Carbon Footprinting of Universities Worldwide Part II: First Quantification of Complete Embodied Impacts of Two Campuses in Germany and Singapo

Helmers, Eckard ; Chang, Chia Chien ; Dauwels, J.H.G.

DOI
10.3390/su14073865

Publication date
2022

Document Version
Final published version

Published in
Sustainability

sustainability

Article

Carbon Footprinting of Universities Worldwide Part II: First Quantification of Complete Embodied Impacts of Two Campuses in Germany and Singapore

Eckard Helmers [1,*], Chia Chien Chang [2] and Justin Dauwels [3]

1 Department of Environ. Planning and Technology, Umwelt-Campus, University of Applied Sciences Trier, P.O. Box 1380, 55761 Birkenfeld, Germany
2 Energy Research Institute (ERI@N), Nanyang Technological University, 50 Nanyang Avenue, Singapore 639798, Singapore; E130185@e.ntu.edu.sg
3 Faculty EEMCS, TU Delft, Mekelweg 4, 2628 CD Delft, The Netherlands; j.h.g.dauwels@tudelft.nl
* Correspondence: e.helmers@umwelt-campus.de

Abstract: Universities, as innovation drivers in science and technology worldwide, should attempt to become carbon-neutral institutions and should lead this transformation. Many universities have picked up the challenge and quantified their carbon footprints; however, up-to-date quantification is limited to use-phase emissions. So far, data on embodied impacts of university campus infrastructure are missing, which prevents us from evaluating their life cycle costs. In this paper, we quantify the embodied impacts of two university campuses of very different sizes and climate zones: the Umwelt-Campus Birkenfeld (UCB), Germany, and the Nanyang Technological University (NTU), Singapore. We also quantify the effects of switching to full renewable energy supply on the carbon footprint of a university campus based on the example of UCB. The embodied impacts amount to 13.7 (UCB) and 26.2 (NTU) kg CO_2e/m^2•y, respectively, equivalent to 59.2% (UCB), and 29.8% (NTU), respectively, of the building lifecycle impacts. As a consequence, embodied impacts can be dominating; thus, they should be quantified and reported. When adding additional use-phase impacts caused by the universities on top of the building lifecycle impacts (e.g., mobility impacts), both institutions happen to exhibit very similar emissions with 124.5–126.3 kg CO_2e/m^2•y despite their different sizes, structures, and locations. Embodied impacts comprise 11.0–20.8% of the total impacts at the two universities. In conclusion, efficient reduction in university carbon footprints requires a holistic approach, considering all impacts caused on and by a campus including upstream effects.

Keywords: carbon footprinting; university sustainability; university carbon footprint; embodied emissions; embodied impacts; zero emission university; greenhouse gas emissions; global warming potential; renewable energy; building emissions; Umwelt-Campus Birkenfeld; Nanyang Technological University

check for updates

Citation: Helmers, E.; Chang, C.C.; Dauwels, J. Carbon Footprinting of Universities Worldwide Part II: First Quantification of Complete Embodied Impacts of Two Campuses in Germany and Singapore. *Sustainability* **2022**, *14*, 3865. https://doi.org/10.3390/su14073865

Academic Editor: Michael Blanke

Received: 13 February 2022
Accepted: 17 March 2022
Published: 24 March 2022

1. Introduction

The recent IPCC report [1] highlights the critical situation the world has arrived in with respect to climate change. Assuming a continuing growth of CO_2 emission, the worldwide carbon budget, projected to arrive at an upper level of 1.5 °C of global warming, will be spent within 8 years, whereas the emission budget to stay below 2 °C will be consumed within 25 years, respectively [2]. To tackle this situation, a careful balancing of climate-relevant emissions in all areas of life is needed (see, e.g., Lannelongue et al. [3]). Buildings and constructions are responsible for 36% of the final energy use and for 39% of the energy-related CO_2-emissions globally, including upstream power generation and manufacturing of materials for building construction [4], which makes these impacts essential to cover.

Universities, as institutions educating all kind of experts, should be leading the transformation towards a carbon-neutral society (e.g., [5]). They should reach out both in sustainability teaching [6,7] as well as in becoming ecologically exemplarily working institutions, as a motivation and a model for society and the young professionals they are educating. At last, universities make up a considerable percentage of a country's economic activities. For example, around 6% of the U.S. population is enrolled at universities [8].

Many universities worldwide, although still only a minority, have picked up the sustainability challenge. Most of them are located in the USA, England, and Australia; some are from European or other Asian countries. Interestingly, as a bibliographic analysis revealed, the number of publications on carbon footprint balancing at universities has been growing since 2010 [9]. Recently, in parallel to the 26th UN Climate Change Conference of the Parties [10], held 2021 in Glasgow, 1050 universities from 68 countries made commitments to reach net-zero carbon emissions by 2050 [11], indicating this is on the way to becoming a global political movement. However, so far, universities engaged in carbon footprint balancing have only quantified use-phase emissions.

In the first part of our study [8], we presented an overview of studies worldwide on carbon footprint balancing at universities. We concluded that the performance of each university can be measured by three carbon footprint (CF) factors: CO_2e emissions per constructed area (m^2), per capita (students plus staff), and per expenditures. However, the university CF data published so far are only comparable to a limited extent, since the impacts that have been included in the CF calculations vary across the different studies. In the first part of our study, we therefore added impacts missing in the reports published so far (impacts mostly mobility related), leading to a standardized calculation of the impacts that makes university CFs more comparable.

When assessing the CFs of organizations, usually, only the use phase is considered [12], which goes back to the GHG Protocol Corporate Accounting and Reporting Standard [13] and its original limitation to in-house emissions and purchased energy (scopes 1 and 2), while the consideration of upstream emissions (scope 3) was optional [14]. The second internationally established method for calculating the CFs of organizations, the ISO 14064 standard, recommends interpreting "indirect GHG emissions from goods purchased by an organization" as "extraction ... manufacturing and processing of raw materials" [15]. Life cycle assessment (LCA) generates even more holistic results for environmental impact assessment. According to the methodical classification by Pandey et al. [16], "the concept of carbon footprinting has been in use since several decades but known differently as lifecycle impact category global warming potential" (GWP). The biggest advantage of LCA is that it also quantifies services and product impacts outside the use phase [17], which are often hidden. Neglecting hidden environmental impacts of services and goods can lead to misdirected consumption habits, political action, or investment decisions, particularly with respect to tackling climate change [18]. Therefore, in the first part of our study, we considered upstream effects even when modelling the use-phase activities of universities [8]. We compiled lifecycle impact data in this study, but we did not perform an LCA according to its standardization [19]. In an LCA, there is a defined system boundary including all system components, and all materials, energy, and emission fluxes inside the boundary are compiled, representing the inventory. A process model is developed, assigning the materials certain ways to take. The model is subsequently connected to a database, adding impacts to inventory entries, which are then summarized to overall impacts of a product or service. For use-phase carbon footprinting, we also quantified energy consumption and emissions whose impacts are then quantified including upstream costs reported in databases [8]. For our embodied impacts, we recorded material quantities and then converted these to lifecycle carbon footprints based on factors reported in databases (see the Appendix A), which were subsequently summarized. These databases report LCA data. Concluding, both LCA and embodied impacts quantification consider impacts from raw materials extraction, transportation, materials manufacture, and end-of-life treatment and will thus provide comparable results.

Quantifying the impact of buildings over their entire lifecycle is also imperative, because buildings require large financial investments, while causing long-term CO_2e

emissions in the use phase; in this study, we considered a lifetime of 40–50 years. Not surprisingly, lifecycle impacts of buildings have broadly been investigated scientifically (see, e.g., Sharma et al. [20]), leading to worldwide activities initiated by practitioners (see, e.g., AIA 2021 [21]), authorities (e.g., Gervasio and Dimova [22]), and databases (see, e.g., Trigaux et al. [23]). It is seen as an essential task, for example, to quantify the efficiency of buildings insulating measures with respect to lifecycle CO_2e emissions, considering both the embodied material impact and use-phase energy consumption [24,25]. This is among the measures to make buildings "greener", i.e., enhance their energy saving. The definition of "green", however, (e.g., better insulated) remains broad [26]. Wu et al. [27] compared a selection of 29 green and non-green commercial and residential buildings located in different climate zones in China and reported up to around 30% lifecycle CO_2e emission reduction by green buildings, whereas the use-phases still dominated in terms of the lifecycle CO_2e impact. The authors, however, benchmark the use phase energy consumption with the high carbon footprint of the coal dominated energy generation in China.

Additionally, the relation of embodied versus operational CO_2e emissions changes, of course, once passive energy buildings are modelled (reviewed by Holdschick [28]). First, the lifecycle GWP of such buildings exhibits very low numbers, down to 10 kg $CO_2e/m^2 \bullet y$ as demonstrated for a residential positive energy house in France [29]. Despite a green (renewable) energy supply, still around 30% of the lifecycle CO_2e emissions were attributed to the use phase of the building, mainly caused by wood combustion, electricity, and domestic water consumption [29].

Translating the concept of lifecycle environmental impacts evaluation to universities means considering their impacts enclosed in buildings and infrastructure, in addition to the use phase. Chang et al. [30] have assessed the lifecycle energy consumption of 22 university buildings, revealing that use-phase energy consumption dominates with between 63–95% within the lifecycle. Generally, lifecycle energy analysis (LCEA) has been popular in buildings efficiency evaluation (e.g., Cabeza et al. [31], D'Agostino et al. [32]), while this is changing along with the global transition towards renewable energies.

At present, comprehensive data on the impact of embodied carbon at university buildings are missing. In individual cases, only CO_2 impacts due to annual construction activities on campuses are taken into account (e.g., King's College [33]). This situation may be comparable with assessing the emissions of an electric car while neglecting the battery, the glider, and the drivetrain production, which would no longer be accepted in science and politics [34]. As shown in Figure 1, the complete CF of a university consists of three parts. So far, university carbon footprinting comprises the use-phase elements A and B only (Figure 1). However, there are deviations in the literature even when reporting these use-phase impacts. For instance, some reports quantify mobility impacts based on direct fuel consumption only (e.g., Li et al. [35]); others consider impacts of the fuel provision chain and report impacts from LCA modelling (e.g., KU [36]). To depict a complete comprehension and comparison, we generally recommend including upstream costs [8].

The third element, the embodied carbon of construction and infrastructure of buildings (part C in Figure 1), has not been reported in addition to use phase elements A and B (Figure 1) so far. Accordingly, the size of this wedge in comparison to the total impact (A + B + C in Figure 1) is unknown so far at university campuses. Lifecycle impacts of single buildings (B + C in Figure 1), however, have intensively been studied outside universities, also called full lifecycle impacts [23].

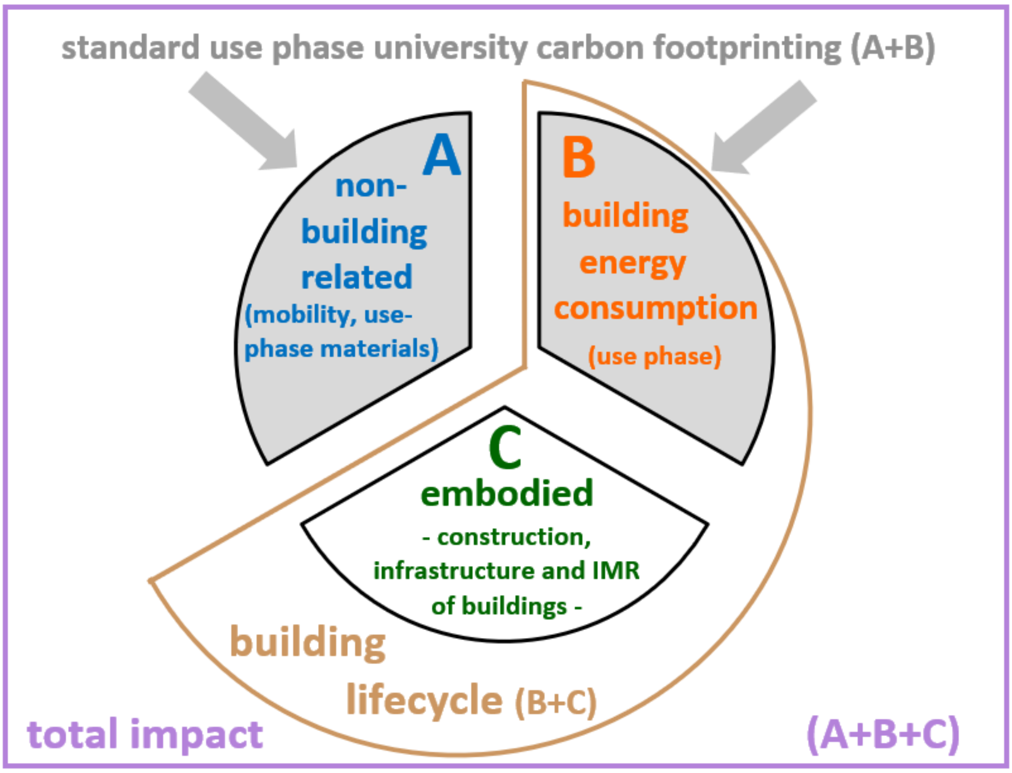

Figure 1. Composition of elements that make up the overall carbon footprint of a university. IMR = inspection, maintenance, repair.

The part of embodied impacts (C, Figure 1) includes all impacts caused by building materials, all technology permanently installed in the buildings (power lines, air condition) or needed to guarantee the functioning of the buildings (lamps, district heating system), and the onsite construction impact. Embodied impacts (C) include IMR (inspection, maintenance, repair), where useful (see Table A1). A rainwater collection unit at Umwelt-Campus Birkenfeld (UCB) represents a borderline case, because it could be added to part C, but we grouped it in part A, because it delivers water which belongs to the use phase consumption materials of part A (Figure 1; for more details, see Helmers et al. [8]). Part A, finally, collects impacts that are not directly caused by the buildings, but by the institution operating in the buildings. This, however, interacts with the infrastructure available in part C (e.g., infrastructure allowing to charge electric vehicles, see below).

Some universities were identified that are successfully minimizing their use phase emissions by opting for renewable energy (specified in Helmers et al. [8]). In parallel, the production of renewable energy is being boosted in, e.g., Europe [37]. However, this is not yet a globally uniform development. Today, already 60% of Chinese electricity is generated by coal-fired power plants [38]. In the existing globalized economy, at the same time, China has the highest global manufacturing output, with 28.7% in 2019 [39]. Consequently, goods produced in China are often connected to high CO_2 emissions and are consumed across the globe. Particularly, high-CF construction materials produced in China are utilized on construction sites worldwide. Therefore, institutions such as universities must, in the future, take into account the CO_2 emissions associated with the construction materials in their buildings.

2. Materials, Methods, and Purpose

2.1. General Purpose

This investigation is the first campus-wide quantification of embodied CF at universities. The main purpose is to evaluate the relevance of embodied (Part C, Figure 1) impacts relative to total institutional emissions (A + B + C, Figure 1): will it be essential to consider embodied impacts in the future when it comes to university CFs, or may they be (further) neglected? The two campuses analysed here, Umwelt-Campus Birkenfeld and Nanyang Technological University (NTU), could also reveal possible implications of different campus sizes, different climate zones, and the availability of green energy. The Umwelt-Campus Birkenfeld is a particular interesting case in point, representing a campus environment consisting of well-insulated new buildings, renewable energy provision both for electricity and heating, and operating a long-distance heating system with so far unknown embodied impacts.

2.2. Modelling Approaches

Architectural drawings were available for the majority of the academic buildings at Umwelt-Campus Birkenfeld. This is not the case for the NTU campus, for which we based the material balancing on measurements taken from the outside and inside the buildings. The enormous complexity of the NTU campus with a population of 40,750 students and staff prevents a precise manual coverage of building materials. As a result, we had to utilize mostly standardized material concentrations for the NTU campus, whereas we had to rely less on those for the UCB campus (see below).

Overall, we applied local emission factors, if available, for modelling the embodied impacts. The German national building materials database "Oekobaudat" [40] is offering CO_2 emissions factors for almost all materials we quantified. This database specifies 50 years as the national building lifecycle period. On the contrary, the typical lifetime for Singapore is 40 years [30]. There is no specific building materials database for Singapore. However, we located some Singapore-specific data, and we also applied global and Asia/China-specific impacts (e.g., specific transportation impacts for Singapore); we refer to Appendix A for details.

We did not consider separate building demolition impacts for the following reasons. First, university buildings may not be removed after having reached the end of their lifetime but may be renovated or repurposed. For example, UCB mainly consists of converted buildings originating from the 1950s. Second, we considered general on-site construction impacts based on national construction industry emissions. These data do not allow us to distinguish between emissions during the construction and the demolition of buildings. Accordingly, parts of the demolition impacts are included in the on-site construction impact. Additionally, as much as possible, we considered EOL (end of life) impacts reported by the databases when compiling material CO_2e factors (see the Appendix A).

We did not consider materials in foundation structures, because they are not included in the available architectural layout maps. Parts of the infrastructure impacts are, however, considered already within the use phase, because upstream effects were integrated into use-phase CO_2e emissions wherever possible. For example, the construction impact of a rainwater collection unit at UCB has been integrated in the freshwater consumption impact (see Helmers et al. [8]).

Concrete, bricks, plasterboard, steel, lamps, floor tiles, glass, and aluminium were quantified at both campuses, whereas the district heating system, wood, paint, insulation, and roof tiles were quantified at UCB only (Tables 1 and 2). Their building structures are very different, although both campuses are relatively young (Table 1). Due to the sheer size of the NTU campus (Table 1, Figure 2), we only analysed 22 buildings and extrapolated the results based on the gross floor area (GFA).

Table 1. General information on the two campuses (year of analysis: 2017). For further details, see Helmers et al. (2021) and [8]. GFA = Gross floor area.

Umwelt-Campus Birkenfeld (UCB), Germany	Nanyang Technological University (NTU), Singapore
2450 students, 281 staff, GFA 24,268 m^2. One of four campuses of Trier University of Applied Sciences, Rhineland-Palatinate, Germany	31,827 students, 8923 staff, GFA 1,382,388 m^2. Main technological University of Singapore
Campus founded in 1998, based on a former military hospital. Between 1996 and now, the former hospital buildings from the 1950s have been converted to academic buildings with labs, offices, and classrooms (marked in orange in Figure 1). In this way, existing walls and windows have been kept, but the interior and building infrastructure have been replaced. Special purpose buildings and student houses have been newly built and added to the campus. Overall, 20 of 26 buildings are built in classic local brick construction with wooden, gabled roofs, and covered by red tiles; 5 buildings have walls made of glass and steel (displayed in light and dark blue in Figure 2), while 3 buildings are based on a concrete construction. The campus has a rural location, is 100% provided by renewable energy, and marketed as Zero emission campus [41].	Founded in 1955, renamed in 1991. NTU campus consists of academic, residential, and commercial buildings. Most building structures are made of concrete, with the exception of the School of Art, Design and Media, with mainly glass walls, and also the Wave Sports Hall. Residential buildings have constructions made of concrete and bricks. In 2017, NTU produced 3% of its electricity consumed by means of photovoltaic installations.

Figure 2. Maps of the two campuses. Top: Umwelt-Campus Birkenfeld (UCB), Germany. Below: Nanyang Technological University (NTU), Singapore. NTU map by courtesy of Fraunhofer Singapore; adapted, the colour markings were added. Yellow: student housing; orange/brown: academic mixed use (lecture rooms, offices, labs), red: administration, blue: dedicated university service buildings (library, open space labs, auditorium), green: sports, purple: conference centre, grey: external companies (not considered at both campuses). GB = glass building; lab = large-capacity labs with walls made of glass and steel (UCB, top).

2.3. The Modelling Strategy

Embodied impacts of buildings are ideally quantified by registering the building materials and components ordered for or delivered to a construction site [42]. We had to compile the building materials, however, many years after completing the building phase. As a consequence, materials can only be quantified by inspecting the existing buildings from the outside and inside, and, as far as available, based on architectural layout maps (Table 2). As a result, it is impossible to measure lengths and diameters of installations hidden behind walls, for example, tubings. We have, therefore, quantified impacts of such installations (e.g., air condition, power lines) based on data in the literature (see Table 2 and the Appendix A). We did not consider waterpipe installations (tap and wastewater), because the material selection behind the walls is unknown. However, the choice of materials can significantly influence the carbon footprint of these installations [43]. The construction components of the water supply and sewage made up 3.8% of the total embodied impacts in a Finnish residential development project [42].

From our literature research, it became clear that different and sometimes very few materials and impacts have been quantified for assessing the embodied impacts of buildings, ranging from only bricks, concrete, wood, plus the heating system [44] to up to 20 different materials covered by Zhang and Zheng [45]. Mostly, only a handful materials make up the complete inventory being modelled so far (reviewed by Cabeza et al. [31]). In our analysis, we include material impacts from aluminium, concrete, bricks, steel, insulation, glass, tiles, wood, plasterboard, and paint; this inventory is aligned with the approach that is followed in the scientific literature (e.g., Wang et al. [46]). In addition to the bulk materials, we considered impacts from installations such as air conditioning, power lines, lamps, and the district heating system at UCB campus.

In addition, we included general on-site construction impacts, often neglected in the literature. Pacheco-Torres et al. [47] reported 359 kg CO_2e/m^2 for on-site construction impacts, considering emissions from 9 different building work units. By contrast, Pöyry et al. [48] indicated 470 kg CO_2e/m^2 for on-site construction impacts of single buildings. As an alternative approach, we divided the total national CO_2e emissions of the building industry by the country-wide GFA constructed in the particular year. This resulted in very similar numbers, compared to the above two sources, both for Germany (312 kg CO_2e/m^2) and Singapore (421 kg CO_2e/m^2), respectively (for details, see the Appendix A). When divided by 50 years of building lifetime for Germany, or by 40 years in case of Singapore, respectively, this results in 6.2–10.5 kg $CO_2e/m^2 \bullet y$.

2.4. Analysis of UCB Campus

The walls of the converted buildings (buildings 12–27 and 30, Figure 2), constructed in the typical local bakestone design, were kept during renovation. Additionally, the windows remained, and they received new glass. These structures already completed one full lifecycle of 50 years, so their materials have not been included into the embodied building impacts compilation. The converted houses, however, received many new walls made of bricks, concrete, or plasterboard inside, which were specified in architecture drawings, meaning the materials were easily quantified. Insulation was newly added to the converted buildings from the outside; therefore, we considered it as well (Table 2).

Most student houses have been added to the campus after 1998 in the same brick stone style. They make up 9981 m^2, which is 41% of the total GFA (Figure 2). The classic brick houses have been complemented by buildings consisting of glassy walls, stabilized by iron bindings and columns, establishing a "house in a house" architecture. Such open structures can be easily surveyed and quantified for their materials. Only three buildings are made in modern standard reinforced concrete construction (Figure 2, blue colour). We assessed their materials based on architecture drawings. Most buildings of UCB are connected by a continuous closed, long vestibule, the materials of which were also quantified and assigned to the buildings according to their share of the total area (Figure 2).

2.5. Analysis of NTU Campus

The NTU campus (Figure 2) mostly consists of modern reinforced concrete buildings at the time of analysis (2017) (see Table 1). Of course, it is impossible to evaluate such a large campus with 57× the GFA of UCB (Table 1). Accordingly, the NTU campus has been largely analysed based on standardized material distribution as per m^2 of GFA (Table 2). During this analysis, the NTU campus was divided into three areas: the first area contained 21 building complexes and covered 407,864 m^2 of GFA on the academic campus; we analysed each of those complexes individually for the distribution of concrete, steel, glass, plasterboard, and aluminium (Table 2) by determining the specifications of the buildings. We then extrapolated those findings to the remaining 478,489 m^2 of the academic campus (Table 2). We evaluated another third of the campus, the housing area (496,035 m^2), by applying standardized material concentrations, as they have been published for housing areas in Singapore (Table 2).

We calculated the number of floor tiles from standardized data (Table 2). We counted the number of lamps in a major academic area of the campus, and we next extrapolated this number to the rest of the campus (see Appendix A).

Table 2. Quantification methods for the respective embodied impacts at the two campuses. For the CO_2e factors applied and for more details, please see the Appendix A. NTU = Nanyang Technological University Singapore. UCB = Umwelt-Campus Birkenfeld.

<table>
<tr><th>Embodied Impact</th><th>Lifetime Calculated for UCB/NTU (Years)</th><th>UCB (Umwelt-Campus Birkenfeld), Germany</th><th>NTU (Nanyang Technological University), Singapore</th></tr>
<tr><td>on-site construction impact</td><td>50/40</td><td colspan="2">Calculated per m² GFA from national building activities and emissions of the building industry</td></tr>
<tr><td>air conditioning system</td><td>50/40</td><td colspan="2" rowspan="2">Standardised technical system impacts taken from literature and applied as per GFA. Individual area air conditioned per building considered</td></tr>
<tr><td>power lines</td><td>50/40</td></tr>
<tr><td>district heating system</td><td>50/-</td><td>Lengths and diameters of the tubing system taken from technical campus layout design maps</td><td>No heating, because of tropical location</td></tr>
<tr><td>concrete</td><td>50/40</td><td rowspan="5">Quantified based on architect's drawings available for the academic buildings (8 cm outside isolation, 1 building isolated with coconut fibre, 8 buildings isolated with mineral wool, 12 with polystyrene). Extrapolated to further buildings based on their structural information.</td><td>Academic buildings: calculation based on a CUI (Concrete Usage Index) of 0.45; total concrete volume = CUI × constructed floor area. Residential housing area: calculation based on Arora et al. [49] with a CUI of 0.5.</td></tr>
<tr><td>bricks</td><td>50/40</td><td>53 kg/m² [50]</td></tr>
<tr><td>insulation</td><td>50/40</td><td>N/A</td></tr>
<tr><td>roof tiles</td><td>50/-</td><td>N/A</td></tr>
<tr><td>plasterboard</td><td>50/40</td><td>12.5 kg/m² [51]</td></tr>
<tr><td>steel</td><td>50/40</td><td>4.8 mass-% from concrete, in additional lengths/thickness of steel girders measured in the glassy buildings, re-checked in architect's drawings</td><td>110 kg of steel in 1 m³ of concrete [30]</td></tr>
<tr><td>lamps</td><td>10/10</td><td>measured for publicly accessible areas of all buildings, impact/GFA calculated, extrapolated</td><td>Lamps quantified in an area of 29,579 m² of GFA at the academic campus, and extrapolated</td></tr>
<tr><td>floor tiles</td><td>50/40</td><td colspan="2">Standardized Oekobaudat [40] data taken</td></tr>
<tr><td>glass</td><td>40/40</td><td>Numbers and sizes of windows measured throughout the campus</td><td>Window are based on window to wall ratio of 0.25 [52]
Wall weight is 25.5% of total concrete weight. [53]</td></tr>
<tr><td>wood</td><td>50/-</td><td>Typical amount as per m² in a roof construction considered. Wooden doors inside the buildings measured and counted.</td><td>N/A</td></tr>
<tr><td>paint</td><td>50/-</td><td>Surface m² of building walls quantified, standardized application of paint considered</td><td>N/A</td></tr>
<tr><td>aluminium</td><td>20/40</td><td>Al considered as a material for lighting housings</td><td>9.72 kg of Al per m² [50] and for windows frames [30]</td></tr>
</table>

3. Results and Discussion

3.1. Single Impacts

The on-site construction impact represents the biggest single embodied carbon emission source at both campuses (Figure 3). Pöyry et al. [48] came to the conclusion that on-site construction impacts contribute to 9% of all embodied GHG emissions, whereas we instead arrived at 45% for UCB and 40% for the NTU campus (Figure 3). We attribute this deviation to the fact our embodied impacts compilation is not complete. For example, we were not able to consider foundation structure materials. Pacheco-Torres et al. [47] reported 39%

CO_2e emissions caused by buildings' foundation construction alone, relative to all on-site construction impacts.

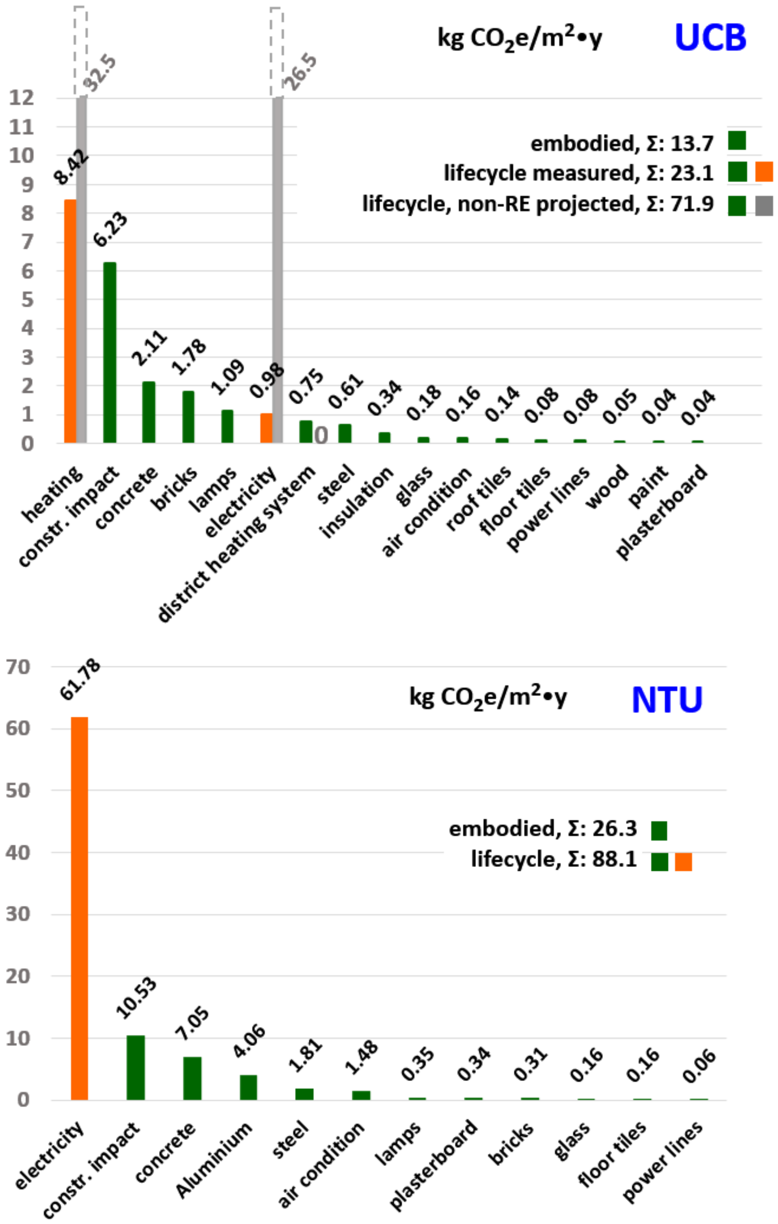

Figure 3. Overview of averaged yearly building-related impacts, contrasting embodied (green) and use phase impacts (orange), and comprising parts B + C impacts (Figure 1). Top: Umwelt-Campus Birkenfeld (UCB, Germany), bottom: Nanyang Technological University (NTU) Singapore. UCB is fully supplied by renewably energy (RE) sources, which is contrasted to a projected non-RE case based on standard 2017 German electricity mix and heating based on natural gas (upper graph, grey columns). For the projected non-RE case, the district heating system was removed (UCB).

At both campuses, GHG emissions from reinforced concrete walls represent the second largest share of embodied impacts with 2.1–7.1 kg CO_2e/m^2•y (Figure 3), or 8–9% over building lifecycle (Figure 4), respectively. All steel used at NTU and part of the steel at UCB (0.6–1.8 kg CO_2e/m^2•y) comes on top of the impact caused by reinforced concrete constructions. Various literature sources identified concrete as adding the highest single embodied CF within the lifecycle of a building (e.g., Gebler et al. [54]: in an automobile factory; Huang et al. [55]: among university dormitories in China, Mahler et al. [56]: Housing concepts in Germany). Decarbonizing the cement industry [57,58] and largely replacing cement by wood in buildings [59] is seen as one of the most important future tasks.

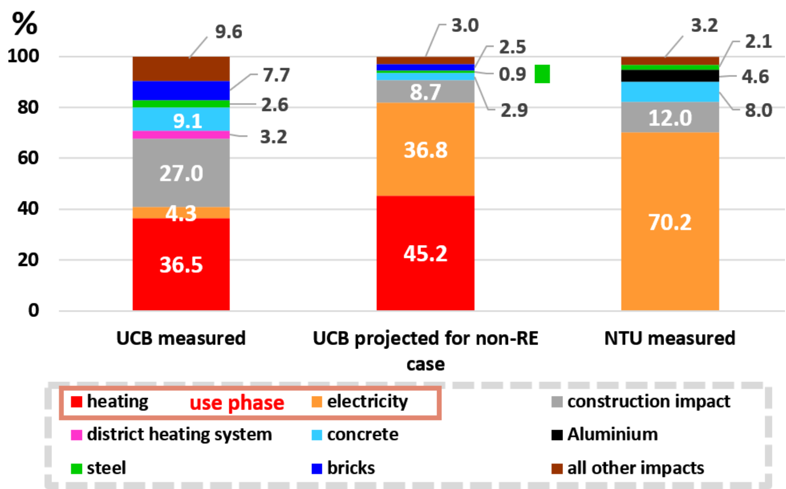

Figure 4. Percentage-wise contributions of yearly building lifecycle impacts from Umwelt-Campus Birkenfeld (UCB, Germany) and Nanyang Technological University (NTU, Singapore), comprising parts B + C impacts (Figure 1). Measured UCB impacts contrasted to a projected non-RE (renewable energy) case based on standard 2017 German electricity mix and heating with natural gas (middle column). Absolute values shown in Figure 3.

At UCB, bricks contain an impact of 1.8 kg $CO_2e/m^2 \bullet y$, which is almost as high as that of concrete, while bricks add only 0.3 kg $CO_2e/m^2 \bullet y$ to the embodied impact of NTU campus (Figure 3). At UCB, most new buildings are brick constructions, different from NTU. Production of bricks has carbon factors similar to those of concrete (Table A1).

Furthermore, light installations generated a relevant carbon impact of 0.4–1.1 kg $CO_2e/m^2 \bullet y$ at both campuses (Figure 3). This infrastructure requires much maintenance: light tubes needed full replacement within 10 years, thus not reaching the lifetime manufacturers guarantee. Additionally, within the first 20 years of building lifetime, many fluorescent tube units have been completely replaced by LED systems at UCB.

Air condition infrastructure has a medium impact of 0.2–1.5 kg $CO_2e/m^2 \bullet y$. As expected, the tropical NTU campus has a much higher impact compared to UCB (Figure 2) due to cooled air provision: all academic and 59% of the housing area is air conditioned at NTU. By contrast, only 11% of UCB academic buildings (lecture halls, server rooms, special purpose labs) and none of the student houses are operating air conditioning.

All other single impacts that we quantified, i.e., plasterboard, paint, wood, powerlines, floor, and roof tiles, are causing embodied CO_2e emissions below 0.4 kg CO_2e/m^2 (Figure 3).

3.2. Campus-Specific Impacts

The district heating system is installed at UCB specifically for the needs of the university, and its CO_2e construction impact needs to be evaluated with respect to its possible CO_2e savings. Therefore, as a benchmark, we also consider an alternative UCB campus that bases its heating system on natural gas, which is the standard heating source in Germany. This would increase the CO_2e emissions due to heating from 8.4 to 32.5 kg CO_2e/m^2 every year (Figure 3). Taking that into account, the construction impact of the district heating system (37.5 kg CO_2e/m^2) was paid back via use-phase CO_2e savings after two years.

We quantified the insulation at UCB only and obtained a relatively small impact of 0.34 kg $CO_2e/m^2 \bullet y$ (Figure 3). Most UCB buildings only have 8 cm of exterior insulation, which was common during the time of converting the buildings, while today, up to twice this isolation layer thickness is used [60]. The degree of insulation in the NTU buildings is much lower than at the UCB; therefore, we neglected it in our calculations.

Aluminium is another major embodied impact at the NTU campus, whereas this material is far less used at UCB. With 4.1 kg CO_2e/m^2•y, aluminium adds 4.6% to building lifecycle impacts at NTU, or 15.4% to the total embodied impacts (Figures 3 and 4). Aluminium is not viewed favourably as alternative future building material because of its very high CO_2 factor (the highest in Table A1) and weak thermal performance [61,62]. At the NTU campus, aluminium is being used as a façade material and for windows frames [30].

3.3. Building GWP Performance of the Two Campuses

Total embodied building impacts vary drastically in the scientific literature due to the reasons reported in the introduction. The most complete overview has been provided by Trigaux et al. [23], evaluating 257 data points. From this overview, the authors derived embodied GWP benchmark values between 1–17 kg CO_2e/m^2•y, with a median at 7 kg CO_2e/m^2•y [23]. Trigaux et al. also presented total lifecycle reference values in the range of 7–64 (median: 25) kg CO_2e/m^2•y [23]. The NTU campus with its embodied impacts of 26.3 kg CO_2e/m^2•y and total lifecycle impacts of 88.1 kg CO_2e/m^2•y seems to be placed above these benchmarks, whereas UCB's embodied CF is placed within the expected magnitude. König and De Cristofaro [44] reported on average 8.5 kg CO_2e/m^2•y for residential buildings in Germany, compiled from bricks, concrete, wood, and the heating system only. This correlates with the embodied 13.7 kg CO_2e/m^2•y we found for the German UCB campus (Figure 3), given the 1.4 times higher impact of non-residential over residential buildings (calculated from Trigaux et al. [23]). On the other hand, UCB represents a campus at which half of the buildings have been converted from original buildings from the 1950s, keeping walls and windows. If these walls had been newly installed composed of reinforced concrete, it would have added another 2.31 kg CO_2e/m^2•y to the embodied impacts of the UCB (modelling based on the volumes of existing stone walls). Accordingly, roughly half of the impacts caused by the construction of walls has been saved by converting existing houses at UCB.

3.4. Renewable Energy Provision as a "Game Changer" at Umwelt-Campus Birkenfeld (UCB)

The 100% renewable energy supply to UCB creates a particular situation. At this campus, most building-related lifecycle impacts are embodied impacts; the CO_2e emissions due to heating and electricity consumption amount to 40.8% of the building lifecycle impacts only (Figure 4). Accordingly, neglecting embodied building impacts could lead to a fundamentally incorrect evaluation of a campus with access to renewable energy. To further illustrate this fact, we modelled a potential non-RE supply for UCB. A conventional heating would be based on natural gas emitting 251 g CO_2e/kWh including upstream impacts [63], whereas conventional electricity purchase would deliver an emission factor of 486 g CO_2/kWh (German electricity mix in 2017, Icha [64]). Together, this would result in a heating impact of 32.5 kg CO_2e/m^2•y, and another 26.5 kg CO_2e/m^2•y due to electricity consumption, respectively (Figure 3), which, in total, would cause 6.3× more CO_2e emissions when compared to the actual 100% RE case at UCB. Despite the sophisticated energy-saving building technology installed [41], this non-RE consumption would have elevated UCB's total building lifecycle impacts up to 71.9 kg CO_2e/m^2•y (Figure 3). This is just 18% less compared to the lifecycle impacts of NTU (Figure 3), the latter operating a much bigger campus located in the tropics and a more complex infrastructure with, for example, a swimming and sports arena. This similarity in CF of the two very different campuses based on a comparable energy supply might come as a surprise. The electricity grid factor in Singapore was similar to the one in Germany in the year 2017, i.e., 420 g CO_2/kWh [65]. In conclusion, the access to renewable energy is the most important factor to save CO_2e emissions.

3.5. Adding Other Use Phase Impacts

As the next step, we add use-phase impacts that are not directly caused by the buildings themselves but by the activities inside in the buildings. There are small additional consumption impacts of the order 0.9–2.5 kg CO_2e/ m^2•y (office supplies, chemicals, and water consumption, Figure 5). The biggest additional impacts (for UCB, even the biggest single impact), however, are related to mobility, and within mobility, mainly from student commuting [8]. It is crucial to include student commuting in university carbon footprinting, not only because of its magnitude (up to 90% of all impacts), but because universities can easily reduce such impacts, as has been demonstrated during the COVID-19 pandemic. Indeed, teaching and even examinations can, at least partially, be conducted via online tools. For example, the carbon footprint of the University of Bournemouth in the UK during the COVID-19 lockdown decreased by 29% due to switching to online-teaching, mainly caused by mobility emission savings [66]. Improving mobility management, or avoiding redundant mobility, may become among the most important measures to reduce university CFs in the future, particularly by offering online lecturing.

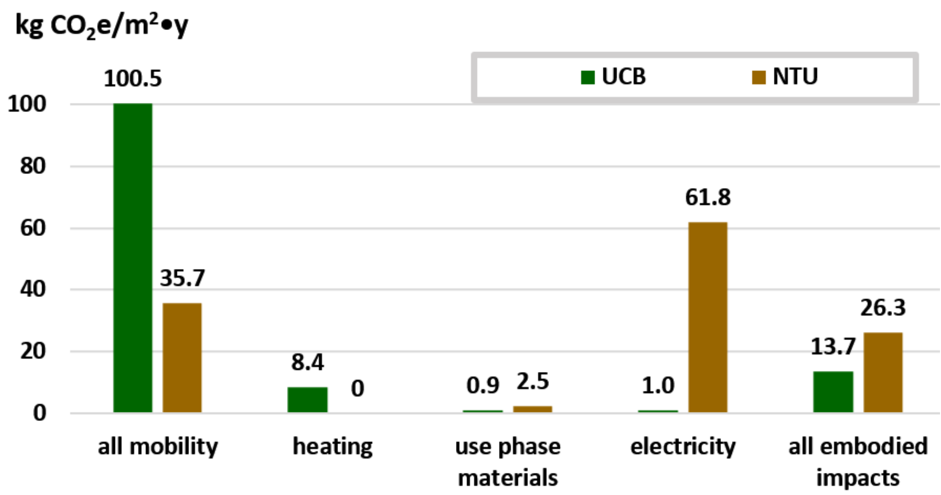

Figure 5. Supplementing yearly building-related impacts (parts B + C, Figure 1) with further use-phase impacts (mobility, use-phase materials, parts A in Figure 1) at the campuses of UCB (Umwelt-Campus Birkenfeld) and NTU (Nanyang Technological University).

There is another link connecting use-phase mobility impacts with building impacts: Universities can reduce commuting emissions by offering charging infrastructure for electric cars and bicycles. For instance, UCB today operates solar carports connected to charging stations (Figure 2), which were added after 2017, the base year of this investigation. In this way, institutions can encourage their staff to switch from a combustion engine to electric cars, thereby reducing the CO_2e emission per passenger km by up to 2/3 [67]. Moreover, universities can operate infrastructure (e.g., protected storerooms with electrical plugs) to motivate staff and students to travel by electric bicycle, again saving emissions. Such infrastructure would be considered among the embodied impacts, while reducing the campus use-phase emissions.

The particular high-mobility impact of UCB is caused by the very rural location of the campus, whereas many universities are connected to big cities partly offering excellent public transportation services [8]. Other local factors can also heavily influence the CF of a campus. In Singapore, for example, up to 56% of energy consumed by buildings is due to air conditioning activity [68]. Improved technology alone could save 20% of this energy [68].

When all institutional impacts at the two universities quantified in this project (see Figure 5) are summarized, the two different universities end up having similar impacts: 124.5 kg CO_2e/m^2•y at UCB, and 126.3 kg CO_2e/m^2•y at NTU, respectively (Figure 6).

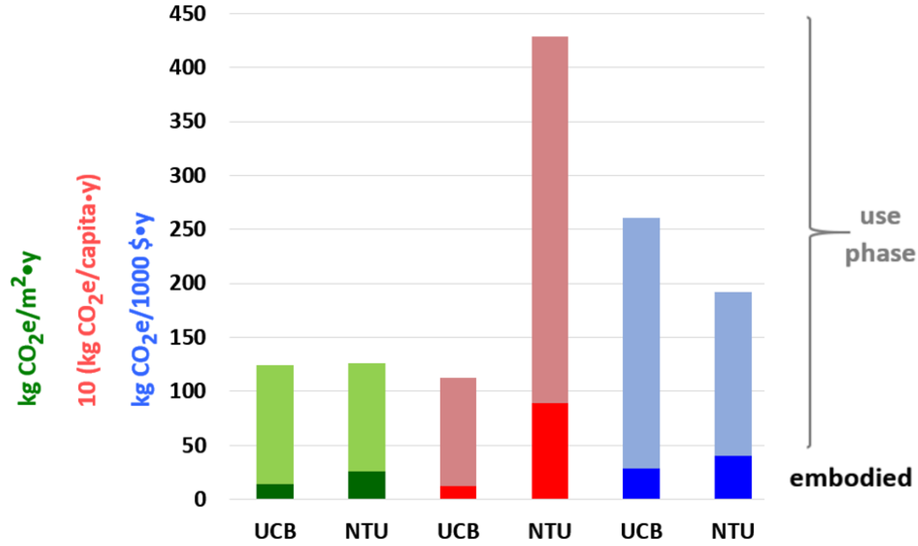

Figure 6. Complete university CF results per year related to constructed area (green), per capita (red), and expenditures (blue), combining use phase impacts (light colours, taken from Helmers et al. 2021, equivalent to parts A + B in Figure 1) and embodied impacts (dark colours, this paper; part C in Figure 1). CF = carbon footprint. UCB = Umwelt-Campus Birkenfeld. NTU = Nanyang Technological University. Data in terms of per kg $CO_2e/1000USD$ related to expenditures were corrected for purchasing power parity (PPP); for details, see Helmers et al. [8].

At last, we added the embodied impacts to the other two CF performance factors, by applying the same emission budget (embodied vs. all other impacts) each to university population and financial expenses (Figure 6). It turns out that among the three carbon performance parameters, embodied impacts make up 11.0% at UCB and 20.8% at NTU, respectively, from the total impacts. Thus, embodied impacts should not be neglected.

In order to aggregate the three university CF performance factors (Figure 6), we additionally introduced a normalized CF performance index [8]. The best CF value in each of the three categories is set to 1.0, and the factors are calculated relative to the best CF value [8]. Applying this approach to the results shown in Figure 6 (embodied plus use-phase impacts) results in an overall normalized CF performance of 3.36 for UCB and 5.84 for NTU, respectively. This is relatively close, as the normalized CF performances, based on use phase impacts only, covering 20 universities worldwide range from 3.53 to 21.44 [8].

3.6. Limitations of This Study

- We contrasted embodied building lifecycle impacts of NTU and UCB with the worldwide building benchmarks collected by Trigaux et al. [23], placing the large NTU campus slightly above the norm. However, such building impact benchmarks may be overinterpreted due to the substantial variabilities in the data across the globe. This is illustrated by the elevated mobility impact found at UCB, which compensates the higher embodied buildings impact of NTU in the comparison of the two campuses (Figure 6, green columns). Such findings at the two university campuses cannot be generalized because of the possible dominance of local factors.
- We found no fundamental difference in the total impacts of the two campuses (despite per capita), although being located in very different climate zones. Climate effects, however, may play an essential role elsewhere. For example, Uva Wellassa University [69] in Badulla, Sri Lanka, is located in the tropics as NTU, but the mountain site leads to convenient temperatures throughout the year, making air conditioning mostly unnecessary.
- Some bigger countries operate national building and construction materials databases, delivering impact information due to LCA (such as Oekobaudat in Germany, [40]);

some smaller countries (such as Singapore) understandably do not offer such a complete documentation (see Appendix A for details). Consequently, we had to resort to partly international, partly Chinese, and partly German data when modelling the materials at NTU Singapore.
- We took several years to collect the use-phase data and as much embodied data as possible at the two campuses, all related to the year 2017. Since the data are related to a single year, we did not explore temporal variations. Whereas we spent much time in methodology development, modelling strategies in the future should be more standardized and accelerated. In this way, the analysis can be continuously repeated, and consequently, temporal fluctuations can be investigated.
- It turned out to be almost impossible to quantify all individual building specifications on the large campus of NTU. The data compiled from a minority of campus buildings had to be extrapolated. We interpret our results accordingly not as precise measurements, but as benchmarks instead specifying the relevance of the embodied versus use phase impacts.

4. Conclusions

Neglecting embodied CO_2e impacts could jeopardize climate protection, because use-phase impacts could be shifted into the supply chain and infrastructure, where emissions are often invisible for the public and practitioners. The electric car is an excellent example for such an impact shift. While delivering use-phase CO_2 emission reduction, its embodied impacts are higher than those of combustion engine cars; accordingly, both use phase and embodied impacts need to be quantified, compared, and analysed for possible trade-offs [67].

This can be translated to carbon emissions at university campuses. As an example, it could be confirmed here that the CO_2e impact due to installing a long-distance heating system at UCB was compensated by heating CO_2e emission savings after two years only. The example of UCB also confirms the emission benefits when existing structures are renovated instead of being replaced. In particular, keeping windows and walls saved 2.3 kg CO_2e/m^2•y. The necessity to upscale renovation activities is globally acknowledged [70].

This study revealed that once university campuses have switched to 100% RE consumption, embodied CFs need to be considered to correctly assess institutional CO_2e emissions. Embodied impacts at UCB turned out to be larger than energy related emissions of the buildings. Accordingly, today's picture of CFs associated with universities [8] is incomplete, and maybe misdirecting. This is highlighted by the case of the Leuphana University in Lüneburg, Germany, the only university that successfully seems to have reached use-phase zero carbon emissions without buying CO_2 certificates [8]. Leuphana University is reaching use-phase climate neutrality by operating a very complex energy infrastructure, but so far, the related infrastructure provision impacts remain unknown (see Helmers et al. [8] for more details).

Furthermore, this investigation came to a surprising conclusion: two very different university campuses—the small, fully RE based UCB campus located in the climatically temperate Germany and the 57-times larger tropical NTU campus with 15 times the UCB population—turned out to yield relatively similar CFs in terms of per kg CO_2e/m^2•y, when all factors are considered. Without access to 100% renewable energy, the building lifecycle impact of the UCB would look relatively similar to the NTU campus, which only has very limited access to RE.

When it comes to the overall institutional emissions, the performance of a campus depends on local conditions rather than on the climate zone or university size. At UCB, for example, over 90% of the campus CF is due to mobility impacts.

We can conclude from this investigation that universities can reach beneficial CF performances (thus operating at low carbon emissions) everywhere, independent of climate zone and size. However, we also expect that small institutions with simple infrastructure at locations with a stable, moderately warm climate will have a comparably easy way to become climate champions.

As an outlook, we believe that the establishment of a worldwide database and the development of a standardized modelling approach would strongly foster university carbon footprinting, optimisation, and comparability.

Our research generates important lessons for future political measures: universities need additional funding to become climate-neutral; they need to quantify their emissions, develop reduction plans (e.g., Osorio et al. [71]), and acquire options to minimize consumptions and impacts, and essentially exploit RE sources. Universities are not merely a relevant factor when it comes to country-wide CO_2e emissions, because they educate future experts for all societal fields. Therefore, universities are in a unique position to be proactive in reducing emissions to save the planet.

Author Contributions: Conceptualization, methodology, validation, analysis, writing—original draft preparation, E.H.; writing—review and editing, project management, E.H. and J.D.; data resources, E.H., J.D. and C.C.C. All authors have read and agreed to the published version of the manuscript.

Funding: The project received funding from Nanyang Technological University Singapore.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data presented in this study are available in the Appendix A.

Acknowledgments: The project goes back to a research stay of E.H. at NTU in Singapore in 2019 which was subsidized by NTU (courtesy of Associate Vice president Prof. Subodh Mhaisalkar, NTU). Sincere thanks to Christoph Frick (Umwelt-Campus Company GmbH), and to Andreas Doll for providing comprehensive UCB buildings impact and consumption data, maps, and architectural drawings. Carmen Lork kindly collected data about paint consumption at UCB buildings and Kira Cloos kindly quantified material consumption for the long-distance heating system at UCB, lamps numbers, and compiled buildings impacts data. Cordial thanks to Conrad Meier for preparing the UCB map. We also thank three anonymous referees and Prof. Dr. habil. Michael Schlaak for their comments on an earlier version of this manuscript.

Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

CF(s)	Carbon footprint(s)
CO_2e	CO_2-equivalent emissions quantifying a global climate change impact (here: carbon impact)
GFA	Gross floor area
GHG	Greenhouse gases
GWP	global warming potential
kWh	Kilowatt hour
Mt	Metric tons
NTU	Nanyang Technological University
RE	= renewable energy = green energy
UCB	Umwelt-Campus Birkenfeld

Appendix A

CO_{2e} Material & Activity Factor Differentiation & Specification, and Related Data Sources

Appendix A.1 General Remarks and Main Emission Factors

As far as possible, materials were quantified based on architecture drawings. Materials were quantified based on the specific materials weights reported in Table A1). Next, CO_2e factors (Table A1) allowed quantification of the carbon footprint (CF) associated with specific materials.

For Germany, CO_2e cradle-to-cradle factors were taken from the German LCA database oekobaudat.de ([40]; remark: "total" Global warming potentials (GWP) were selected generally). For Singapore, international or Asia-specific factors were taken from ICE (2019) [72]; these data are mostly from cradle-to-gate only. In case Asia-specific or global EOL factors were not available in ICE (2019) [72], material impacts were also taken from German database Oekobaudat [40]; see also Table A3 for specific EOL factors applied for Singapore. For Singapore, transportation impacts are individually calculated applying the factors in Table A2.

Recycling factors were considered when specified in databases. From the database Oekobaudat [40], reporting material impacts for Germany, we included waste processing and standardized transportation impacts.

Table A1. CO_2e factors directory. If not stated otherwise, the specific material weight factors and the CO_2e factors were taken from the same data sources. Replacement and IMR (=Inspection, Maintenance, and Repair), factors adapted to local circumstances documented at the two campuses.

	Materials and Activities	CO_{2e} Factor (kg CO_2e/kg); and Data Source	Specific Material Weight Applied	IMR Considered, Usually 1.1%/year [56]
aluminium	Aluminium, Singapore	14.67 (China), including recycling, including 0.07 for transportation; ICE (2019) [72]	2500 kg/m^3	no
concrete	concrete Germany	0.121 including recycling potential and transportation; Oekobaudat [73]	2400 kg/m^3 (4.8% to be subtracted from volumes measured (this percentage is made of steel))	no
	concrete Singapore	0.166 + 0.024 kg for transport + 0.046 (EOL) = 0.236 in total; ICE (2019) [72]	2400 kg/m^3	no
steel	steel Germany (=4.8 mass-% from con-crete).	steel prod. (including production, waste + recycling) 0.7134 + 60 km steel transport 0.21275 kg CO_2e/1000 kg·km (truck, UK, 2021 [74]) = 0.732; Oekobaudat [75]	7850 kg/m^3	no
	steel (rebar), Singapore	1.2 (including recycling) + 0.12 for transportation; ICE (2019) [72]	7700 kg/m^3	no
		Steel used in Singapore comes from South Korea, China, and Japan		
glass	glass, Germany: triple glazed	1.23 including EOL, transp. + recycling potential; Oekobaudat [76]	30.15 kg/m^2	replacement after 40 years
		Window glass has not been exchanged at UCB for 25 years. However, due to fast advances in window isolation technology, the windows will probably not remain unchanged for 50 years		
	glass, Singapore: double glazed	1.22 due to Oekobaudat.de, but without transportation. 0.03 added due to transportation.	30.15 kg/m^2	no
		Oekobaudat.de [40] data taken as well for Singapore, because ICE (2019) [72] database does not include EOL impacts.		
bricks	bricks pumice, Germany	0.097; Oekobaudat [77]	900 kg/m^3	no
	bricks sand-lime, Germany	0.136 (no recycling impact data available; Oekobaudat, [78])	1800 kg/m^3	no
	bricks, Singapore clay	0.213 (no recycling impact data available) + 0.02 transport; ICE (2019) [72]	1800 kg/m^3	no
insulation	insulation polysty rene, Germany	4.18; Oekobaudat [79]	20 kg/m^3 IVH (2015) [80]	no
	insulation coconut fibre, Germany	25.5 [81] + 0.15 container ship transport from Colombia [82]	65 kg/m^3; Manohar et al. [83]	no
	Mineral wool, Germany	0.29; Oekobaudat [84]	155 kg/m^3	no

Table A1. *Cont.*

	Materials and Activities	**CO_{2e} Factor (kg CO_2e/kg); and Data Source**	**Specific Material Weight Applied**	**IMR Considered, Usually 1.1%/year [56]**
plasterboard	plasterboard, Germany	0.179; Oekobaudat [85]	8.47 kg/m^2 for 1 cm of thickness (own measurement)	no
plasterboard	plasterboard Singapore	0.48 including EOL + 0.03 for transport; Gyproc [86]	12.5 kg/m^2	no
wood	wood, roof, Germany	0.67; Oekobaudat [87]	22.5 kg/m^2	no
wood		weight of a wooden roof structure (Germany): Digdach [88]		
wood	wooden doors, UCB, Germany	0.67; Oekobaudat [87]	25.76 kg/m^2	no
PE	high density polyethylene for pipes, Germany	4.17; Oekobaudat [89]	950 kg/m^3	Yes, 1.1% per year
tiles	ceramic floor tiles, Germany	0.71 (incl. maintenance); Oekobaudat [90]	18.65 kg/m^2	maintenance included
tiles	roof tiles, UCB, Germany	0.361; Oekobaudat [91]	45 kg/m^2; Oekobaudat [92]	no
tiles	ceramic floor tiles, Singapore	0.71 (incl. maintenance), + 0.02 for transport; Oekobaudat [90]	18.65 kg/m^2	maintenance included
paint	paint, UCB, Germany	2.11; Oekobaudat [93]	0.17 kg/m^2	Yes, 1.1% per year
Impacts adjusted to the GFA of buildings				
air conditioning	Kiamili et al. [94]: 46 kg CO_2e/m^2 on average; García-Sanz-Calcedo et al. [95] 48.95 kg CO_2e/m^2; the average of both is 47.475 kg CO_2e/m^2 (applied both for Germany & Singapore) over lifetime		UCB Germany: just 2751 m^2 of 24,668 m^2 (GFA) air conditioned, NTU Singapore: all academic indoor GFA air conditioned, NTU housing area: 5–80% of GFA air conditioned, impact individually considered	Yes, 1.1% of lifetime impact per year
lamps	lamps (UCB, Germany); 1.09 kg CO_2e/m^2 GFA (see below)			replacement every 10 years
lamps	lamps (Singapore); 0.35 kg CO_2e/m^2 GFA (see below)			
on-site construction impact	**Germany: 312 kg CO_2e/m^2** Calculation was performed for Germany based on the year 2014. 33,052,000 m^2 of new floor space was added due to construction of new buildings [96]. At the same year, 10.3 million metric tons of CO_2e have been emitted due to direct "emissions from the construction industry/share of building construction", reported by BBSR [97].			N/A
on-site construction impact	**Singapore: 421 kg CO_2e/m^2.** CEIC [98] reports the number of residential units (14,116) completed in 2018. No. of units was multiplied with the average GFA of a residential unit which is reported to be 70 m^2 (due to SCMP [99]) and resulting in the total GFA built in 2018. This number is then related it to the 0.416 Mio Mt CO_2e emitted by Singapore's building industry in 2018 due to NCCS [100].			N/A
district heating system (Germany): materials production impacts, installation impact and IMR considered and adjusted to individual buildings GFA (see below)				Yes (see below)
power lines (Germany + Singapore): Weißenberger [101]: 2.9 m/m^2, Oekobaudat [102]: 0.464 kg CO_2e/m (cable 3-wire, incl. Recycling + transport).				no

Table A2. CO_2 factors for transportation from production sites to NTU campus Singapore (taken from [74]). Mt = metric tons.

Material	Country of Origin	Distances (km)	kg CO_2e/Mt km (Diesel Truck; * = Sea Tanker)
cement (for concrete)	from factory to port	20	0.131
	Japan	5908	0.01896 *
	to local mixing plant	20	0.131
aggregate (for concrete)	from factory to port	20	0.131
	from Indonesia to Singapore	83	0.131
	to local mixing plant	20	0.131
	to construction site	15	0.131
sand (for concrete)	from factory to port	20	0.131
	from Indonesia to Singapore	83	0.131
	to local mixing plant	20	0.131
	to construction site	15	0.131
steel	from factory to port	20	0.131
	South Korea to Singapore	6065	0.01896 *
	to construction site	20	0.131
plasterboard/Tiles/Bricks	from factory to port	20	0.131
	from Malaysia to Singapore	80	0.131
	to local mixing plant	20	0.131
	to construction site	20	0.131
aluminium/Light bulb/Cable	from factory to port	20	0.131
	China to Singapore	3443	0.01896 *
	to construction site	20	0.131
glass	from factory to port	20	0.131
	Vietnam to Singapore	1196	0.01896 *
	to construction site	20	0.131

Table A3. EOL factors applied for Singapore materials (added to impact factors collected in Table A1).

Material	kg CO_2e/kg (Unless Specified)	Source
concrete	0.0046	Oekobaudat [73]
aluminium		Only recovery rate (recycling) considered
steel		−0.79 kg CO_2e/kg considered as for recycling due to ICE (2019) [72]
plasterboard	0.03 kg CO_2e per m^2 at 12.5 kg material/m^2	Gyproc [86]
glass		Oekobaudat [76]
ceramic tiles		Oekobaudat [90]
power lines		Oekobaudat [102]

Appendix A.2 Special Impacts

Appendix A.2.1 Long Distance Heating System at UCB Campus, Germany

There are 4078 m of tubes transporting heated water from a regional combined heat and power plant based on waste wood combustion with 29 MW thermal and 8.5 MW electric capacity [8]. The tubing system contains 10 types of tubes with different width from 3.2 to 20 cm inner diameter. The inner tube is made from iron, surrounded by a high-density (HD) polyethylene (PE) sheath with 3–4.9 mm of thickness. The outer layer is made of 31–43 mm polystyrene for insulation. The whole system comprises 12.55 metric tonnes of HD-PE, 65.16 metric tonnes of iron, and 6.62 metric tonnes of polystyrene. As parts of the system already needed repair within the first 25 years of the campus, 1.1% of the material impact was added as for yearly inspection, maintenance, and repair (IMR). 113 kg CO_2 per meter [43] were added as for pipe laying effort.

Appendix A.2.2 Lighting

Umwelt-Campus Birkenfeld (UCB)

At UCB, there are fluorescent lamps (Philips TLD 58 W), and, since a couple of years, they are replaced by LED lamps (Valuco D 2014, 2 × 14 W). The lengths of these lamps were measured in all accessible building areas and extrapolated, resulting in 490 m of LED tubes and 11,373 m of fluorescent tubes (1 unit = 1 m of length). A literature search led to the lifecycle carbon footprints depicted in Table A4. We averaged the impacts given by Casamayor et al. [103] and Scholand et al. [104] and extrapolated them to a power of 14 W matching the power of the LED tubes as applied at UCB, resulting in an average impact of 16.71 kg CO_2e/LED unit (Table A4). The production impact for a fluorescent lamp, as found in the literature, has been doubled to match the 40,000 h of lifetime given for LED bulbs (Table A4). An activated lamp over 8 h/day in every workday would result in 2000 h/year which would results in 10–20 years in total. We observed higher replacement numbers at the campuses and decided to relate the overall impact to only 10 years (replacement every 10 years).

Because of the higher efficiency, we assigned the 59.5 cm LED tube the same light flux as a 1 m fluorescent tube and paired the 16.71 kg CO_2e/unit (1 m) of LED to the 11.06 kg CO_2e/unit (1 m) of fluorescent tube.

Multiplying 490 m of LED tubes (=490 units) and 11,373 m of fluorescent tubes (1 unit = 1 m of length) with the calculated impacts (Table A4), related to the GFA of UCB campus (24,264 m^2), and diving it by 10 years of working, results in 0.55 kg CO_2e/m^2•y.

We add 3 kg of aluminium for the housing of each of the two tubes (14.67 kg CO_2e/kg, Table A1), which probably will be exchanged every 20 years with new lighting technology, resulting in 5931 housing boxes (3 kg of Al each). With the campus GFA of 24,264 m^2, this results in 0.54 kg CO_2e/m^2•y. The same CO_2e factor for aluminium at the NTU campus is used here, because it is assumed that Chinese products are purchased (Table 1). Altogether a lifecycle impact of 1.09 kg CO_2e/m^2•y is resulting for lighting technology at Umwelt-Campus Birkenfeld.

Nanyang Technological University (NTU)

Different from the UCB campus, the number of lamp units was quantified in an area of the academic campus with 29,579 m^2 of GFA (Table A4). The length of tubes was not considered here. The power output of the four types of lamps found was as well documented and allowed to quantify a manufacturing impact relative to the literature data (Table A4).

We added 3 kg of aluminium for the housing of each of the two tubes in the 554 ceiling units (14.67 kg CO_2e/kg, Table A1). Assuming a lifetime of 20 years, this results in an additional impact 0.02 kg CO_2e/m^2•y.

Based on a lifetime of 10 years for the bulbs, this amounts to an overall average impact of 0.35 kg CO_2/m^2•y (including the aluminium housing material) which was extra-polated to the whole campus.

Table A4. Light bulb lifecycle carbon footprints found in the literature and products used at the two campuses (without use phase).

Type of Lamp	Source/Product (Campus)	Light Flux (lm/W)	Power (W)	Lifetime (h)	kg CO_2e/Unit (Manufacturing + Transport + EOL)	
literature sources						
LED bulb	Casamayor et al. [103]	55	17.2	40,000	18.64→15.2 (14 W)	average: 16.71
LED bulb	Scholand and Dillon [104]	65	12.5	(25,000-) 40,000	16.27→18.2 (14 W)	
fluorescent tube	Welz et al. [105]		58	20,000 h	5.53→11.06 (40,000 h)	
lamps found at Umwelt-Campus (UCB)						
LED tube light	Trilux Valuco D 214 1 unit = 59.5 cm	(58.8)	14	40,000 h	16.71	
fluorescent tube	Philips TLD 58 1 unit = 1 m	90	58	20,000 h	11.06	
lamps found at Nanyang Technological University (NTU)						
type of lamp		**Units** (per 1000 m^2) *		**Power** (W)	kgCO_2e/unit ** (manufacturing + transport + EOL)	
ceiling LED Module		442		47	56.1	
LED		300		10	11.9	
direct LED		87		18	21.5	
fluorescent light Philips TLD		112		30	21.4	

* number rounded from inventory taken from 29,579 m^2. ** recalculated with respect to power to production impact relation specified by Casamayor et al., Scholand and Dillon, and Welz et al. [103–105].

References

1. IPCC. Climate Change 2021—The Physical Science Basis Summary for Policymakers. Working Group I Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. 2021. Available online: https://www.ipcc.ch/report/sixth-assessment-report-working-group-i/ (accessed on 22 September 2021).
2. MCC. That's How Fast the Carbon Clock Is Ticking. Mercator Research Institute on Global Commons and Climate Change. 2021. Available online: https://www.mcc-berlin.net/en/research/co2-budget.html (accessed on 22 September 2021).
3. Lannelongue, L.; Grealey, J.; Bateman, A.; Inouye, M. Ten simple rules to make your computing more environmentally sustainable. *PLoS Comput. Biol.* **2021**, *17*, e1009324. [CrossRef]
4. Buschka, M.; Bischof, J.; Meier-Dotzler, C.; Lang, W. Developing non-residential building stock archetypes for LCI—A German case study of office and administration buildings. *Int. J. Life Cycle Assess.* **2021**, *26*, 1735–1752. [CrossRef]
5. Wolf, S.; Teitge, J.; Mielke, J.; Schütze, F.; Jaeger, C. The European Green Deal—More Than Climate Neutrality. *Intereconomics* **2021**, *56*, 99–107. [CrossRef] [PubMed]
6. Helmers, E.; Ilchmann, F. Sustainability subjects in university education—Development of a comprehensive indicator system and quantitative analysis of degree programs at German Universities. *Eur. J. Sustain. Dev. Res.* **2019**, *3*, em0092. Available online: https://www.ejosdr.com/article/sustainability-subjects-in-university-education-development-of-a-comprehensive-indicator-system-5771 (accessed on 10 February 2022).
7. Filho, W.L.; Sima, M.; Sharifi, A.; Luetz, J.M.; Salvia, A.L.; Mifsud, M.; Olooto, F.M.; Djekic, I.; Anholon, R.; Rampasso, I.; et al. Handling climate change education at universities: An overview. *Environ. Sci. Eur.* **2021**, *33*, 109. [CrossRef]
8. Helmers, E.; Chang, C.C.; Dauwels, J. Carbon footprinting of universities worldwide: Part I—Objective comparison by standardized metrics. *Environ. Sci. Eur.* **2021**, *33*, 30. [CrossRef]
9. Li, Z.; Chen, Z.; Yang, N.; Wei, K.; Ling, Z.; Liu, Q.; Chen, G.; Ye, B.H. Trends in research on the carbon footprint of higher education: A bibliometric analysis (2010–2019). *J. Clean. Prod.* **2021**, *289*, 125642. [CrossRef]
10. UNFCCC. United Nations Framework Convention on Climate Change. More Ambitious Climate Plans Needed Ahead of COP27. 2022. Available online: http://unfccc.int/ (accessed on 9 February 2022).
11. UNEP. Over 1000 Universities and Colleges Make Net-Zero Pledges as New Nature Initiative Is Unveiled. UN Environment Program, Press Release, 28 October 2021. 2021. Available online: https://www.unep.org/news-and-stories/press-release/over-1000-universities-and-colleges-make-net-zero-pledges-new-nature (accessed on 4 March 2022).
12. Juric, Z.; Ljubas, D. Comparative Assessment of Carbon Footprints of Selected Organizations: The Application of the Enhanced Bilan Carbone Model. *Sustainability* **2020**, *12*, 9618. [CrossRef]

13. WRI. Corporate Value Chain (Scope 3) Accounting and Reporting Standard—Supplement to the GHG Protocol Corporate Accounting and Reporting Standard. Report, World Resources Institute. 2011. Available online: https://ghgprotocol.org/sites/default/files/standards/Corporate-Value-Chain-Accounting-Reporing-Standard_041613_2.pdf (accessed on 19 September 2021).
14. WRI. The Greenhouse Gas Protocol a Corporate Accounting and Reporting Standard. Report, World Resources Institute. 2001, p. 68. Available online: http://www.co2-sachverstaendiger.de/pdf/GHG%20Protocol%20a%20corporate%20accounting%20and%20reporting%20standard%20First%20Edition.pdf (accessed on 5 March 2022).
15. DIN ISO. Greenhouse Gases—Part 1: Specification with Guidance at the Organization Level for Quantification and Reporting of Greenhouse Gas Emissions and Removals (ISO 14064-1:2018); German and English version EN ISO 14064-1:2018. 2019. Available online: https://wiki.stuvus.uni-stuttgart.de/download/attachments/105564480/ISO%2014064-1.pdf?version=1&modificationDate=1600421322652&api=v2 (accessed on 19 September 2021).
16. Pandey, D.; Agrawal, M.; Pandey, J.S. Carbon footprint: Current methods of estimation. *Environ. Monit. Assess.* **2011**, *178*, 135–160. [CrossRef]
17. Klöpffer, W.; Grahl, B. *Life Cycle Assessment (LCA)—A Guide to Best Practice*; Wiley-VCH: Weinheim, Germany, 2014; p. 440. ISBN 978-3-527-32986-1.
18. EU. Making Sustainable Production and Consumption a Reality. A Guide for Business and Policy Makers to Life Cycle Thinking and Assessment. Joint Research Center, European Commission. 2010. Available online: https://eplca.jrc.ec.europa.eu/uploads/LCT-Making-sustainable-consumption-and-production-a-reality-A-guide-for-business-and-policy-makers-to-Life-Cycle-Thinking-and-Assessment.pdf (accessed on 23 January 2022).
19. ISO. ISO 14044:2006 Environmental Management—Life Cycle Assessment—Requirements and Guidelines. Available online: https://www.iso.org/standard/38498.html (accessed on 13 December 2019).
20. Sharma, A.; Saxena, A.; Sethi, M.; Shree, V. Varun Life cycle assessment of buildings: A review. *Renew. Sustain. Energy Rev.* **2011**, *15*, 871–875. [CrossRef]
21. AIA. Building Life Cycle Assessment in Practice. An AIA Guide to LCA. The American Institute of Architects. 2021. Available online: https://www.aia.org/resources/7961-building-life-cycle-assessment-in-practice (accessed on 19 September 2021).
22. Gervasio, H.; Dimova, S. *Model for Life Cycle Assessment (LCA) of Buildings*; EU Joint Research Center Report JRC110082, 29123 EN; Publications Office of the European Union: Luxembourg, 2018. [CrossRef]
23. Trigaux, D.; Allacker, K.; Debacker, W. Environmental benchmarks for buildings: A critical literature review. *Int. J. Life Cycle Assess.* **2021**, *26*, 1–21. [CrossRef]
24. Kunič, R. Carbon footprint of thermal insulation materials in building envelopes. *Energy Effic.* **2017**, *10*, 1511–1528. [CrossRef]
25. Kylili, A.; Ilic, M.; Fokaides, P.A. Whole-building Life Cycle Assessment (LCA) of a passive house of the sub-tropical climatic zone. *Resour. Conserv. Recycl.* **2017**, *116*, 169–177. [CrossRef]
26. Zuo, J.; Zhao, Z.Y. Green building research–current status and future agenda: A review. *Renew. Sustain. Energy Rev.* **2014**, *30*, 271–281. [CrossRef]
27. Wu, X.; Peng, B.; Lin, B. A dynamic life cycle carbon emission assessment on green and non-green buildings in China. *Energy Build.* **2017**, *149*, 272–281. [CrossRef]
28. Holdschick, A. Life Cycle Assessment of Sustainable Residential Building Concepts. Master's Thesis, Universität für Bodenkultur Wien, Vienna, Austria, 2015; p. 140. Available online: https://epub.boku.ac.at/obvbokhs/download/pdf/1935743?originalFilename=true (accessed on 19 January 2022).
29. Thiers, S.; Peuportier, B. Energy and environmental assessment of two high energy performance residential buildings. *Build. Environ.* **2012**, *51*, 276–284. [CrossRef]
30. Chang, C.C.; Shi, W.; Mehta, P.; Dauwels, J. Life cycle energy assessment of university buildings in tropical climate. *J. Clean. Prod.* **2019**, *239*, 117930. [CrossRef]
31. Cabeza, L.F.; Rincón, L.; Vilariño, V.; Pérez, G.; Castell, A. Life cycle assessment (LCA) and life cycle energy analysis (LCEA) of buildings and the building sector: A review. *Renew. Sustain. Energy Rev.* **2014**, *29*, 394–416. [CrossRef]
32. D'Agostino, D.; Parker, D.; Melià, P. Environmental and economic implications of energy efficiency in new residential buildings: A multi-criteria selection approach. *Energy Strat. Rev.* **2019**, *26*, 100412. [CrossRef]
33. King's College. King's College London Environmental Sustainability Report. 2020, p. 17. Available online: https://www.kcl.ac.uk/aboutkings/strategy/pdfs--resources/environmentalsustainabilityreport201819.pdf (accessed on 7 March 2022).
34. EEA. Electric Vehicles from Life Cycle and Circular Economy Perspectives. TERM 2018: Transport and Environment Reporting Mechanism (TERM) Report. European Environmental Agency Report No 13/2018. 2018. Available online: https://www.eea.europa.eu/publications/electric-vehicles-from-life-cycle/download (accessed on 11 March 2022).
35. Li, X.; Tan, H.H.; Rackes, A. Carbon footprint analysis of student behaviour for a sustainable university campus in China. *J. Clean. Prod.* **2015**, *106*, 97–108.
36. KU. Sustainability at KU Leuven 2014–2017. 2014. Available online: https://www.kuleuven.be/duurzaamheid/sustainability/doc/sustainability-at-ku-leuven-2014-2017.pdf (accessed on 11 March 2022).
37. EU. A Clean Energy Transition. 2022. Available online: https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal/energy-and-green-deal_en (accessed on 23 January 2022).
38. IEA. China. International Energy Agency. Available online: https://www.iea.org/countries/china#policies (accessed on 23 January 2022).

39. Statista. China Is the World's Manufacturing Superpower. Published 4 May 2021. 2022. Available online: https://www.statista.com/chart/20858/top-10-countries-by-share-of-global-manufacturing-output/ (accessed on 23 January 2022).
40. Oekobaudat. Sustainable Construction Information Portal. 2021. Available online: https://www.oekobaudat.de/en.html (accessed on 16 September 2021).
41. Umwelt-Campus. Environmental Campus—Experience Green Technology. *Brochure.* 2016, p. 16. Available online: https://www.umwelt-campus.de/fileadmin/Umwelt-Campus/Oeffentlichkeitsarbeit/Tech-Broschuere/Broschuere-GrueneTechnologien-am-Campus-ENG-klein-WEB.pdf (accessed on 10 February 2022).
42. Säynäjoki, A.; Heinonen, J.; Junnila, S. Carbon Footprint Assessment of a Residential Development Project. *Int. J. Environ. Sci. Dev.* **2011**, *2*, 116–123. [CrossRef]
43. Chilana, L.; Bhatt, A.H.; Najafi, M.; Sattler, M. Comparison of carbon footprints of steel versus concrete pipelines for water transmission. *J. Air Waste Manag. Assoc.* **2016**, *66*, 518–527. [CrossRef] [PubMed]
44. König, H.; De Cristofaro, M.L. Benchmarks for life cycle costs and life cycle assessment of residential buildings. *Build. Res. Inf.* **2012**, *40*, 558–580. [CrossRef]
45. Zhang, X.; Zheng, R. Reducing building embodied emissions in the design phase: A comparative study on structural alternatives. *J. Clean. Prod.* **2020**, *243*, 118656. [CrossRef]
46. Wang, T.; Seo, S.; Liao, P.-C.; Fang, D. GHG emission reduction performance of state-of-the-art green buildings: Review of two case studies. *Renew. Sustain. Energy Rev.* **2016**, *56*, 484–493. [CrossRef]
47. Pacheco-Torres, R.; Jadraque, E.; Roldán-Fontana, J.; Ordóñez, J. Analysis of CO_2 emissions in the construction phase of single-family detached houses. *Sustain. Cities Soc.* **2014**, *12*, 63–68. [CrossRef]
48. Pöyry, A.; Säynäjoki, A.; Heinonen, J.; Junnonen, J.-M.; Junnila, S. Embodied and Construction Phase Greenhouse Gas Emissions of a Low-energy Residential building. *Procedia Econ. Financ.* **2015**, *21*, 355–365. [CrossRef]
49. Arora, M.; Raspall, F.; Cheah, L.; Silva, A. Residential building material stocks and component-level circularity: The case of Singapore. *J. Clean. Prod.* **2019**, *216*, 239–248. [CrossRef]
50. Wang, J.; Yu, C.; Pan, W. Life cycle energy of high-rise office buildings in Hong Kong. *Energy Build.* **2018**, *167*, 152–164. [CrossRef]
51. Smith, P.S. *Introduction to Structural Mechanics*, 1st ed.; Palgrave McMillan Publ.: New York, NY, USA, 2001; p. 356.
52. BCA. GM NRB: 2015. Green Mark for Non-Residential Buildings NRB Including Hawker Centres, Healthcare Facilities, Laboratory Buildings and Schools. 2020. Available online: https://www.bca.gov.sg/GreenMark/others/GM_NRB2015_Technical_Guide_Requirements.pdf (accessed on 14 September 2021).
53. Liang, S.; Gu, H.; Bergman, R.; Kelley, S. Comparative life-cycle assessment of a mass timber building and concrete alternative. *Wood Fiber Sci.* **2020**, *52*, 217–229. [CrossRef]
54. Gebler, M.; Cerdas, J.F.; Thiede, S.; Herrmann, C. Life cycle assessment of an automotive factory: Identifying challenges for the decarbonization of automotive production—A case study. *J. Clean. Prod.* **2020**, *270*, 122330. [CrossRef]
55. Huang, L.; Liu, Y.; Krigsvoll, G.; Johansen, F. Life cycle assessment and life cycle cost of university dormitories in the southeast China: Case study of the university town of Fuzhou. *J. Clean. Prod.* **2018**, *173*, 151–159. [CrossRef]
56. Mahler, B.; Idler, S.; Nusser, T.; Gantner, J. Energieaufwand für Gebäudekonzepte im Gesamten Lebenszyklus (Energy Expenditure over the Entire Life Cycle of Different Building Types and Energy Concepts for Housing)—Abschlussbericht. Umweltbundesamt, Texte 132/2019. 2019. Available online: https://www.umweltbundesamt.de/sites/default/files/medien/1410/publikationen/2019-10-29_texte_132-2019_energieaufwand-gebaeudekonzepte.pdf (accessed on 16 September 2021).
57. Nele, F.; Erdogmus, G.; Duscha, V. Comparative Analysis of Options and Potential for Emission Abatement in Industry—Summary of Study Comparison and Study Factsheets. CLIMATE CHANGE 19/2018 report, German Environment Agency. Available online: https://www.umweltbundesamt.de/sites/default/files/medien/1410/publikationen/2018-07-16_climate-change_19-2018_ets-7_analyse-minderungspotenzialstudien_fin.pdf (accessed on 10 February 2022).
58. Nilsson, A.; Hans, F.; Legarreta, P.L.; Lui, S.; Röser, F. *Decarbonisation Pathways for the EU Cement Sector—Technology Routes and Potential Ways Forward*; Report; New Climate Institute Cologne: Berlin, Germany, 2020; p. 44. Available online: https://newclimate.org/wp-content/uploads/2020/12/SGCCC-EU-Cement-paper-NewClimate_Nov2020.pdf (accessed on 29 September 2021).
59. EU. Investing in Nearly Zero-Energy Wooden Buildings Helps Combat Climate Change. *Internet Page.* 2021. Available online: https://cordis.europa.eu/article/id/430649-investing-in-nearly-zero-energy-wooden-buildings-helps-combat-climate-change (accessed on 29 September 2021).
60. UBA. Weiterentwicklung des Umweltzeichens Blauer Engel für Wärmedämmverbundsysteme: Kriterien für Dämmstoffe Sowie Biozidfreie Putze und Beschichtungen. UBA Texte 30/2018. 2018; p. 234. Available online: https://www.umweltbundesamt.de/sites/default/files/medien/1410/publikationen/2018-06-01_texte_30-2018_waermedaemmverbundsysteme_korr.pdf (accessed on 26 September 2021).
61. Sinha, A.; Kutnar, A. Carbon Footprint versus Performance of Aluminum, Plastic, and Wood Window Frames from Cradle to Gate. *Buildings* **2012**, *2*, 542–553. [CrossRef]
62. Asdrubali, F.; Roncone, M.; Grazieschi, G. Embodied Energy and Embodied GWP of Windows: A Critical Review. *Energies* **2021**, *14*, 3788. [CrossRef]
63. UBA; Bettgenhäuser, K.; Boermans, T. Umweltwirkung von Heizungssystemen in Deutschland. Climate Change Report 02/2011, German Environment Agency. 2011. Available online: https://www.umweltbundesamt.de/sites/default/files/medien/461/publikationen/4070.pdf (accessed on 10 February 2022).

64. Icha, P. Entwicklung der Spezifischen Kohlendioxid-Emissionen des Deutschen Strommix in den Jahren 1990–2018. Umweltbundesamt, Report 10/2019. 2019; p. 29. Available online: https://www.umweltbundesamt.de/sites/default/files/medien/1410/publikationen/2020-04-01_climate-change_13-2020_strommix_2020_fin.pdf (accessed on 30 September 2021).
65. EMA. Energy Transformation, Chapter 02. Energy Market Authority, Singapore Government. 2019. Available online: https://www.ema.gov.sg/singapore-energy-statistics/Ch02/index2 (accessed on 2 October 2021).
66. Filimonau, V.; Archer, D.; Bellamy, L.; Smith, N.; Wintrip, R. The carbon footprint of a UK University during the COVID-19 lockdown. *Sci. Total Environ.* **2021**, *756*, 143964. [CrossRef] [PubMed]
67. Helmers, E.; Dietz, J.; Weiss, M. Sensitivity analysis in the life-cycle assessment of electric vs. combustion engine cars under approximate real-world conditions. *Sustainability* **2020**, *12*, 1241. [CrossRef]
68. NTU. A.I. Technology That Cuts Energy Use by more than 20%, Wins Top Prize at Inaugural Innovation Challenge by ENGIE, NTU Singapore and JurongHealth Campus. Nanyang Technological University, Published 2 July 2020. Available online: https://www.ntu.edu.sg/mae/news-events/news/detail/a.i.-technology-that-cuts-energy-use-by-more-than-20-wins-top-prize-at-inaugural-innovation-challenge-by-engie-ntu-singapore-and-juronghealth-campus (accessed on 22 January 2021).
69. UWU. Uva Welllassa University. 2022. Available online: http://www.uwu.ac.lk/ (accessed on 22 January 2022).
70. UN. 2020 Global Status Report for Buildings and Construction. Towards a Zero-Emissions, Efficient and Resilient Buildings and Construction Sector. Executive Summary, United Nations Environment Programme. 2020. Available online: https://wedocs.unep.org/20.500.11822/34572 (accessed on 22 January 2022).
71. Osorio, A.M.; Úsuga, L.F.; Vásquez, R.E.; Nieto-Londoño, C.; Rinaudo, M.E.; Martínez, J.A.; Filho, W.L. Towards Carbon Neutrality in Higher Education Institutions: Case of Two Private Universities in Colombia. *Sustainability* **2022**, *14*, 1774. [CrossRef]
72. ICE. ICE DB VS 3.0 (ICE Inventory of Carbon & Energy, 10 November 2019). 2019. Available online: https://circularecology.com/embodied-carbon-footprint-database.html (accessed on 14 September 2021).
73. Oekobaudat. Process Data Set: Ready-Mix Concrete C30/37 (en). 2021. Available online: https://www.oekobaudat.de/OEKOBAUDAT/datasetdetail/process.xhtml?lang=en&uuid=a758fb6a-7fb1-4cdc-b652-c42cf2f7632c&version=20.20.020 (accessed on 16 September 2021).
74. UK. UK Government GHG Conversion Factors for Company Reporting. Full set, VS 2.0, 1.6.2021. 2021. Available online: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1005677/conversion-factors-2021-full-set-advanced-users.xlsm (accessed on 14 September 2021).
75. Oekobaudat. Process Data Set: Structural Steel: Sections and Plates (en). 2021. Available online: https://oekobaudat.de/OEKOBAUDAT/datasetdetail/process.xhtml?uuid=5cb2c568-76fe-4803-8b46-0084e79800c8&version=00.14.000&stock=OBD_2021_I&lang=en (accessed on 16 September 2021).
76. Oekobaudat. Process Data Set: Glass—Bundesverband Flachglas e.V.—Insulating Glass Unit, Triple Glass Configuration (en). 2021. Available online: https://oekobaudat.de/OEKOBAUDAT/datasetdetail/process.xhtml?uuid=353f77b3-e4cf-4f57-96d6-36eb34b567ff&stock=OBD_2019_III&lang=en (accessed on 16 September 2021).
77. Oekobaudat. Process Data Set: Pumice Stone (SFK-4) (en). 2021. Available online: https://www.oekobaudat.de/OEKOBAUDAT/datasetdetail/process.xhtml?lang=en&uuid=8aa75389-7865-41ad-9763-6252c5ab1fe5&version=20.21.060 (accessed on 16 September 2021).
78. Oekobaudat Prozess-Datensatz: Kalksandstein (de). 2021. Available online: https://www.oekobaudat.de/OEKOBAUDAT/datasetdetail/process.xhtml?uuid=f7235d64-16e5-42d0-94c8-797a3cd6cd37&stock=OBD_150820&lang=de (accessed on 16 September 2021).
79. Oekobaudat. Prozess-Datensatz: EPS-Hartschaum (Styropor ®) für Decken/Böden und als Perimeterdämmung B/P-040 (de). 2021. Available online: https://www.oekobaudat.de/OEKOBAUDAT/datasetdetail/process.xhtml?uuid=d63926ea-8473-4ea7-b965-a7bae6e5e022&lang=de (accessed on 1 September 2021).
80. IVH. Umwelt-Deklaration nach ISO 14025 und EN 15804. EPS-Hartschaum (Styropor ®) für Wände, Dächer W/D-035; Industrieverband Hartschaum e.V. Report. 2015, p. 12. Available online: https://www.hirsch-porozell.de/wp-content/uploads/2021/02/N-EPS-Hartschaum-Styropor-fuer-Waende-und-Daecher-WD-035-07.10.2020.pdf (accessed on 1 September 2021).
81. Hidalgo-Salazar, M.; Correa-Aguirre, J.P.; Montalvo-Navarrete, J.M.; Lopez-Rodriguez, D.F.; Rojas-González, A.F. Recycled Polypropylene-Coffee Husk and Coir Coconut Biocomposites: Morphological, Mechanical, Thermal and Environmental Studies. In *Thermosoftening Plastics*; Evingür, G.A., Ed.; IntechOpen: London, UK, 2018. [CrossRef]
82. UBA. Carbon Footprint-Teilgutachten "Monitoring für den CO_2-Ausstoß in der Logistikkette". Report 29/2012 German Federal Environmental Agency (Umweltbundesamt). 2012. Available online: https://www.umweltbundesamt.de/sites/default/files/medien/461/publikationen/4306.pdf (accessed on 16 September 2021).
83. Manohar, K.; Ramlakhan, D.; Kochhar, G.; Haldar, S. Biodegradable fibrous thermal insulation. *J. Braz. Soc. Mech. Sci. Eng.* **2006**, *28*, 45–47. [CrossRef]
84. Oekobaudat. Process Data Set: ROCKWOOL Stone Wool Insulation Materials in the High Bulk Density Range (en). 2021. Available online: https://www.oekobaudat.de/OEKOBAUDAT/datasetdetail/process.xhtml?uuid=b0e3aedd-a5e2-4b97-b0f3-e51548912687&stock=OBD_2020_II&lang=en (accessed on 1 September 2021).
85. Oekobaudat. Process Data Set: Gypsum Plaster Board (Perforated Board) (12.5 mm); 8.5 kg/m^2 (en). 2021. Available online: https://www.oekobaudat.de/OEKOBAUDAT/datasetdetail/process.xhtml?lang=en&uuid=207cde6a-73be-4ffb-972d-30d3d8619fc3&version=20.19.120 (accessed on 3 September 2021).

86. Gyproc. Environmental Product Declaration in Accordance with EN 15804 and ISO 14025 (Manufacturer: Saint-Gobain Gyproc Thailand. 2018, p. 19. Available online: https://portal.environdec.com/api/api/v1/EPDLibrary/Files/8f0c3325-9f2a-4ced-a95a-a7e28524a822/Data%20pdf (accessed on 14 September 2021).
87. Oekobaudat. Process Data Set: Laminated Wood Board Softwood (Generic). 2021. Available online: https://oekobaudat.de/OEKOBAUDAT/datasetdetail/process.xhtml?lang=en&uuid=ac361408-4ede-4ed2-a638-598ee3c53285&version=20.20.120 (accessed on 31 August 2021).
88. Digdach. Dead Weight of a Wooden Roof. 2021. Available online: http://www.digdach.at/content/die-firma/dach-info/dach-abc/e.html (accessed on 31 August 2021).
89. Oekobaudat. Process Data Set: Sewer Pipe PE-HD.; PE-HD (en). 2021. Available online: https://www.oekobaudat.de/OEKOBAUDAT/datasetdetail/process.xhtml?uuid=a198cf71-f033-4b76-9228-d22ca191b2f6&version=20.21.060 (accessed on 3 September 2021).
90. Oekobaudat. Process Data Set: Ceramic Tiles (en). 2021. Available online: https://oekobaudat.de/OEKOBAUDAT/datasetdetail/process.xhtml?uuid=a2b5b7c9-db13-4dbd-be23-b0ff9f0cbd98&stock=OBD_2019_III&lang=en (accessed on 3 September 2021).
91. Oekobaudat. Process Data Set: Roof Tile; 1800 kg/m^3 (en). 2021. Available online: https://www.oekobaudat.de/OEKOBAUDAT/datasetdetail/process.xhtml?uuid=826fa2c2-c691-4844-83d3-aea0e8a54bcd&version=20.19.120 (accessed on 3 September 2021).
92. Oekobaudat. Product Flow Data Set: Roof Tile (m2) (en) 2021. Available online: https://www.oekobaudat.de/OEKOBAUDAT/datasetdetail/productFlow.xhtml?uuid=897539a2-8ce3-41cb-9786-1fd0fe7cd8b1&version=39.00.000 (accessed on 3 September 2021).
93. Oekobaudat. Process Data Set: Application Paint Emulsion, Dispersion Paint; 1 kg (en). 2021. Available online: https://www.oekobaudat.de/OEKOBAUDAT/datasetdetail/process.xhtml?lang=en&uuid=fcf6494c-aad2-4180-b1a2-392cc954ae52&version=20.19.010 (accessed on 10 April 2021).
94. Kiamili, C.; Hollberg, A.; Habert, G. Detailed Assessment of Embodied Carbon of HVAC Systems for a New Office Building Based on BIM. *Sustainability* **2020**, *12*, 3372. [CrossRef]
95. García-Sanz-Calcedo, J.; Neves, N.D.S.; Fernandes, J.P.A. Measurement of embodied carbon and energy of HVAC facilities in healthcare centers. *J. Clean. Prod.* **2021**, *289*, 125151. [CrossRef]
96. Destatis. Database of the Federal Statistical Office of Germany. Available online: http://www-genesis.destatis.de/genesis/online (accessed on 14 June 2021).
97. BBSR. Bundesinstitut für Bau-, Stadt- und Raumforschung (BBSR) im Bundesamt für Bauwesen und Raumordnung (BBR) (Hrsg.): Umweltfußabdruck von Gebäuden in Deutschland. Kurzstudie zu Sektorübergreifenden Wirkungen des Handlungsfelds "Errichtung und Nutzung von Hochbauten" auf Klima und Umwelt. BBSR-Online-Publikation 17/2020, Bonn, Dezember 2020. p. 35. Available online: https://www.bbsr.bund.de/BBSR/DE/veroeffentlichungen/bbsr-online/2020/bbsr-online-17-2020-dl.pdf?__blob=publicationFile&v=3 (accessed on 14 June 2021).
98. CEIC. Singapore Bldg. Completed: Gross Floor Area: Office Space 1998–2018. Quarterly Report. Urban Redevelopment Authority. 2018. Available online: https://www.ceicdata.com/en/singapore/buildings-completion/bldg-completed-gross-floor-area-office-space (accessed on 4 July 2021).
99. SCMP. Singapore Outclasses Hong Kong when It Comes to Average Home Size. Report, 19 October 2018. 2018. Available online: https://www.scmp.com/business/article/2169204/singapore-outclasses-hong-kong-when-it-comes-minimum-home-size (accessed on 4 July 2021).
100. NCCS. National Climate Change Secretariat: Singapore's Emissions Profile. 2021. Available online: https://www.nccs.gov.sg/singapores-climate-action/singapore-emissions-profile/ (accessed on 3 September 2018).
101. Weißenberger, M. Lebenszyklusbasierte Analyse der ökologischen Eigenschaften von Niedrigstenergiewohngebäuden unter Besonderer Berücksichtigung der Gebäudetechnik. Ph.D. Thesis, Technical University of Munich, Munich, Germany, 2016; p. 228. Available online: http://mediatum.ub.tum.de/?id=1325463 (accessed on 10 February 2022). [CrossRef]
102. Oekobaudat. Process Data Set: Cable 3-Wire; 1 Piece (en). 2021. Available online: https://www.oekobaudat.de/OEKOBAUDAT/datasetdetail/process.xhtml?lang=en&uuid=ca2a6fc9-8d86-451c-a2d9-592d5288a0ee&version=20.17.009 (accessed on 3 September 2021).
103. Casamayor, J.L.; Su, D.; Ren, Z. Comparative life cycle assessment of LED lighting products. *Light. Res. Technol.* **2018**, *50*, 801–826. [CrossRef]
104. Scholand, M.J.; Dillon, H.E. Life-Cycle Assessment of Energy and Environmental Impacts of LED Lighting Products. Part 2: LED Manufacturing and Performance. US Department of Energy, Building Technologies Program. 2012; p. 78. Available online: https://www.pnnl.gov/main/publications/external/technical_reports/PNNL-21443.pdf (accessed on 15 September 2021).
105. Welz, T.; Hischier, R.; Hilty, L. Environmental impacts of lighting technologies—Life cycle assessment and sensitivity analysis. *Environ. Impact Assess. Rev.* **2011**, *31*, 334–343. [CrossRef]