04% of its CF is caused by offices supplies, while KU Leuven publishes an amount of 14.8% for this contribution (see Fig. 2 and Appendix: Table 2). 0.1–1.3% (on average: 0.4%) of the overall CFs was caused by freshwater consumed and wastewater generated. The consumption of chemicals, gases, and detergents adds another 0.01–1.3% (on average: 0.5%) to the overall CFs of the universities. Most universities reported several impacts due to waste disposal, such as liquid, solid, laboratory and paper wastes, and composting impacts. Altogether, these result in 0.1–4% (on average: 2.7%) of the overall university CFs (Fig. 2 and Appendix: Table 2).

Impacts suggested to omit

Apart from the aforementioned impacts that are essentially to be covered, there are other impacts in which we believe can be omitted to limit data complexity and ensure fair comparability. First, there is food, and its impact has been often reported (e.g., [26, 27]). However, humans need food independent to location or occupation. Although there are quite some local diet differences, we do not think that university CFs differ significantly in diet provision, particularly, in the light of the increasing fast food consumption among students, even in Asian countries (e.g., [28]). On the other hand, it can be the policy of a university to provide healthy and low CF food with little or no meat, or to integrate a responsible food consumption into the education for a sustainable development [29]. University canteens, however, are operated by external private companies at some campuses (like at Umwelt-Campus Birkenfeld and NTU Singapore), which result in limited data availability, and hence cause a lack in policy attempts to make food consumption more sustainable. The biggest argument against considering food consumption as part of university carbon footprinting is the fact that students and university personal consume only part of their daily meal in the university, typically only lunch.

One study quantified the mobility behavior in the students' private time (vacation travelling, [30]). Due to personal data protection policies, private mobility behavior can usually not be regularly recorded.

De Montfort University (Leicester) considered the impact of travels made by visitors to the university. Including such travels may jeopardize the standardized comparison between universities: large universities tend to organize more scientific conferences as they have more resources than small universities. Also, third parties may be (co-)organizing conferences held on university campuses, which brings up the question who is responsible for the impact. Therefore, we decided not to consider this impact in the present study.

Generally, as confirmed in this overview, university CF quantification today emphasizes the use phase impact of a university. Occasionally, we came across impact elements which lay outside the use phase, but are not clearly separated from it, for example, yearly investments in the buildings structure or IT architecture (as for example reported by the King's College and De Montfort University), partly called procurement impacts (e.g., [26]). Although infrastructure investments were often considered in university impact assessment [20], we believe use phase impacts and embodied impact assessment should be separated like it is common in Life Cycle Assessment (e.g., [31]). Embodied impacts of universities will be separately discussed in Part II of this project presentation (in preparation).

Acquisition of furnishings and IT architecture (servers, computers, and WLAN systems) cannot be clearly assigned to either the use phase or embodied impacts. On one hand, a university will purchase such infrastructure every year; on the other hand, it may be in use for many years. For the benefit of comparability, we have removed related procurement impacts. Additionally, almost all universities worldwide will be working with quite similar IT technology (central data servers and personal computers), almost every student today owns a notebook or tablet produced from only a few companies worldwide. Accordingly, we believe that the related impacts would not significantly distinguish universities from each other. This might change in the future when green(er) information technology becomes increasingly available for purchase [32, 33].

The life-cycle perspective, on the other hand, is considered in this study in the way that we based carbon impact calculations on input data which included supply chains, as far as possible (see Appendix). This refers to the impact calculations of our own universities (UCB Birkenfeld and NTU Singapore) but also to impacts of other universities which we supplemented (mostly commuting, see Table 1).

Resulting university carbon footprints and their interpretation

Universities physically consist of buildings, and buildings and construction together account for 39% of energy-related CO_2 emissions in the world [34]. Accordingly, there are plenty of initiatives worldwide targeting to decrease the energy consumption of buildings, measured in terms of per m^2 [34]. Square meters is accordingly an established functional unit in carbon footprinting of households [35], as it is as well the per-capita measurement of impacts from households [36].

The most detailed study available so far reported individual CFs for 42 buildings of Carleton university campus in Canada [37], ranging from 10 to 200 kg CO_2e/m^2, and from 0.01 to 7.4 Mt CO_2e/capita and year, respectively,

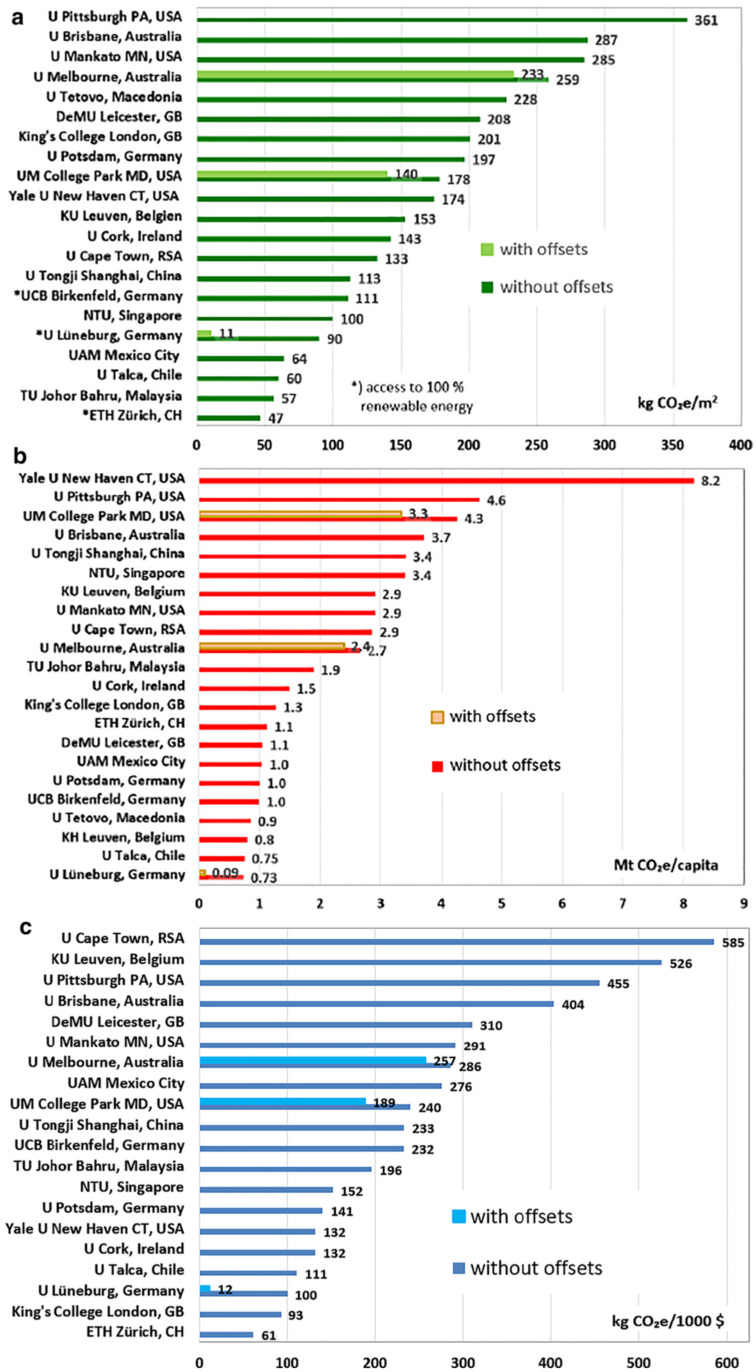

Fig. 3 Detailed university CF results per year for constructed area (**a**), per capita (**b**), and expenditures (**c**). Notes: 2C is based on university expenditures without salaries and has been corrected for purchasing power parity (PPP)—for details, we refer to the Appendix: Fig. 6. Offsets: three of the universities covered are compensating CO_2 emissions by purchasing carbon credits or producing a surplus of renewable energy. Mt = metric tons. U = University. Universities are named in the graphs with respect to the cities they are located. Some have deviating/completing names: UM College Park MD = University of Maryland. U Mankato MN = University of Minnesota. U Melbourne, Australia = Monash University. U Brisbane = University of Queensland. U Pittsburgh PA = Duquesne University. DeMU Leicester = De Montfort University. NTU = Nanyang Technological University. UCB = Umwelt-Campus Birkenfeld. UAM = Universidad Autonoma Metropolitana-Cuajimalpa. Tongji University Shanghai (3c) based on research budget only

which is quite similar to the ranges which we observed in our international comparison (Fig. 3 a + b). Based on current literature review, there is no study on any area-related international university CF comparison (kg CO_2e/m^2 and year), and hence, this study should be the first one (see Fig. 3a).

The results of all three CF units span one order of magnitude (Fig. 3a–c). Relating the carbon impacts to PPP-corrected university expenditures is smoothing the results considerably: As an example, University of Cape Town generates an outlier with 1,067 kg CO_2e/1000 $ without PPP correction which is almost halved after PPP correction (Fig. 3c, also see Appendix: Fig. 6 for more details). We suggest to establish this economic CF factor as an additional unit expressing how efficient a university is decreasing its CF related to budget. Specifically, a budget might be invested to purchase carbon offsets (see below). This would quickly improve the CF of a university in terms of its kg CO_2e/1000 $ record. Also, a university can generally decide to invest into carbon-efficient products and services (e.g., [38]), which can be more expensive, but would also reduce the CF in terms of the kg CO_2e/1000 $ record.

Among the university CFs discussed in the literature, the CF per capita is the one most frequently reported. In a few cases, the per capita CF has been related to university students only (e.g., [30, 39]) instead of to the entire university population (students plus staff). Relating the CF to students alone would reduce the functions of a university to teaching alone. We believe that university research is having the same relevance, and it is performed largely by the scientific university staff, only to a smaller part by students. The technical and administration staff is supporting both functions of a university. Concluding, we see decisive reasons to base the university CF on the entire university population (staff plus students).

We found 0.73–8.17 (average: 2.41) Mt CO_2e/capita and year among 22 universities covered (see Fig. 3b). This order of magnitude has been confirmed by earlier studies: for example, the carbon emissions per staff and student amounted to around 1–3 Mt CO_2/capita and year among 20 British HEIs, with an upward trend between 2005/06 and 2009/10 [21]. In a recent review, Mendoza-Flores et al. [40] reported 0.29–6.51 (average: 1.80) Mt CO_2/capita and year among 15 universities worldwide covering the years 2007–2017, however, that is without the corrections and amendments, we are applying in this study. Li et al. [30] published unusually high CF numbers in terms of Mt CO_2e/person and year, ranging from 3.84 (China) to 7–10 (Japan, Europe), arriving at 20 Mt CO_2e/person and year in USA, which cannot be explained by the fact that they related the CF to students alone.

While the two CF parameters kg CO_2e/m^2 (Fig. 3a, mean: 2.36) and kg CO_2e/1000 $ expenditures (Fig. 3c, mean: 248) both exhibit a linear distribution of results, the per capita parameter displays an agglomeration of 11 from 22 universities around 1 Mt CO_2e/person and year (see Fig. 3b). This number today seems to indent a university working carbon efficiently. However, whether or not a university consumes green electricity has an enormous impact on this result which we are illustrating with the following example. NTU (Singapore) ends up with a CF of 3.4 Mt CO_2e/person and year (Fig. 3b), based on an electricity consumed with a CF of 0.5 kg CO_2e/kWh. In case NTU would have access to the same green electricity that the ETH Zürich is consuming (0.013 kg CO_2e/kWh, [41]), NTU's CF per capita would decrease from 3.4 to 1.35 Mt CO_2e/person and year, As a result, it would belong to the group of universities with the lowest CF in this investigation. However, there is no such green electricity in sufficient quantity available in Singapore. In such a situation, buying carbon offsets might be the option to decrease the university's CF (see below).

Finally, we assign an overall score in carbon performance to each of the 20 best documented universities. The carbon footprint of the best performer in each of the three categories is set to 1.0, and then, the three category records are summarized for the respective university. The best possible score (lower scores are better) in this way is 3.0; ETH Zürich reaches a 3.53 as this university performs best in two of the three impacts and is No 9 in the per capita CF (see Fig. 3). Table 1 reports the results of this overall carbon performance score (3.53–21.44) establishing a ranking of the 20 universities. This overall carbon performance score is visualized as well in Fig. 1. Carbon offsetting measures, undertaken by three universities, were not considered at this point, but are discussed below.

Global distribution of university CF performances

Appendix: Fig. 7 graphically depicts the overall scores in carbon performance. It is headed by a group of three: ETH Zürich (Switzerland), University of Talca (Chile), and Leuphana University of Lüneburg (Germany). Seven more universities belong to the top 10 performers: TU Johor Bahru (Malaysia), University of Cork (Irland), Universidad Autonoma Metropolitana-Cuajimalpa (UAM) in Mexico City, Umwelt-Campus Birkenfeld (Germany), King's College London (Great Britain), University of Potsdam (Germany), and Nanyang Technological University of Singapore. Interestingly, in this group of top 10 performers, there are small and big universities, spreading across eight countries and three continents (Europe, Asia, and South America).

Figure 1 allows to search for a possible global correlation of CFs with, for instance, geographical latitude, based on the assumption that universities in warm countries would need to consume more electricity because of air-conditioning. There is no such trend visible (see Fig. 1). Universidad Autonoma Metropolitana-Cuajimalpa (UAM) in Mexico City, a university in a tropical climate, is having one of the best carbon performances (taking aside the CF related to expenditures, Fig. 1). Also Nanyang Technological University with its tropical location exhibits a relatively well carbon performance altogether (see Fig. 1).

Instead of with latitude, the per capita CFs correlate with the national CFs per capita (see below). Accordingly, universities in Australia and the USA exhibit the highest CFs (see Fig. 1). Europe, on the other hand, shows a striking number of low CF universities. One reason can be infrastructure: Other than in USA, in Europe, most buildings do not have air conditioning. Another reason is availability of green energy: in Germany and Switzerland, for example, institutions can opt for 100% green electricity.

Correlation between the parameters investigated

Intercorrelations were investigated each between the following parameters: kg CO_2e/1000 $ expenditures, Mt CO_2e/person, kg CO_2e/m^2, aggregated carbon performance, the number of staff plus students, and constructed enclosure area. From 12 correlation combinations investigated, there were just two exhibiting a correlation: the CF per capita and year related to the number of students and staff, and, respectively, the CF per capita and year related to the constructed enclosure area of the respective universities (see Fig. 4). The very low degree of intercorrelation, however, should not come as a surprise given the enormous heterogeneity in the distribution pattern of partial university carbon emissions (see Fig. 2).

Although these correlations are weak (see Fig. 4), universities seem to face difficulty in achieving a low per capita CF when growing in size. The problems of larger universities are most obvious when correlating the per capita CF with constructed enclosure areas (see Fig. 4b). We believe that this is due to the fact that larger universities are running infrastructure which is absent in smaller universities. For example, NTU (Singapore) is operating extended sports facilities including a swimming area, while such infrastructure is not available at the much smaller Umwelt-Campus Birkenfeld (Germany).

Correlation between university population and Mt CO_2e/person spent (Fig. 4a) exhibited further peculiarities. First, we have excluded Yale University from the correlation, because Yale is generally enrolling, due to local university politics, a particularly low number of students. While the 20 universities investigated (excluding Yale) have enrolled 2.4–17.2 (average: 6.2) times more students than staff employed, Yale enrolls just 0.8 times the number of students compared to number of staff available. Perhaps surprisingly, a high number of students-to-staff ratio does not automatically result in an advantageous capita-related CF: while University of Tetovo (Macedonia) with 16.2 × more students than staff exhibits 0.9 Mt CO_2e/person, the Minnesota State University in Mankato with its 17.2 × more students than staff ends up with a three times higher footprint (2.9 Mt CO_2e/person, see Fig. 3b). Vice versa, De Montfort University Leicester (GB) with its students-to-staff ratio of only 5.4 is placed in the top group with around 1 Mt CO_2e/person.

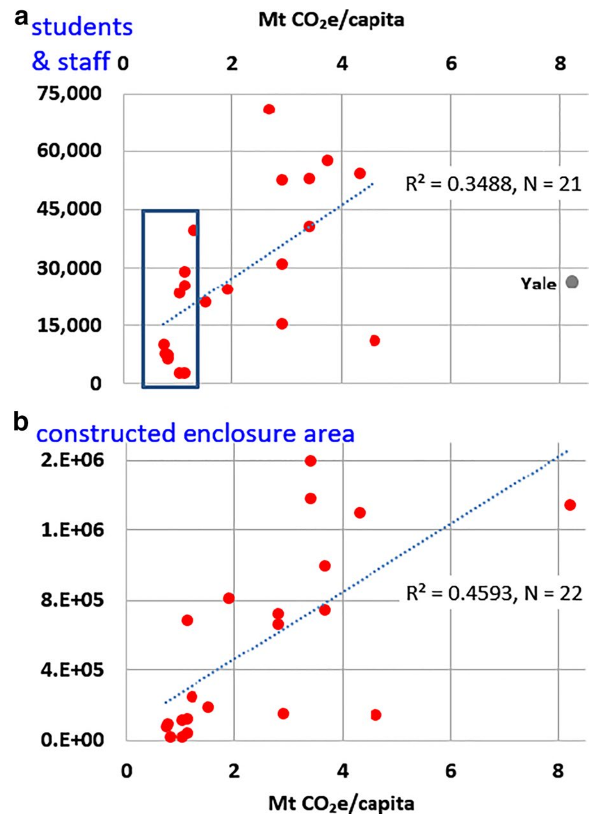

Fig. 4 University population (students plus staff, **a**) and constructed enclosure area (**b**) both related to Mt CO_2e/capita and year. Coefficient of determination in graph A calculated excluding Yale University. The box (graph A) includes 10 universities reaching a per capita carbon footprint of lower than or close to 1.0 Mt CO_2e/person and year. Mt = metric tons

Astonishingly, however, the correlation between University population and Mt CO_2e/person spent (Fig. 4a) points to a group of universities maintaining a low per capita CF of up to or near 1.0 Mt CO_2e/person, independent to the size of university population (see the box added in Fig. 4a). In other words, the ETH Zürich, Kings College London, University of Potsdam, and De Montfort

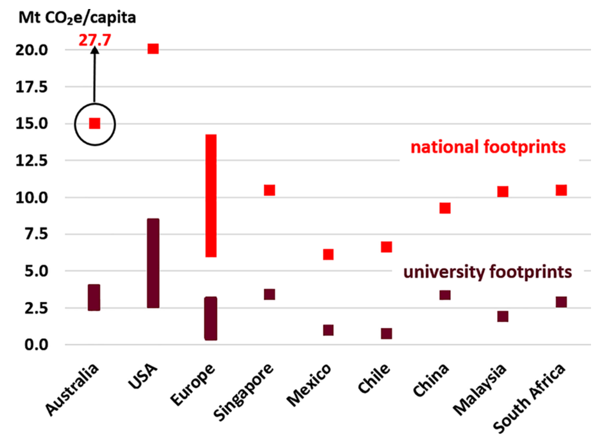

Fig. 5 University CFs per capita and year relative to national per capita footprints (the latter for 2015, taken from [42], areas shown for Australia, USA, and European countries with universities covered in this investigation (Mt = metric tons)

University Leicester successfully reached around 1.0 Mt CO_2e/person and year although being relatively large with 20,000–30,000 students enrolled. Vice versa, the five universities in this comparison with the highest enrollment numbers (39,383–47,000 students, Tongji University Shanghai [China], the University of Maryland [USA], University of Leuven [Belgium], and the Universities of Brisbane and Melbourne [Australia]) all belong to the group of universities with the highest CF in terms of Mt CO_2e/person.

University CFs relative to national per capita CFs

On average, university CFs per capita resulted in 23% of the national per capita footprints (range: 12 – 37%, Fig. 5). National per capita carbon emissions, as published by the EU commission, comprise emissions from fossil fuel use, industrial processes and product use [42]. These are consolidated in the Emissions Database for Global Atmospheric Research (EDGAR) providing past- and present-day anthropogenic emissions of greenhouse gases and air pollutants by country, including energy and manufacturing facilities, and road networks [43]. Accordingly, EDGAR data are in principle comparable to our determination of university CFs which are dominated by energy use and mobility. However, whereas EDGAR summarizes national emissions, we have based our university impact quantification on use phase plus supply chains. A part of the supply chains (e.g., vehicle production) may reach beyond the country in which the university is located.

When it comes to the carbon footprint of workplaces, economy sectors are compared with varying degree of energy intensity. The EU commission [44] emphasized that 70% of all workforce produces less than 12% of all CO_2 emissions, including the sectors of construction, wholesale, retail trade, and other services. More specifically, Eurostat [45] reports that the sector of scientific research and development services in the EU28 spent just 12 kg CO_2 per inhabitant, and all education services spent 100 kg CO_2 per inhabitant, respectively, both domestic plus imported emissions for the year 2017. The overall GHG emission footprint in the European countries covered in our investigation, however, amounts to 10 Mt CO_2e/capita in 2017 (calculated from [42]). Because we considered commuting and business travel within the universities' CF, we might also compare the overall mobility impact of Europeans: 1.8 Mt CO_2e/capita in 2017 [42], and 0.8 Mt CO_2e/capita of it being related to travelling with cars and trains (calculated from [46]. The latter emissions plus the education and research/development sector emissions amounts to 0.91 Mt CO_2e/capita in 2017, equivalent to 9.1% of the overall per capita GHG emissions in Europe, and close to the 12% CF per capita, we quantified for European universities relative to the national impacts (Fig. 5).

University per capita CFs correlate with the national CFs (Fig. 5), which is to be expected: while emissions from electricity production often dominate the national CFs [42], this is as well the case for emissions from electricity consumption of universities. Universities are connected to the national electricity grid, as long they do not separate themselves by operating their own power plants.

Europe exhibits a striking number of low CF universities (see Table 1), as the 10 European universities studied here have on average just 12% CF per capita compared to the national per capita CFs (as well averaged). On the other hand, this investigation lacks representativity and may be biased: we did not specifically search for carbon-efficient universities, but for universities publishing sufficient data necessary for a full evaluation. However, universities with good documentation may be just the universities successful in carbon emission minimization, and therefore publishing their success. In other words, we would not have (any) data from those universities not interested or not engaged in CF optimization.

Given the relatively high magnitudes of per capita university footprints (see Fig. 5), saving energy/reducing CFs within universities would conversely decrease the respective national footprints: at German universities, for example, there are 2.9 million students enrolled [47]. Adding around 10% university staff results in 3.2 million people, equivalent to 3.85% of the national population [48]. There are nations with higher numbers: college enrollment alone makes up roughly 5.6% of the entire US population (based on data from [49]). Hence, transforming universities into carbon-efficient institutions should be handled as a high-priority national endeavour.

Relating the CF to research orientation of universities

It may be expected that research oriented universities might show higher carbon footprints than universities that are less research active, due to the more complex infrastructure and more staff members necessary to support research activities. However, this is not reflected in the results here: The university of Lüneburg as a research oriented HEI is among the leading institutions when it comes to its carbon footprints (Figs. 1, 3 and Table 1). Umwelt-Campus Birkenfeld, which may be regarded as less research oriented, even displays a slightly weaker carbon record (see Figs. 1, 3 and Table 1). Both represent relatively small campuses. The expectation that research activities increase the footprints is also not confirmed for big institutions. The nine universities in this study with the lowest CF (performance ranks 1–9, see Table 1) include five research oriented HEIs with between 18,464 and 31,377 students, among them the ETH Zürich and the King's College London as top research universities (Table 1), the latter two each operating a medical department with its very high infrastructure costs and impacts.

The critical factors for attaining a low carbon footprint on a university campus are as follows. It needs dedicated low-energy building technology and access to renewable energy (e.g., University of Lüneburg and Umwelt-Campus Birkenfeld, Germany), as well as continuous investments and resources necessary to optimize energy consumption and reduce emissions. Not by chance, the ETH Zürich published its first CO_2-emission report already in 2004 which included a historical analysis back to 1990 [50], while the King's College London is recording CO_2 emissions since 2005 [51], and is running a program to stimulate carbon-efficient behavior by distinguishing sustainability champions [52].

Approaching zero emissions: carbon offsetting

Reducing CO_2 emissions by a small fraction is no longer sufficient to reach a long-term stable climate globally. Many institutions and technologies will have to try to reach zero emissions. The European Commission has accepted this challenge and is aiming for climate neutrality by the year 2050 [53]. The term "zero emissions", however, needs to be defined: carbon neutrality, for example, would require (net) zero CO_2 emission in the global economy, and technically, it is a hypothetical concept today: there is not a single IPCC concept achieving it [54]. In contrast, "net zero carbon emissions can be achieved by balancing any remaining CO_2 emissions by CO_2 removals of exactly the same amount" (Rogelj et al. 2015, note: net zero GHG emissions should be targeted instead of just CO_2). Monash University (Melbourne) seems to embrace this concept in its "Net zero initiative" [38]. It intends to reach zero carbon emissions in 2030 by implementing zero energy buildings, establishing renewable electricity plants and halving energy consumption. However, a net zero concept today can only work with an excess of green energy production or when combined with another compensation mechanism.

The much smaller Leuphana University Lüneburg is demonstrating this: by maximum employment of modern building technology and highly sophisticated green energy management (e.g., a high-temperature aquifer thermal energy storage), the university produces a surplus of energy and can thus almost completely offset its own GHG emissions (recalculated after [16], see Appendix).

Leuphana University Lüneburg even claims to have several 1,000 Mt of negative CO_2e emissions per year [16]. However, when recalculating the balances more conservatively (not assuming hydropower electricity to be spent, not neglecting commuting and business trips, and quantifying the offset CO_2e earnings due to feeding in the surplus renewable electricity into the net more realistically with respect to the average German carbon footprint, for more details, see Appendix), then the university can certainly compensate its emissions. We found Leuphana university having the third lowest aggregated carbon performance (see Table 1), without considering the offsets. Because of its very low overall CF, even the 100% renewable energy consumption of this campus makes up to 30.7% of its overall CF. However, when considering the energy offsets earned by Leuphana University Lüneburg (after recalculation, see Appendix), then the CFs reach very low numbers, almost approaching zero Fig. 3a–c). Leuphana University Lüneburg thus can be treated as the only zero (carbon) emission university in this investigation.

Consuming 100% renewable electricity alone, however, does not qualify universities to become zero emission entity today, although this misunderstanding has been noticed in the statements of two universities in this investigation [18, 38]. It goes back to the definition of zero carbon buildings having zero net CO_2 emissions from energy use [12]. Also energy producers in Germany actually mark their green electricity production as emitting 0.0 g CO_2/kWh, this way ignoring upstream emissions (e.g., [55]). In contrast, even renewable electricity production has a carbon footprint today (e.g., PV electricity production comes with around 50–80 gCO_2e/kWh, according to [56]). This impact needs to be compensated. The above reduced definition of "zero emission" also ignores impacts caused by people working in buildings.

Carbon emission compensation ("offsetting") can be implemented with the Clean Development Mechanism (CDM) allowing the use of compensation mechanisms through flexible application of the Kyoto Protocol [57].

Other than Udas et al. [9] state, CDM may open a standard way to become carbon–neutral. Several universities are already on this way: University of Maryland, also planning to reach zero carbon emissions, reported an offset of around 50,000 Mt CO_2e due to purchasing carbon credits [58]. Monash University (Melbourne) reported an 18,883 Mt CO_2e offset as follows: "Car fleet fuel consumption was offset with permanent biodiverse native forests planted by a greenhouse friendly approved abatement provider" [59]. Further universities covered in this investigation have announced to start a carbon offset program (e.g., the University of Queensland, see [60]).

How expensive is the compensation of CO_2e emissions? An international pollutant valuation review resulted in monetarized impacts of 27–164 (average: 77) $/Mt of CO_2 [61]. The purchase of voluntary certificates for CO_2 compensation is more reasonable with 5–80 (average of five commercial programs: 27.3) €/ Mt of CO_2 [62]. Given the 2,696 Mt CO_2e emitted by the Umwelt-Campus Birkenfeld in 2017, it would need an investment of 73,601 € to fully compensate its emissions and reach net zero, equivalent to just 0.8% of expenditure (without salaries) made in 2017. To compensate its 32,869 Mt CO_2e emission, the ETH Zürich would have to buy carbon certificates for 897,324 €, equivalent to only 0.17% of its expenditures (without salaries) made in 2017. The question arises why this is not done yet at universities.

Limitations and strengths of this investigation

- While emissions from energy consumption and business travels can be exactly measured, the questionnaires on which quantification of commuting impacts is based deliver relatively weak estimations: only a fraction of students and staff out of the whole population is participating in such exercise, and the student generations are interchanging quickly which can continuously modify their habits. However, so far, there has been no alternative available for quantification of commuting emissions.
- University CFs from single (budget) years are subjected to meteorological changes causing a bias to the data. Universities seeking to manage their CF should, therefore, quantify the meteorological influence. Schwartzkopf and Urban [63] provided weather-normalized data for Minnesota State University (Mankato), exhibiting an up to 15% of meteorological influence on heating energy consumption, for example.
- Next to the influence of weather conditions, the emissions of specific years might be biased by university growth and opening of new buildings. Metha et al. [64] have developed a method quantifying these influences.
- This investigation provides a status quo in worldwide university CFs based on 1-year university data in the period of 2008–2018. Thus, we hereby only see snapshots in the long-term carbon performance of these universities. Instead, a long-term longitudinal study would be more appropriate, but data are often lacking for such endeavour.
- Almost all universities documenting CFs set themselves goals for CF reduction. As universities started at different years in managing and decreasing their CFs, this should not cause an additional bias.
- Missing impacts had to be estimated for a couple of universities resulting in lower data precision. However, even a not so precise estimation of impacts like commuting improves the accuracy of the university CF compared to when omitting the respective impact. Consequently, this enabled a more harmonized inter-university CF comparison.

Conclusions

Although already initiated in 1993, the process of eco-impact reduction seems to be still in its infancy among universities worldwide. Several hundred universities have started to document climate relevant emissions, developing plans to minimize them. An even smaller number of universities are publishing their emission records. However, emissions of important sources such as commuting are often not included. It also turned out that published emission budgets need critical reviewing, not only because they may be incomplete, but also because budgets may be based on unrealistic assumptions and uncommon definitions.

Universities can actually reach zero carbon emissions, proven by Leuphana University in Germany, which achieves this goal through maximum use of modern technology and on-site surplus renewable energy production. However, maximum use of technology means a particular high upstream carbon impact due to the materials incorporated. This can implicate extended pay-back times and change the carbon performance, an effect which has not yet been quantified for universities.

Besides modern technology, low or even zero carbon emissions can be achieved by purchasing carbon certificates. We believe that both pathways will need to be combined.

Moreover, we realized that almost every university in the world, independent of its climate zone, its focus and profile, can reach very low carbon footprints, based on the political will, necessary investments granted and the creativity needed from their researchers. Smaller and universities in urban areas can go achieve low CFs more easily because of less infrastructure and mobility impacts. The availability of a green energy supply, however, is generally a crucial factor. Based on the expected worldwide transition towards increasing renewable energy production in the coming decades [65], carbon footprints of energy provision might need a new way of quantification [66, 67].

This is in no way a criticism on certain universities for having a higher CF than others. All universities considered in this overview are to be commended in the way that they quantify and publish (parts of) their CF, hence are thus among the leading universities worldwide in this regard. Obviously, the majority of worldwide universities do not publish any or any useful impact data. As universities are innovation drivers in science and technology, and thus are willing to accept their responsibility to support the transformation towards a sustainable world, this should change and become a much broader movement.

Appendix

Impacts were quantified in most cases from process data obtained from the German/international GEMIS/ProBas databases, which generally consider upstream effects [68, 69].

Umwelt-Campus Birkenfeld (UCB), University of Applied Sciences Trier (Germany)

UCB: Energy

The campus is provided with electricity and heat by a neighbouring combined heat and power plant (CHP) burning waste wood. This plant is owned by the regional electricity company, which also provides 100% renewable electricity to the campus. We quantified the electricity impacts with a matching impact specified by GEMIS [70]: 18 g CO_2e/kWh. The campus purchased electricity with an impact of 22.94 Mt CO_2e this way.

PV electricity is additionally provided by campus-own CdTe-moduls having an impact of 0.024 kg CO_2/kWh. (impact factor provided by [71]). Additionally there is electricity produced by monocrystalline PV, calculated with 0.061 kg CO_2e/kWh [70]. This way the campus indirectly emitted 1.3 Mt CO_2e.

The district heating system loaded by the above CHP plant provides heat with an impact factor of 0.065 kg CO_2e/kWh [70] resulting in an impact of 206.5 Mt CO_2e. Heat is as well produced by a campus-own solar collector (0.025 kg CO_2e/kWh, [70]) adding 0.35 Mt CO_2e.

UCB: Water, wastes and office material

Freshwater consumption is considered with a conversion factor of 0.381 kg CO_2/m^3 [72] causing 3.27 Mt CO_2. A campus-own rainwater collection unit added freshwater with an impact of 0.33 kg CO_2/m^3 [73], another 0.51 Mt CO_2 were brought about this way. Wastewater disposal was considered based on 0.254 kg CO_2/m^3 [72] adding 3.8 Mt CO_2 to the CF of the campus. All solid wastes were quantified with a conversion factor of 0.0218 kg CO_2/kg, just composting material with 0.006 kg CO_2/kg [74], resulting in an impact of 1.41 Mt CO_2.

Office material was converted to CO_2 impacts as follows: envelopes and paper with a factor of 1.28 kg CO_2/kg [72], toner with a factor of 4.8 kg CO_2/kg [75], respectively. Taken together, both resulted in an impact of 9.7 Mt CO_2.

UCB: Mobility impact assessment

Input data used for mobility impact modelling were taken from different sources. Carbon footprint for international flight km were taken from the German federal "process based basic data for environmental management systems", resulting in 153 g CO_2/km including supply chain [76].

CF when using personal cars were quantified during full LCA modelling resulting in 268,5 g CO_2e/km [25]. CFs of public buses and trains have been researched in the literature resulting in averages of 120,9 g and 68,9 g CO_2e/PKM, respectively [25]. Business trips caused an impact of 177.1 Mt CO_2e, internal business cars added another 10.7 Mt of CO_2 at Umwelt-Campus Birkenfeld.

Commuting

Detailed quantification of commuting impacts is based on questionnaires. First of all, it is essential to estimate how many days/weeks a year students visit the university. This was quantified as being 36 weeks/year on average at Umwelt-Campus Birkenfeld, which was applied as well on other universities.

A questionnaire at Umwelt-Campus Birkenfeld in 2015 delivered the following numbers:

- 16,06% of the students live on campus. They drive home once a week by car (180 km per weekend).
- The rest of the students commute 3 days a week from home to university driving 66.66 km/day (43.6% by train, 6.5% by bus, 33.9% by car), due to the questionnaire.
- There are lectures on 30 weeks in a year; additionally the students need to arrive for 20 written exams per year, resulting in 110 days of commuting to the cam-

pus per year (→ 7,326 km of commuting/student x year with the above mix of transport).

- Among the staff, 36% commute by train, 3.9% by bus, 60.1% by car. Driving impacts were calculated based on the same distances applied for the students. 184 working days were calculated per year.

Student commute results in an impact of 1,826.8 Mt CO_2e, while the commuting impact of the staff amounted to 431.5 Mt CO_2e at Umwelt-Campus Birkenfeld.

Commuting of students for foreign universities were calculated considering the number of places available for students to live on campus.

ETH Zürich (Switzerland)

Only recently that ETH Zürich has opened around 900 student rooms. Before this, there were no student dorms so far at ETH campus. Accordingly, most students (19,707) have to commute daily for which we assume only half of the distance (30 km) per day compared to Umwelt-Campus Birkenfeld (UCB), because UCB is a rural site which requires longer distances for staff and students to travel, while e.g. the ETH Zürich is located in a metropolitan area.

Based on an excellent public transportation network available in the Zürich area (mostly train and tram), most students will travel using such transportation (→ 68,9 g CO_2e/PKM, see [25]). 110 × 30 × 68.9 g CO_2/km × 19.707 → 4,481 t CO_2e. This number exhibits that the 1,714 t CO_2 mentioned as spent for commuting, but without specification in detail, obviously means staff commuting [41].

University of Cape Town (South Africa)

UCT offers 6000 places in student dorms [77], hence the remaining 20,000 students need to commute. As 44% (8800) use their cars [27], student commuting CF was calculated by: 8,800 × 110 × 30 × 268.5 g/km → 7,797 Mt CO_2e. 38% commute via a shuttle service (mini bus): 20, 000 × 0.38 × 110 × 30 × 120.9 g CO_2e/km→ 3,235 t. Students commuting together: 11,032 Mt CO_2e.

King's College London (Great Britain)

[22] reported that 75.5% of the students commute with public transport, most of all by trains. Accordingly the commuting carbon impact was quantified as (comparably to the above universities in metropolitan areas): 110 days × 30 km x (31.377 × 0,755) × 68.9 g/ CO_2e PKM → 5,386 Mt CO_2e.

Monash University, Melbourne (Australia)

The number of places in student dorms was not available in the internet, however, it was mentioned that there are many of such dorms in a distance of 10–65 km off campus(es). Therefore an average distance of 30 km a days was assumed for half of the students, travelled by train/tram: → 31,623 × 110 days × 30 km × 68.9 kg CO_2/km → 7,190 CO_2 for student commuting.

Universiti Teknologi Malaysia, Johor Bahru (Malaysia)

It was not possible to figure out the number of professors as the data is not available online. Accordingly we could not estimate the business flight activity. Commuting impacts, however, have been included [78].

Leuphana University Lüneburg (Germany)

Based on [16] the consolidated CF of the university is composed of its electricity production (296 Mt CO_2e), heat production (2,036 Mt CO_2e), freshwater and paper consumption (50 Mt CO_2e), commuting impacts (3,694 Mt CO_2e), business travelling (1517 Mt CO_2e), resulting in 7,593 Mt in total.

Calculation of offsets: Due to [16] the aquifer thermal energy storage installation results in additional savings of 2,424 t CO_2e/y which obviously corresponds with the excess thermal energy delivered to the neighbourhood.

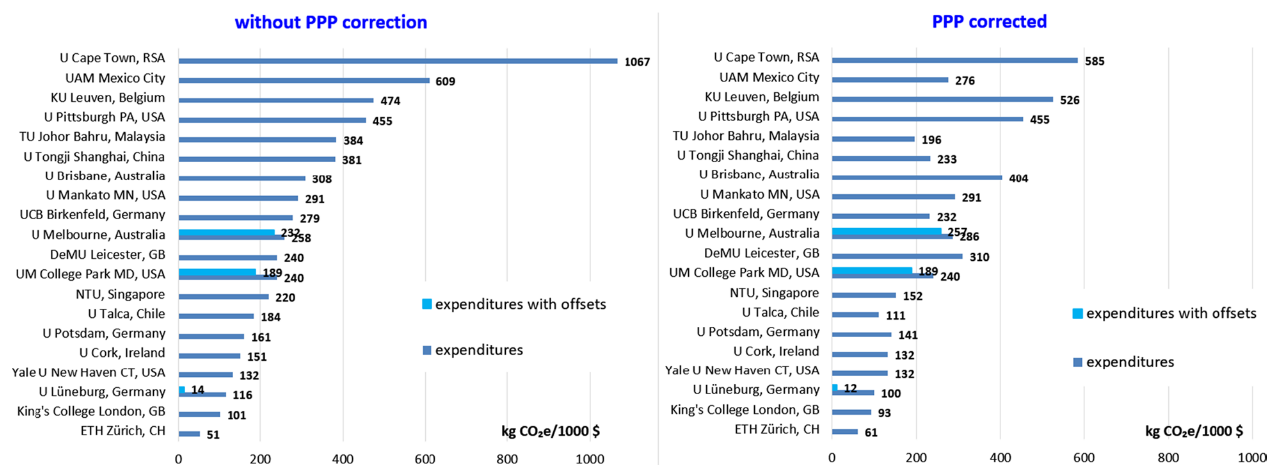

Fig. 6 Carbon footprints based on university expenditures without and with purchasing power parity (PPP) correction

Additionally the university feeds in excess electricity into the network. [16] quantified the production impact based on hydropower (5 g CO_2e/kWh). We believe this should more realistically be based on the PV electricity production available (80 g CO_2e/kWh). [16] quantified the outside electricity CF saved based on electricity generation by coal fired power plants (821–921 g CO_2e/kWh), we quantify it based on the German electricity production impact specified by the German federal environmental agency [79] for the year 2015, which is 575 g CO_2e/kWh. Based on 8.65 GWh surplus electricity production of the university [16], this results in an electricity offset of 4,282 Mt CO_2e. Together with the surplus in heat production this results in an offset of 6,706 Mt CO_2e which has been confronted to the 7,593 Mt of CO_2e emissions.

Currency conversion and expenditure related CF quantification (PPP correction)

University expenditures were taken from financial university reports [80–96].

The expenditures of the Umwelt-Campus Birkenfeld (UCB) and Universidad Autononma Metropolitana (UAM) in Mexico-City were provided by the university administrations.

Currency conversion factors were applied relative to the individual year of study. Singapore $ were converted to US $ according to [97], Malayan Ringgit were converted to US $ according to [98]. All other currencies were converted to US $ according to [99]. Dividing the carbon emissions (Mt CO_2e emitted/y, Table 1) of the respective universities by the university expenditures in US $ resulted in the CFs displayed in Appendix: Fig. 6 (left: without, right: with PPP correction), as well as in the CFs displayed in Fig. 3c. For PPP correction, university expenditures were corrected before division applying the factors provided by [24], specific to the respective year.

Numerated partial carbon impacts of universities covered (supplementing Fig. 2)

See Table 2.

Table 2 Distribution pattern of partial carbon impacts at 18 universities worldwide (reproducing Fig. 2 in numerical form)

Impact/university	All waste materials	Chemicals, gases, detergents	Office supplies (e.g. paper)	Fresh- & wastewater	Domestic business trips	Internat. business trips	All business trips	Staff commuting	Student commuting	All commuting	Campus vehicles	Transport	(Heating) gas	Heat	Electricity	Electricity & heat	Impact/university
UM College Park MD, USA	2.1					19.4				15.1	3				6.5	53.9	UM College Park MD, USA
U Pittsburgh PA, USA	0.1		0.04			10.92				16.74						72.2	U Pittsburgh PA, USA
U Mankato MN, USA						0.6		6.2	16.1		0.3		22.9		53.9		U Mankato MN, USA
ETH Zürich, CH		0.3					55.9	5.2	13.6					20.3	4.7		ETH Zürich, CH
U Cape Town, RSA	0.2		0.5	0.1		2.3	0.4	10.9	12.5						73.1		U Cape Town, RSA
King's College London, GB	0.1		4.9	0.7		13.5	0.1		10.7		0.1		21.4	3.8	38.8	5.9	King's College London, GB
U Brisbane, Australia	4	0.01				15.1				12.09		0.6	0.4		67.8		U Brisbane, Australia
KH Leuven, Belgium	0.08		14.8	0.02								54.9			30.2		KH Leuven, Belgium
U Melbourne, Australia	1					17.4			3.8		1			12.3	64.5		U Melbourne, Australia
DeMU Leicester, GB	2		0.8	1.2			4	11.2	28		3.3			16.1	33.4		DeMU Leicester, GB
NTU, Singapore	2.3			0.3			8.4			27.295	0.005				61.7		NTU, Singapore
UCB Birkenfeld, Germany	0.1		0.4	0.3	2.2	4.2		16	67.78		0.4		0.02	7.7	0.9		UCB Birkenfeld, Germany
KU Leuven, Belgium	1.3	0.2	0.3	1.2								30.2				66.8	KU Leuven, Belgium
UAM Mexico City	0.003	1.28	0.56	0.257			16.4			52.6	2.9		0.8		25.2		UAM Mexico City
U Talca, Chile	1.6	0.6	0.2		0.3	5.73		23.1	31.1		1.2		2.67		33.5		U Talca, Chile
U Cork, Ireland	0.1			0.01			5.3	7.6	13.79					24.2	37.4	11.6	U Cork, Ireland
U Potsdam, Germany	2.3		0.2	0.1	0.2	15				49.5	0.2			26.6	5.9		U Potsdam, Germany
U Lüneburg, Germany			0.3	0.3			20			48.7				26.8	3.9		U Lüneburg, Germany

U = Universities; for specifications see Table 1. All data in %. Each horizontal column results in 100%

Normalized carbon footprint (CF) performances

See Table 3 and Fig. 7.

Table 3 Normalized carbon footprint (CF) performances. The lowest yearly CF each found for constructed area, per capita, and per expenditures (see Fig. 3 a–c) is set to 1.0

University	A CF performance [kg CO_2e/m^2] normalized to 1.0 for the best performer	B CF performance [Mt CO_2e/capita] normalized to 1.0 for the best performer	C CF performance [kg CO_2e/1000 $] normalized to 1.0 for the best performer	Overall normalized CF performance (A + B + C)	overall carbon performance rank
ETH Zürich, CH	**1.00**	1.53	**1.00**	3.53	1
U Talca, Chile	1.29	1.03	1.82	4.14	2
U Lüneburg, Germany	1.92	**1.00**	1.63	4.55	3
TU Johor Bahru, Malaysia	1.20	2.59	3.20	6.99	4
U Cork, Ireland	3.03	2.04	2.16	7.23	5
UAM Mexico City	1.37	1.42	4.50	7.29	6
UCB Birkenfeld, Germany	2.36	1.36	3.79	7.51	7
King's College London, GB	4.28	1.74	1.51	7.53	8
U Potsdam, Germany	4.19	1.37	2.30	7.86	9
NTU, Singapore	2.13	4.66	2.48	9.27	10
U Tongji Shanghai, China	2.40	4.67	3.80	10.87	11
DeMU Leicester, GB	4.43	1.44	5.06	10.93	12
UM College Park MD, USA	3.80	5.84	3.92	13.56	13
U Melbourne, Australia	5.50	3.64	4.67	13.81	14
U Mankato MN, USA	6.06	3.97	4.75	14.78	15
KU Leuven, Belgium	3.26	3.97	8.58	15.81	16
U Cape Town, RSA	2.83	3.92	9.55	16.30	17
Yale U New Haven CT, USA	3.71	11.19	2.16	17.06	18
U Brisbane, Australia	6.11	5.10	6.59	17.80	19
U Pittsburgh PA, USA	7.67	6.34	7.43	21.44	20

The CFs reported for all universities (see Fig. 3) are related to the best performer in each category (without offsets). The overall performance is summarized from A-C, also shown in Table 1, and results in an overall performance rank. The best possible score of a university would be a 3.0 (A + B + C). These data are plotted in Appendix: Fig. 7 below. Mt = metric tons

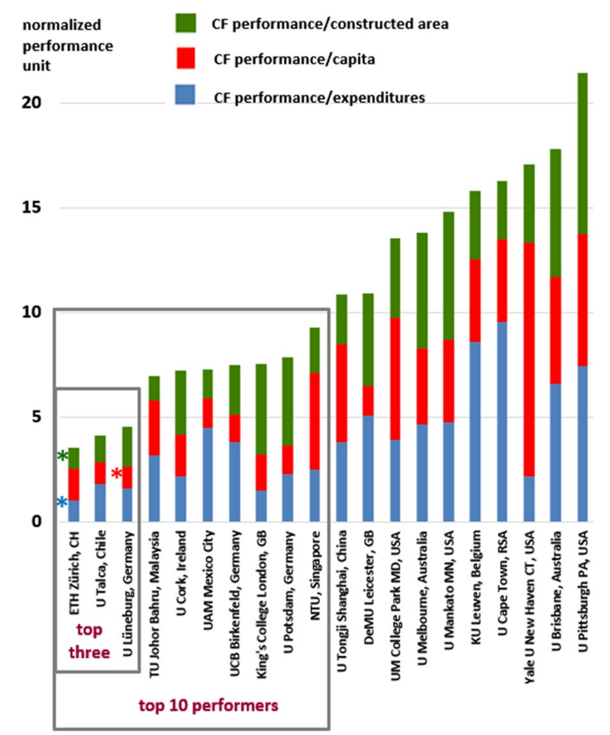

Fig. 7 Normalized carbon footprint performances. The plots display the data of Appendix: Table 3. The best performer in the categories A-C is set to 1.0 (marked by an asterisk). Without the offsets specified in Fig. 3a–c for three universities. The columns shown here are displayed on the world map in Fig. 1. CF = Carbon footprint. U = University. Universities are named with respect to the cities they are located. Some have deviating/completing names: UM College Park MD = University of Maryland. U Mankato MN = University of Minnesota. U Melbourne, Australia = Monash University. U Brisbane = University of Queensland. U Pittsburgh PA = Duquesne University. DeMU Leicester = De Montfort University. NTU = Nanyang Technological University. UCB = Umwelt-Campus Birkenfeld. UAM = Universidad Autonoma Metropolitana-Cuajimalpa. Tongji University Shanghai: CF performance/expenditures based on research budget only

Abbreviations

Mt: Metric tons; CF(s): Carbon footprint(s); HEI(s): Higher education institution(s); NTU: Nanyang Technological University; UCB: Umwelt-Campus Birkenfeld; GHG: Greenhouse gases; kWh: Kilowatt hour; GWh: Gigawatt hour; CO_2e: CO_2-equivalent emissions quantifying a global climate change impact (here: carbon impact).

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Authors' contributions

EH conceived the original idea, collected and analysed the data, and wrote and revised the manuscript. CCC and JD corrected and completed the manuscript. All authors read and approved the final manuscript.

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Availability of data and materials

The datasets supporting the research are included in the Appendix.

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Consent for publication

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Competing interests

The authors declare that they have no competing interests.

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