EMISSION FREE EUROPEAN UNIVERSITIES

Strategic Development of Students' Sustainability Competencies in Engineering Sciences

Work Package #4 Part C

University practices assessment – keeping on track to emission neutrality

Part C - Activity 4.3: Carbon Footprint in Higher Education

Authors

Mehran Attar, Klaus Homann

Contributors

Ferdinand Pfund, Julian Frank, Tom Grams, Efekan Kocak, Hagen Rinas, Marco Wacker

PUBLISHED

May 2025

Contact:

For any inquiries or questions about the unrestricted use of the project results, please get in touch with the project coordinator: klaus.homann@dhbw-stuttgart.de

Disclaimer

EFEU is funded by Erasmus+ and DAAD to expand the exchange of best practices and enable strategic partnerships among European universities and companies. This project has been funded with support from the European Commission. This publication reflects the views only of the authors, and the Commission cannot be held responsible for any use which may be made of the information contained therein.

Table of Contents

Figures

Tables

List of Abbreviations

CF	Carbon Footprint
CO2	Carbon Dioxide
CO2e	Carbon Dioxide Equivalent
EF	Emission Factor
EFEU	Emission Free European Universities
GHG	Greenhouse Gas
KWh	Kilowatt hours
SDG	Sustainable Development Goals

Definitions

Several words and phrases are used in this report that some readers might be unfamiliar with. Therefore, a list of definitions is listed here to make the report more accessible to a wide variety of readers. The definitions are mainly from the GHG Protocol (2004) and Defra's Guidance (2009).

Activity data is the quantified activity level multiplied by an emission factor to achieve GHG emissions for that activity. Examples of activity data include distance travelled, floor area of a building, amount of fuel consumed, and kWh electricity used.

Boundaries determine which emission sources are included in an organisation's GHG inventory. They also determine the geographical area, gases, and timeframe to be considered for the GHG inventory of an organisation.

Carbon dioxide equivalent (CO_2e) is a standard unit for comparing emissions caused by different greenhouse gases based on their global warming potential. For example, the global warming potential for methane over 100 years is 21. Therefore, 1 tCH_4 is equivalent to 21 tCO_2 over this period.

Carbon neutrality is the net zero balance between all GHG emissions produced and removed in a certain system.

Direct emissions are those emissions that are either owned or controlled by the organisation.

Downstream emissions are the emissions caused by selling goods and services. They include distribution, processing, use, and end-of-life treatment of the sold products and the investments an organisation makes.

Emission factor, also known as conversion or emission coefficient, is a conversion unit that is multiplied by activity data to produce GHG emissions data. For example, kg CO_2e/km travelled, or kg CO_2e/€ purchased.

Indirect emissions are emissions that occur off-site but are the consequences of the activities of the reporting organisation.

Global warming Potential (GWP) is a metric used to express the relative impact of different greenhouse gases on global warming, indicating how much heat a particular gas can trap in the atmosphere compared to carbon dioxide over a designated period.

Scopes define the operational boundaries concerning indirect and direct GHG emissions. Emission sources are categorised into three distinct Scopes. All the existing frameworks agree on the definition of these three Scopes.

Scope 1: All direct emissions that occur on-site originate from sources owned or controlled by the organisation.

Scope 2 Indirect emissions generated off the site, resulting from the purchase of electricity, heating, and steam.

Scope 3 All the other indirect emissions that occur off-site but result from activities that take place on-site.

A supply chain is a network of organisations involved in different stages of a product's sale from when it is manufactured until it reaches the customer. These include retailers, manufacturers, and distributors.

Upstream emissions are all the emissions that are caused by the purchase of goods and services. GHG Protocol defines eight categories of upstream emissions: purchased goods, services and capital, waste, business travel, and commuting.

About this Publication

This publication presents one of several reports reports from the fourth work package of the Erasmus+ Strategic Partnership project, "Emission Free European Universities" (EFEU).

It documents the development and implementation of the EFEU Carbon Footprint of Teaching Calculator (EFEU CFTC) as a WP4 deliverable.

This report summarises the findings of an extensive research study of the EFEU consortium during the period between October 2024 and May 2025.

The aim of this EFEU CFTC is to provide a structured and accessible initial assessment of the carbon footprint associated with different teaching formats in higher education - specifically in-person, online, and hybrid models. The developed framework is designed to be universally applicable across institutions and locations

EFEU Carbon Footprint of Teaching Calculator (EFEU CFTC) was distributed to project partners as well as to the public through the project website at:

https://www.dhbw-stuttgart.de/forschung-transfer/technik/projekte/efeu/project-outcomes/

1 Introduction

1.1 Context and Significance

Universities play a pivotal role in the sustainable transition of society. As institutions of education and research, they must lead efforts to equip future professionals with both technical competencies and awareness to act as passionate and dedicated change-makers. To meet these demands, universities must adapt their curricula to prioritise sustainability.

In this context, the Emission-Free European Universities (EFEU) Project aims to transform learning and teaching activities so that the campuses of institutions of higher learning within Europe can evolve into true beacons of sustainability. The project unites four European institutions: Duale Hochschule Baden-Württemberg (Stuttgart, Germany), Instituto Politécnico de Leiria (Leiria, Portugal), Metropolia Ammattikorkeakoulu Oy (Helsinki, Finland), and Université Polytechnique Hautsde-France (Valenciennes, France).

From December 31, 2022, to August 30, 2025, the EFEU consortium is dedicated to ensuring the successful implementation of project activities including the development of the EFEU Carbon Footprint Calculator, Sustainability Awareness and Mobility surveys and reports, Teaching Modules (in-person and online), a Blended Intensive Program, a Carbon Dioxide Emission Prediction Software, and an EFEU Summer School.

Through the development of the EFEU Carbon Footprint of Teaching Calculator (EFEU CFTC), theEFEU team recognised the need to develop a standardised approach to comprehensively assess the carbon footprint associated with different teaching formats

1.2 Problem Statement and Objectives

The education sector contributes to greenhouse gas emissions in various ways. Although its share is estimated to be moderate compared to more emission-intensive sectors such as industry or transport, it still has a relevant impact on the climate due to its infrastructural size and social importance. The sources of emissions include both the operation of the facilities themselves and the indirect effects resulting from mobility and digitalization.

A significant emission factor is the energy demand of educational buildings. The operation of schools, universities and other educational institutions requires considerable amounts of energy for heating, cooling, lighting and the supply of technical equipment. The energy condition of the buildings has a decisive influence here: older, less renovated buildings often have a higher specific energy requirement than newer, energy-efficient facilities (UBA, 2021).

Added to this are emissions caused by the mobility of students, teachers and administrative staff. Commuter traffic plays a key role, particularly at universities, which often have supra-regional catchment areas. Studies show that the proportion of emissions caused by mobility can even exceed building-related emissions in some cases, especially if motorized private transport dominates (Klimabilanz Hochschulen NRW).

With the increasing digitalization of the education system, the energy consumption of digital infrastructures is also becoming more important. The operation of servers, data centers, networks and the use of digital end devices causes electricity consumption, which also results in relevant greenhouse gas emissions depending on the energy provided8. Shifting teaching and learning processes to virtual formats can reduce mobility emissions on the one hand, but can also create new sources of emissions through digital technologies on the other.

The aim of this EFEU CFTC is to provide a structured and accessible initial assessment of the carbon footprint associated with different teaching formats in higher education - specifically in-person, online, and hybrid models. The developed framework is designed to be universally applicable across institutions and locations, requiring only limited input data, thereby enabling universities to quickly gain insights into their current emission profile. Rather than delivering an exhaustive carbon accounting tool, the focus lies on offering a pragmatic baseline model that identifies key emission drivers and highlights relative differences between formats. In addition to this quantitative orientation, the CFTC aims to raise awareness of the environmental impacts of teaching design and to stimulate sustainability-oriented thinking in academic planning. It provides evidence-based recommendations and incentives for reducing emissions in each format and offers practical guidance for optimizing teaching structures with climate considerations in mind. By integrating environmental, organizational, and technical perspectives, the CFTC supports universities in aligning their educational strategies with climate goals - without compromising pedagogical flexibility or accessibility.

1.3 Relevance and limitations

The relevance of EFEU CFTC stems from the growing need of HEIs to reduce greenhouse gas emissions in all areas of their activities – in this case in teaching as the core process of universities.

Teaching formats - whether in-person, online, or hybrid—play an increasingly important role in this context. Their ecological impact is no longer a secondary concern but a central factor in institutional sustainability strategies.

Especially in light of increasing digitalization and ongoing global mobility, the question of how teaching can be designed in an ecologically responsible way has become more pressing.

The EFEU CFTC contributes to that discussion by offering a functional, comparative framework for evaluating the carbon footprint of different teaching formats. Rather than focusing on isolated case-specific data, the study develops a generalizable KPI-based model that abstracts key emission drivers and enables cross-format comparison. The approach combines a structured synthesis of existing literature with a piloted application to a real-world institutional setting (DHBW Stuttgart). This dual perspective enhances both theoretical validity and practical relevance and provides orientation for universities aiming to align teaching structures with sustainability objectives.

At the same time, the approach is subject to a number of limitations. The model relies in part on standardized assumptions and secondary data, which introduces uncertainty and reduces granularity. Although the case study includes empirical data from DHBW Stuttgart, some values - such as commuting distances or household energy use - are based on estimates or national averages.

Furthermore, the model intentionally excludes certain emission categories, such as the production of IT equipment, based on the assumption that their use occurs across all formats and is therefore not format-specific. Likewise, household electricity and heating are only considered in the case of online teaching, while such usage is excluded for students attending in-person sessions.

In addition, the approach focuses narrowly on the ecological dimension. Social, psychological, pedagogical, and economic aspects of teaching formats - while highly relevant to overall evaluation - are not systematically examined.

These limitations are consciously accepted to enable a focused and methodologically consistent examination of the climate-relevant aspects of teaching formats. Within this scope, the approach provides a well-founded contribution to the debate on sustainable higher education and offers a transferable, transparent approach that can serve as a foundation for institutional decision-making.

1.4 Current State of Research Field

The environmental implications of educational technology are receiving growing attention, particularly in light of global sustainability goals and the ongoing digital transformation of higher education. This chapter synthesizes recent research on the carbon footprint (CF) of various university teaching formats—face-to-face, online, and hybrid—and provides comparative insights into their respective greenhouse gas (GHG) emissions.

1. Schomburg et al. (2024): Comprehensive Emissions Analysis of Teaching Formats

Schomburg et al. examine the CF of higher education at Technische Hochschule Mittelhessen (THM), focusing on the ecological implications of different teaching modalities. They compare traditional in-person classes, fully online formats, and hybrid models, emphasizing the environmental consequences of each. Their lifecycle-based approach includes direct emissions (Scope 1), indirect energy emissions (Scope 2), and indirect value chain emissions (Scope 3), such as commuting and ICT use.

Using a standardized module unit (15 weeks × 90 minutes/week), they find that face-to-face instruction generates the highest emissions due to building energy use and student travel. Online teaching results in considerably lower emissions but is still influenced by server and device energy use. Hybrid formats occupy a middle ground, with environmental impact highly sensitive to the proportion of physical sessions. A key insight is the dominant role of Scope 3 emissions, especially mobility-related ones, and the importance of electricity sources—green power significantly reduces total emissions.

The study offers strategic recommendations, including the promotion of digital and hybrid teaching, investment in efficient building technology, and decarbonization of digital infrastructure. It highlights the necessity of integrating ecological factors into educational planning beyond didactic and administrative considerations.

2. Mustafa et al. (2022): International Mobility and Carbon Emissions

Mustafa et al. focus on the carbon impact of international student mobility, particularly within UK universities, and explore the potential of digital learning formats to reduce emissions. The study underscores the environmental costs of long-distance travel, noting that a single round-trip flight (e.g., Malaysia to the UK) emits approximately 1.8 tons of CO_2 per student—well above sustainable per capita limits.

Though lacking detailed quantification of hybrid models and relying partially on qualitative methods, the study points to the underrepresentation of Scope 3 emissions in institutional sustainability strategies. It recommends alternatives to physical mobility, such as virtual exchange programs and dual online degrees, to mitigate the environmental burden of internationalization.

The authors argue that digital teaching should be developed into a permanent sustainability tool rather than a pandemic-era contingency. Their work expands the CF discussion to the global movement of students and advocates for systemic integration of low-emission digital formats in international education strategies.

3. Yin et al. (2022): Quantifying Emission Reductions in China

Yin et al. adopt a model-based, quantitative approach to estimate CO_2 reductions from online teaching at Chinese universities. Focusing primarily on commuting (Scope 3) and home electricity use (Scope 2), they demonstrate that shifting to online instruction can cut emissions by several hundred thousand tons per semester—equivalent to China's hourly national emissions.

The model incorporates national commuting data, transport modes, and electricity consumption statistics, revealing that reduced campus building use and elimination of travel are key factors in CF reduction. However, increased household electricity consumption poses a rebound effect, and the net benefit is contingent on the regional electricity mix.
The study emphasizes that digitalization's environmental advantage is strongest where clean electricity predominates. It also suggests that online teaching can serve national climate objectives when paired with measures like energy-efficient devices and digital infrastructure decarbonization.

4. Little & Cordero (2014): Hybrid Learning at Commuter Universities

Using San José State University as a case study, Little & Cordero analyze how hybrid and online course delivery affects commuting emissions at commuter-heavy institutions. Their findings indicate that small-scale online instruction yields marginal benefits, but broad adoption of hybrid formats, combined with strategic scheduling, can significantly reduce car-based commuting and parking infrastructure needs.
While the focus is on transportation emissions, the study highlights broader institutional advantages, including reduced congestion and better space utilization. It underscores the importance of logistical planning and behavioral incentives in realizing environmental gains and positions digital learning as a long-term sustainability strategy, particularly for urban campuses with limited public transit options.

5. Attar et al.: The EFEU Carbon Footprint Calculator

Attar et al. present the Emission Free European Universities (EFEU) Carbon Footprint Calculator, a standardized tool for assessing emissions at European HEIs. Developed through a multi-country Erasmus+ project, the calculator integrates Scopes 1–3 based on the Greenhouse Gas Protocol, accounting for energy use, mobility, procurement, and waste.
Pilot applications in Germany, France, Finland, and Portugal revealed that commuting and energy use are major emission drivers. The tool helps identify high-

impact areas and guides strategic planning. It is designed for ease of use, enabling HEIs to benchmark, monitor progress, and support carbon neutrality objectives.

The EFEU initiative addresses a major gap in emission accounting for universities and offers a scalable, regionally adaptable model for sustainability governance. It reflects a growing recognition of the operational impact of higher education institutions and the necessity of actionable data for institutional change.

Conclusion

Across contexts, the studies converge on key insights: digital and hybrid teaching formats have substantial potential to reduce the CF of higher education, especially by eliminating student travel and optimizing energy use. However, these benefits are conditional upon systemic factors such as electricity sourcing, institutional planning, and behavioral change. Collectively, the research underscores the need for comprehensive emission accounting and the integration of sustainability into pedagogical innovation, positioning digital transformation as a strategic lever in the fight against climate change.

Emission Factors	Schomburg et.al. (2024)	Mustafa et. al. (2022)	Little & Cordero (2014)	Yin et. al. (2022)	Attar et. al. (2024(	Comments
Mobility	✓ comprehensively considered	✓ international focus	✓ detailed commuting	✓ commuting avoided	✓ comprehensively considered	Covered in all studies
Device electricity use (students)	✓ in detail	✗ not considered	✗ not considered	✓ partially cosidered	✓ partially cosidered	Schomburg et. al. most detailed
Digital infrastructure	✓ well covered	✓ mentioned only	✗ not considered	✓ partially cosidered	✓ well covered	Attar et. al. especially detailed
Campus heating & lighting	✓ In detail	✗ not considered	✗ not considered	✗ not considered	✓ in detail	Only Schonburg et. al. and Attar et. al.
Material consumption (paper etc.)	✓ comprehensively considered	✗ not considered	✗ not considered	✗ not considered	✓ partially considered	Relevant for in- person formats
IT equipment lifecycle	✓ comprehensively considered	✗ not considered	✗ not considered	✗ not considered	✓ comprehensively considered	Not a focus across most studies
Student housing emissions	✗ weakly considered	✓ mentioned only	✗ not considered	✗ not considered	✓ Partially cosideres	Potentially relevant add-on

Table 1: Analysis of considered emission factors

1.5 Definitions and Characteristics of Teaching Formats

In contemporary higher education, three core teaching formats have become firmly established: online teaching, hybrid teaching, and traditional in-person teaching. Each of these formats is characterized by distinct structural, technological, and pedagogical features, which are described below (Heinrich-Heine-Universität, 2022).

Online teaching refers to a mode of instruction in which both lecturers and students participate entirely through digital means. Two primary approaches can be distinguished. In synchronous online teaching, classes take place in real time via platforms such as video conferencing tools. Instructors deliver live content, and students join remotely at the same time, enabling real-time interaction through chat, audio, or video (Kerres 2013). In contrast, asynchronous online teaching involves access to pre-recorded lectures, reading materials, or assignments that can be completed independently of time and place. Students work through these resources at their own pace. In practice, many courses combine synchronous and asynchronous elements to strike a balance between structure and flexibility. Online teaching offers high levels of spatial and temporal independence but requires strong self-management skills and adequate digital infrastructure (Kerres 2013).

Hybrid teaching combines aspects of both face-to-face and online instruction. However, the term encompasses multiple subtypes, each with different implications for technology use and learning dynamics. In the simultaneous hybrid model, some students attend the session physically on campus while others participate online at the same time. The instructor engages with both groups concurrently, which requires appropriate technical equipment - such as cameras, microphones, and displays - and a thoughtful didactic setup that ensures inclusivity and interaction (Egger et al. 2022). Alternatively, the rotational hybrid model organizes instruction so that students alternate between on-site and online attendance on different days (e.g., two days on campus, three days remote). This time-based hybrid approach ensures that all students experience both environments, albeit sequentially. (Kerres 2013).

Another common form is blended learning, where face-to-face and online phases are intentionally scheduled in succession. For example, students may study theory online and then apply that knowledge during hands-on sessions on campus. In contrast to the simultaneous model, blended learning does not involve real-time parallel participation but rather a pedagogical integration of separate phases (HHU, 2022).

Across all hybrid formats, the goal is to combine the benefits of physical interaction - such as social exchange and immediate feedback - with the flexibility and accessibility of digital instruction. However, hybrid teaching also introduces greater complexity in terms of planning, technology, and didactic design.

In-person teaching, also known as face-to-face or classroom-based instruction, is the traditional mode in which lecturers and students are physically present in the same location at the same time. It enables direct, unmediated interaction, allowing for spontaneous dialogue, immediate feedback, and non-verbal communication such as gestures and facial expressions. This fosters a strong sense of social presence and group cohesion. However, in-person teaching is bound to fixed times and places, limiting flexibility for learners and educators alike. (Egger et al. 2022)

2 Methodology

This work takes an interdisciplinary approach to analyzing the carbon footprint of different teaching formats, with a particular focus on the systematic collection and evaluation of data. The methodology combines quantitative and qualitative approaches to provide a comprehensive perspective on emissions in different teaching and learning contexts.

This thesis adopts a comparative, literature-based research design to analyze the carbon footprint of different teaching formats - namely in-person, online, and hybrid models. The core objective is to enable a systematic and transferable evaluation of these formats based on key emission factors that are directly influenced by teaching practices and can be shaped by institutional decisions.

The analysis focuses exclusively on emission drivers that are inherent to the delivery of instruction. These include mobility patterns, energy consumption (both on campus and at home), and material use. Emission sources unrelated to teaching activities - such as infrastructure ownership or national policy frameworks - are deliberately excluded to maintain the model's generalizability and relevance across diverse institutional and geographical contexts.

Rather than producing a detailed carbon inventory for a specific university, the study develops a generalized, KPI-based model that allows for comparison across teaching modes. This abstraction highlights ecological strengths and weaknesses of each format and supports the identification of targeted improvement areas.

By integrating and synthesizing existing research, the design aims to distill key influencing factors and provide practical insights for reducing emissions in higher education. Ultimately, the research contributes to the development of strategic recommendations for more sustainable teaching practices.

2.1 Data Collection Methods

The approach is based on secondary data, drawn from existing scientific publications, reports, and quantitative surveys. The aim is to systematically compile and evaluate data on CO_2 emissions associated with different teaching formats—specifically face-to-face, online, and hybrid models.

The selection of sources was guided by their relevance to key emission factors, particularly those related to commuting, building usage, digital infrastructure, and domestic energy consumption. In addition, the studies were assessed for methodological transparency and data quality to ensure their suitability for comparative analysis.

To enable structured evaluation, the identified data were categorized by teaching format and emission type. Where possible, CO_2 values were standardized and converted into relational units (e.g., emissions per participant per hour or per teaching event). Each source's underlying system boundaries and assumptions were also documented to critically assess the degree of comparability.

2.2 Selection criteria for data sources and key figures

The selection of data sources was guided by three key criteria: relevance, reliability, and timeliness. Priority was given to studies focusing on the carbon footprint of higher education institutions, particularly those that account for specific geographical, infrastructural, and organizational conditions.

Of particular interest were sources offering a differentiated breakdown of key emission drivers, including:

- Commuting patterns of students and faculty,
- Energy consumption in university buildings,
- Energy Consumption of students at home,
- Material use of students and faculty,
- Data transmission for video based teaching,

The analysis primarily relies on peer-reviewed journal articles, research reports, and official data from universities, environmental authorities, and international organizations. Special emphasis was placed on sources with transparent methodologies and detailed emission data, as well as on studies that compare teaching formats or propose calculation models for assessing climate impact.

The specific studies used are presented and discussed in later sections. Their inclusion was based on their ability to contribute to a comprehensive and comparable understanding of the ecological impact of different teaching formats in higher education.

The selection of emission sources and key performance indicators (KPIs) was based on their direct relevance to teaching activities and practical measurability. Five main categories were identified for comparison:

- Mobility (student and faculty commuting),
- Data Transmission
- Electricity consumption,
- Heating energy, and
- Material usage.

By contrast, emissions from the lifecycle of IT equipment were excluded due to their high dependency on institution-specific and external factors (e.g. national energy mix, individual usage patterns). Their inclusion would compromise comparability and the transferability of the model.

All emission factors (e.g., for electricity, heating, transport, and materials) were based on national average values provided by authoritative institutions such as the German Environment Agency (UBA). To support international applicability, all data were normalized per person, per hour, or per kilometer. This unit-based structure ensures that the model can be easily adapted to other countries by substituting locally relevant emission values while maintaining a consistent calculation logic.

2.3 Assumptions and delimitations

To ensure comparability and manage the complexity of the analysis, this study is based on a set of clearly defined assumptions. The three teaching formats under investigation— in-person, online, and hybrid - are each considered under typical, realistic conditions commonly found in higher education institutions in German- and English-speaking countries.

It is assumed that:

- Online teaching involves substantial home energy consumption (electricity and heating) as well as the data transmission for video streaming by both students and lecturers.

- In-person teaching is primarily associated with mobility-related emissions, material (paper) use and on-campus energy use.
- Hybrid formats represent a functional combination of both, with variable weighting depending on implementation.

To ensure a fair comparison, it is further assumed that students do not use additional electricity or heating at home during days spent on campus, as they are assumed to be absent for the full teaching period. Moreover, the use of laptops and internet infrastructure - while essential for online teaching - is not considered a differentiating factor, since these technologies are assumed to be used across all formats to some extent, including in in-person teaching (e.g., for follow-up work, communication, or accessing materials). Their emissions are therefore treated as background usage and excluded from the comparative analysis.

To enable standardization across formats, average participation rates and usage values are assumed. Calculations are generally based on CO_2 emissions per teaching hour and participant. In cases where the underlying data vary or are incomplete, estimates or value ranges are used to maintain consistency without overstating precision.

The scope of the study is limited to the higher education sector. Other educational levels - such as schools or vocational training providers - are excluded. Likewise, the content quality or pedagogical effectiveness of the teaching formats is not assessed; the sole focus lies on their ecological impact. Broader social, psychological, or economic aspects (e.g., student satisfaction, accessibility, cost structures) are acknowledged as relevant but remain outside the scope of this analysis.

Importantly, this study does not collect primary data but is instead based entirely on existing literature and secondary sources, with the exception of institution-specific data used in the case study application.

In line with the goal of abstraction and comparability, the study deliberately avoids using the Scope 1, 2, and 3 categories defined by the Greenhouse Gas Protocol (WBCSD / WRI. 2024). While useful in institutional carbon accounting, they are not well suited to evaluating the functional emissions associated with teaching. For example, heating demand is treated uniformly as a consumption-based value per person and per hour, regardless of whether it is provided by on-site or external systems.

Likewise, emission sources such as emergency power systems, university-owned vehicles, or laboratory processes are excluded, as they are either marginal or not directly attributable to the teaching process itself. This focus on directly influenceable and teaching-related emissions enables a higher level of abstraction, ensures comparability, and keeps the analysis centered on factors that can be shaped through instructional design and policy decisions.

2.4 Data analysis

The data analysis is based on a systematic evaluation and comparative interpretation of CO_2 emission values and influencing factors derived from selected studies and official reports. As a first step, the methodological approaches, system boundaries, and core assumptions of the individual sources are critically examined to assess their validity and ensure cross-format comparability.

Where possible, quantitative data are standardized and normalized to a uniform reference unit (e.g., CO_2 emissions per participant and teaching hour). This allows for direct comparison between teaching formats. In cases of data variability, average values, value ranges, and confidence intervals are documented to reflect uncertainty and provide a nuanced picture of emission levels.

A central part of the analysis involves identifying dominant emission drivers within each teaching format and assessing their relative environmental efficiency. Both absolute emissions (e.g., kg CO_2 per student per year) and relative emissions (e.g., per unit of instructional time) are considered to capture differences in intensity and total impact. This enables a differentiated understanding of reduction potential under varying institutional or structural conditions.

To ensure consistency and comparability across all teaching formats, the model is based on the following standard baseline assumptions:

- One student accounts for one unit of teaching-related activity per hour.
- Professors are treated equally in terms of presence and emissions.
- Building-related energy consumption is allocated over 365 days to reflect continuous demand.
- Emission factors are expressed in kilograms of CO_2 (kg CO_2) per relevant unit: per kilometer (mobility), per kilowatt-hour (electricity/heating), or per kilogram (material use).

These assumptions form the analytical backbone of the model and ensure transparency and reproducibility of results. Emission profiles for each teaching format are derived by consistently applying this calculation logic, enabling structured comparison and robust interpretation of the ecological impacts associated with university-level instruction.

2.5 Limitations

Despite a structured methodological approach and the use of empirical data for the case study, this study is subject to several limitations that must be considered when interpreting the results.

The comparative model developed in this thesis is primarily based on secondary data from published studies, institutional reports, and official statistics. As such, its quality and level of detail are contingent on the availability, accuracy, and methodological transparency of these external sources. Differences in system boundaries, assumptions, and calculation methods among the underlying studies can reduce the comparability of CO_2 values across teaching formats.

However, the case study of DHBW Stuttgart integrates institution-specific data - including building energy consumption, student numbers, and material use - which enhances the empirical foundation of the analysis. These real-world data points are supplemented by standardized assumptions (e.g., commuting distances, household energy use, average data transmission per video call per hour), where institution-specific measurements were not available. This combination allows for a realistic yet generalizable application of the model, though it still involves estimated or average values in several key areas.

The analysis remains limited to the higher education sector and does not address other educational contexts such as schools or continuing education providers. Likewise, non-ecological aspects - such as pedagogical effectiveness, economic implications, or social outcomes - are outside the scope of this study. The focus is exclusively on the ecological impact of teaching formats.

Certain emission sources, particularly indirect emissions along supply chains (e.g., for IT hardware production or backend data infrastructure), are not included in the model. These exclusions are deliberate, aiming to maintain simplicity, comparability, and applicability across institutions.

Additionally, the use of national average emission factors introduces limitations in precision, especially with respect to regional variations in energy mix, infrastructure, and mobility behavior. Similarly, the current data landscape on digital infrastructure and home energy use in educational settings is still limited, which adds uncertainty to some of the modeled values.

Importantly, the DHBW case study is not intended as a full carbon footprint of the institution or its buildings. Rather, it serves to demonstrate the applicability and functionality of the abstract KPI model in a real-world higher education context.

While these limitations affect the precision of individual emission values, they do not undermine the study’s ability to identify general patterns, highlight key emission drivers, and offer practical insights into the ecological effects of different teaching formats. The strength of the approach lies in its clarity, flexibility, and transferability, rather than in exhaustive quantification.

3 Development and Application of a CO_2-Emission Calculation Model

3.1 Rationale and Derivation of the Calculation Mode

To demonstrate the practical applicability of the KPI-based model, a comparative calculation of CO_2 emissions for in-person, hybrid, and online teaching formats was conducted. The calculations were based on the assumptions and methodological framework outlined in Chapter 2. The goal was not to create a precise emissions inventory for a specific institution, but rather to illustrate the functionality and transferability of the model using typical data.

The emission calculations include the following categories:

- Mobility-related emissions, based on average commuting distances and transportation modes (e.g., car, public transport, bicycle)
- Streaming emissions, based on average data transmission per one hour of HD video calling.
- Electricity consumption, differentiated by use on campus versus at home
- Heating energy, likewise separated by location of use
- Material use, primarily related to printed documents and other physical teaching aids, particularly in in-person settings

Each of these categories was assessed per teaching hour and per person. Emission factors were applied using national averages expressed in kilograms of CO_2 (kg CO_2) per unit: per kilometer (km) for mobility, per kilowatt-hour (kWh) for electricity and heating, and per kilogram (kg) for material use. These unit-based KPIs allow for clear, transparent comparison across teaching formats.

To demonstrate the practical application of the model, a case study that applies this KPI-based framework was integrated. Drawing on typical values and assumptions derived from the literature, the CO_2 emission profiles for each teaching format were calculated. The calculation methods are presented transparently and consistently across formats to ensure comparability. These include mobility-related emissions per round trip, electricity and heating consumption per teaching hour per person (on-campus vs. at-home), and material use per unit.

In this context, the model was applied specifically to the Duale Hochschule Baden-Württemberg Stuttgart (DHBW Stuttgart). As a practice-oriented higher education institution with a dual study structure and a balanced mix of in-person, hybrid, and online teaching formats, DHBW Stuttgart provides a representative setting to test the framework's applicability. The university's clearly structured academic calendar, standardized teaching volumes, and heterogeneous commuting patterns among students and staff offer valuable conditions for assessing the environmental impact of different instructional modes. This case study illustrates how the abstract model can be grounded in a concrete institutional context to inform data-driven decision-making in higher education.

To enable a meaningful comparison of CO_2 emissions across different teaching formats (in-person, hybrid, and online), we identified key emission sources and abstracted them into Key Performance Indicators (KPIs). These KPIs allow for standardized evaluation regardless of specific institutional or national contexts.

The application of Key Performance Indicators (KPIs) across different teaching formats enables a consistent and comparative assessment of CO_2 emissions. Each format - In- Person, Hybrid, and Online - relies on a distinct configuration of relevant emission sources, which are evaluated through specific KPI components. The following outlines the interpretation and use of KPIs for each format.

KPI	Formula
Mobility KPI	Average km per person per session × CO_2/km (based on transport mix)
Streaming KPI	Average data use (GB) per hour per person × CO_2 per GB
Electricity KPI	Average electricity use (kWh) per hour per person (Campus vs. Home) × CO_2 per kWh
Heating KPI	Average heating energy use (kWh) per hour per person (Campus vs. Home) × CO_2 per kWh
Material KPI	Average material use per session × CO_2 per unit (e.g., kg paper)

Table 2: Logic of KPIs

3.1.1 In Person Teaching

In the context of in-person teaching, mobility remains a major source of emissions. Calculations are based on the total number of participants - including both students and instructors - the average round-trip distance per teaching session, and the specific mix of transportation modes used (e.g., private cars, public transportation, bicycles). Emissions from international students are not included, as air travel is excluded from this analysis.

Campus electricity consumption is determined by the average hourly energy demand of campus facilities, adjusted for the share of on-site renewable electricity generation (such as solar panels). This net value is then divided by the number of participants and multiplied by the total number of teaching hours, yielding a per-person, per-hour electricity-related emission estimate.

Heating energy is evaluated in a similar manner. The total thermal energy used to heat teaching spaces during instructional hours is calculated, reduced by any renewable heating contributions (e.g., solar thermal systems), and distributed proportionally across all participants and instructional hours. Seasonal variation is considered by applying annual average heating loads to ensure consistency across the academic year.

Material usage typically includes printed lecture materials, worksheets, and other physical teaching aids. The emissions associated with material consumption are calculated on a per-participant basis, based on average paper consumption and the emission factor per kilogram of printed material.

Component	Formula
Mobility	Average Distance per Roundtrip [km] × Emission Factor [kg CO_2/km] ÷ Teaching Hours (per day) **Note:** Use standard profiles for emission factor (e.g., low/medium/high impact transport mix – country specific).
Campus electricity	((Total Electricity Demand per Year [kWh] − Own Renewable Supply [kWh]) / 365 Days) ÷ Number of Students ÷ Teaching Hours (per day) × Emission Factor [kg CO_2/kWh] **Note:** Use standard profiles for emission factor (electricity mix – region specific).
Campus heating	((Total Heating Demand per Year [kWh] − Own Renewable Heating [kWh]) / 365 Days) ÷ Number of Students ÷ Teaching Hours (per day) × Emission Factor [kg CO_2/kWh] **Note:** Use standard profiles for emission factor (type of heating – building specific).
Material	Material Demand per Year [kg] ÷ Teaching Days (per year) ÷ Number of Students ÷ Teaching Hours (per day)) × Emission Factor [kg CO_2/kg] **Note:** Use standard profiles for emission factor (type of material).

Table 3: Calculation In-Person Teaching

3.1.2 Hybrid Teaching

In hybrid teaching formats, all major emission components remain relevant but are dynamically weighted based on the proportion of on-site and remote instruction. A key parameter are the OnlineShare and OnCampusShare, which define the relative distribution of activities between campus and home environments. Each emission category is calculated as a weighted combination of its on-campus and remote counterparts, using this share as a scaling factor.

Mobility-related emissions are significantly reduced compared to fully in-person teaching, as participants commute less frequently. The remaining emissions are calculated by applying the OnCampusShare to the average commuting distance, multiplied by an appropriate mobility emission factor. This factor can be adapted to reflect different transport mode profiles (e.g., car, public transport, cycling).

Streaming emissions become increasingly relevant as portions of teaching shift online. For the remote component, we included estimated emissions for data transfer and processing based on average internet usage.

Electricity consumption is divided into two parts. Campus-related electricity use is derived from the net energy demand per hour, corrected for on-site renewable supply, and multiplied by the number of on-site teaching hours. This is combined with home-based electricity use, calculated per hour and per participant during online sessions. Both values are then multiplied by the respective emission factors and aggregated into a total.

In the case of hybrid formats with simultaneous on-site and online participation (e.g., students freely choosing between physical and virtual attendance), a purely proportional

calculation based on OnCampusShare may underestimate actual campus energy use. Therefore, an alternative method introduces a fixed and variable component for campus electricity and heating consumption. A baseline (fixed – marked green – only applicable for mix model) share represents the non-reducible operational load of the building (e.g., lighting, ventilation, server infrastructure), while the other (variable – marked green – only applicable for mix model) share scales with actual presence. This reflects the fact that building systems often remain in operation even if only a portion of the students are physically present.

Heating energy follows the same dual approach. On-campus heating demand is calculated per hour, adjusted for renewable thermal input, and weighted by the on-site teaching proportion. Home heating is based on typical residential consumption per hour, multiplied by OnlineShare. The relevant emission factors are applied to each environment respectively. Seasonal fluctuations are normalized across the academic year using average values.

Material usage is generally lower in hybrid formats. The OnlineShare reduces the reliance on printed materials, while the OnCampusShare retains a baseline level of physical resource use. Emissions are therefore calculated as a weighted combination of material consumption in both settings, each multiplied by the corresponding material emission factor.

Component	Formula
Mobility (Reduced)	OnCampusShare × (Average Distance × Emission Factor [kg CO_2/km] / Teaching Hours (per day)) **Note:** Use standard profiles for emission factor (e.g., low/medium/high impact transport mix – country specific).
Streaming	OnlineShare × (Data Transmission per Hour per Student [GB] × Emission Factor [kg CO_2/GB]) **Note**: Use literature-based values due to lack of available EFs (45.5 g CO_2e/GB).
Campus Electricity (Reduced)	(FixedShare + VariableShare × OnCampusShare) × (Total Electricity Demand per Year [kWh] – Own Renewable Supply [kWh]) ÷ 365 Days ÷ Number of Students ÷ Teaching Hours (per day) × Emission Factor [kg CO_2/kWh]) **Note**: Use standard profiles for emission factor (electricity mix– region specific).
Home Electricity	OnlineShare × (Home Electricity Use (kWh per year) / 365 Days / Teaching Hours (per day) × Emission Factor [kg CO_2/kWh]) **Note:** Use standard profiles for emission factor (electricity mix – region specific).
Campus Heating (Reduced)	(FixedShare + VariableShare × OnCampusShare) × (Total Heating Demand per Year [kWh] – Own Renewable Heating [kWh]) ÷ 365 Days ÷ Number of Students ÷ Teaching Hours (per day) × Emission Factor [kg CO_2/kWh]) **Note:** Use standard profiles for emission factor (type of heating – building specific).
Home Heating	OnlineShare × (Home Heating Use (kWh per year) / 365 Days / Teaching Hours (per day)) × Emission Factor [kg CO_2/kWh]) **Note:** Use standard profiles for emission factor (heating mix – country specific).
Material (Reduced)	OnCampusShare × (Material Demand per Year [kg] / Teaching Days (per year) / Number of Students / Teaching Hours (per day)) × Emission Factor [kg CO_2/kg] **Note:** Use standard profiles for emission factor (type of material).

Table 4: Calculation Hybrid Teaching

3.1.3 Online Teaching

Online In online teaching formats, many traditional emission sources associated with physical campus presence are no longer relevant. Mobility-related emissions are effectively eliminated, as both students and instructors participate from home without the need for commuting. This marks a significant reduction in total emissions compared to formats that require physical attendance.

Electricity consumption becomes the primary emission driver. Each participant consumes electricity through the use of personal electronic devices, lighting, and internet connectivity during both synchronous and asynchronous teaching activities. This consumption is calculated per person and per hour of instruction, using average household electricity values and appropriate emission factors based on national or regional energy mixes.

Another significant source of emissions for online teaching is the emissions from streaming and data transmission due to the teaching modules being fully online. To account for these emissions, we introduce a standardized estimate based on data consumption per student per teaching hour, combined with published emission factors.

Heating energy in the home environment also becomes an important consideration, particularly during the colder months of the academic year. As participants remain in their private living spaces throughout teaching hours, home heating is likely to be used continuously during these periods. Emissions from domestic heating are therefore included in the analysis using seasonal average values for energy consumption per person per hour.

Material usage in online teaching is largely negligible. The instructional process is almost entirely digital, with minimal reliance on printed documents, handouts, or physical teaching aids. Any emissions resulting from occasional material use are considered too minor to significantly influence the overall emission profile and are therefore excluded from the calculation.

Component	Formula
Mobility	Not applicable
Streaming	Data Transmission per Hour per Student [GB] × Emission Factor [kg CO_2/GB] **Note**: Use literature-based values due to lack of available EFs (45.5 g CO_2e/GB).

Home Electricity	Home Electricity Use (kWh per Student per year) ÷ 365 Days ÷ Teaching Hours (per day) × Emission Factor [kg CO_2/kWh] **Note:** Use standard profiles for emission factor (electricity mix – region specific).
Home Heating	Home Heating Use (kWh per Student per year) ÷ 365 Days ÷ Teaching Hours (per day) × Emission Factor [kg CO_2/kWh] **Note:** Use standard profiles for emission factor (heating mix – country specific).
Material	Negligible or not applicable

Table 5: Calculation Online Teaching

3.2 Case Study: DHBW Stuttgart

To test the practical applicability and functionality of the calculation model developed in this thesis, we apply it to a concrete institutional example: the Duale Hochschule Baden- Württemberg Stuttgart (DHBW Stuttgart). As one of the largest universities of applied sciences in Germany, DHBW Stuttgart combines academic instruction with practical workplace experience and features a broad range of study programs with varying teaching modalities, including in-person, hybrid, and online formats.

The case study focuses specifically on the building of the Faculty of Engineering located at Lerchenstraße in Stuttgart, which serves as a representative campus setting for teaching activities. The faculty's structured academic calendar, fixed teaching schedules, and diverse commuting patterns make it particularly suitable for illustrating how emission-relevant factors vary across teaching formats.

It shows how core parameters such as mobility, electricity use, heating demand, and material consumption can be systematically estimated and compared across teaching modes. The results are intended to provide both a plausibility check of the model and an example of how similar institutions might conduct their own assessments using the same logic.

To assess the weekly per-student carbon footprint associated with university-related and home-based activities, this study focuses on seven components: mobility, electricity use on campus, heating demand on campus, material consumption, data transmission and streaming, household electricity use, and household heating use. The average commuting distance per roundtrip is set at 32 km, based on data from the State of Baden-Württemberg (2023). Emission factors were drawn from authoritative sources: 0.139 kg CO_2/km for transportation, 0.055 kg CO_2/kWh for electricity and 0.221 kg CO_2/kWh for heating. Paper-related emissions were calculated using a factor of 0.753 kg CO_2/kg. For the emission factor per GB of data transmitted, we refer to Al Kez et al. (2022), which reports a range between 28 and 63 grams CO_2 per GB, depending on network infrastructure. For simplicity and generalizability, we apply the average value of 0.0455 kg CO_2/GB in our calculations.

Campus electricity consumption totals 1,479,021 kWh55 annually, of which 140,000 kWh are covered by on-site renewable generation, based on an estimated 300–350 photovoltaic panels. The annual heating demand amounts to 692,320 kWh, with no renewable contribution reported. A typical online teaching session (e.g., Zoom, Teams, Google Meet) consumes approximately between 1 to 2 GB per hour per person during active video conferencing. This estimate is derived from empirical measurements published by Polomik (2025) and supported by other independent assessments.

The student population analyzed consists of 8,000 individuals. Material use is estimated at 1.5 kg (one sheet per day) per student annually.

For the case study calculation, an even distribution between on-site and remote participation is assumed, with an OnCampusShare and OnlineShare of 50% each. To account for varying attendance patterns in hybrid teaching, two calculation methods are considered for campus-related energy consumption. The first split-model assumes a fully proportional approach, where electricity and heating demand scale linearly with the OnCampusShare. The second, more differentiated method introduces a mix-model, dividing total building energy demand into a FixedShare and a VariableShare. For electricity, a FixedShare of 70% represents the base load (e.g., lighting, servers, standby equipment) that remains largely constant regardless of occupancy, while the remaining 30% scales with actual on-campus presence. Heating emissions follow a similar pattern, with 80% attributed to non-reducible base heating and 20% adjusted according to presence levels. This dual-method approach allows for a more realistic assessment of campus energy use in hybrid scenarios and reflects typical building operation behavior.

Additionally, the analysis includes indirect emissions from average household energy use per student. Annual home electricity consumption is assumed to be 1,500 kWh58 per person, while heating demand is estimated at 4,200 kWh59 annually, based on a 30 m² living space and typical energy intensity of 140 kWh/m². All emission estimates are normalized per student and per week, assuming a 5-hour on-campus presence per day and a standard academic calendar.

3.3 Results of the Case Study

The underlying calculations for emissions per category are based on the values and emission factors described above. For transparency and brevity, only the final weekly per-student results are presented in tabular form. All computations follow standard multiplication of activity data and emission coefficients and can be reproduced using the provided parameters.

CO_2-Emissions ($kgCO_2$)	In-Person	Hybrid (50%)	Online
Per Student Per Hour	~ 0,906	Split: ~ 0,770 Mix: ~ 0,764	~ 0,621
All Students Per Year	~ 7.974.100	Split: ~ 6.773.243 Mix: ~ 6.720.819	~ 5.467.512

Table 6: Results of Case Study (Numbers)

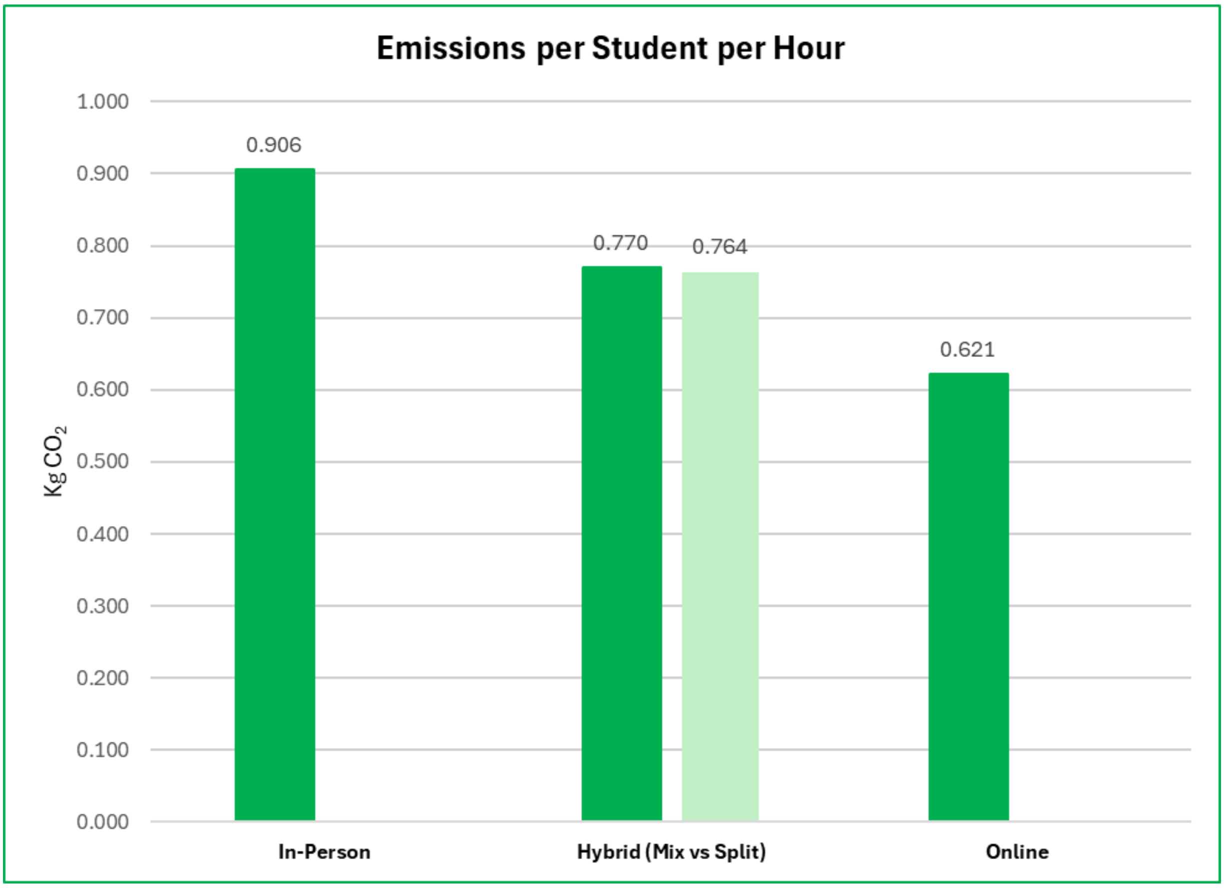

Figure 1: Results of Case Study (Diagram)

3.4 Interpretation of the Case Study Results

The application of the KPI-based model to the DHBW Stuttgart case study yields several important insights into the ecological profiles of different teaching formats. Although the model involves simplifications and standard assumptions, the results highlight distinct emission patterns and underscore the relevance of format-specific emission drivers.

3.4.1 Mobility as a dominant factor in in-person teaching

The results clearly show that mobility-related emissions are the primary driver of the carbon footprint in face-to-face teaching. With an average commuting distance of 32 km per round trip, and thousands of students and faculty traveling to campus daily, transport emissions significantly outweigh emissions from on-campus energy use. This underlines the environmental cost of physical presence and points to commuting behavior as a key lever for emissions reduction. Measures such as promoting public transport, ride-sharing programs, or incentivizing remote participation on selected days could help mitigate this impact.

3.4.2 Video conferencing as a relevant factor in online and hybrid teaching

Data transmission from video-based teaching represents a non-negligible source of emissions in online and hybrid formats. With an added ~0.068 kg CO_2 per student-hour, online teaching still shows the lowest overall footprint compared to hybrid and in-person formats. However, it also highlights the often-overlooked environmental cost of cloud services and network infrastructure. While emissions from data streaming remain lower than those from household heating or campus commuting, they contribute a measurable share to the total footprint of digital instruction. Especially in high-volume or extended online teaching scenarios, these emissions can accumulate significantly and should be considered in sustainability assessments of remote learning models.

3.4.3 Shift of emissions in online formats

In online teaching scenarios, emissions from commuting and campus facilities are largely avoided. This results in the lowest overall carbon footprint among the evaluated formats, with an average of ~0.621 kg CO_2 per student per hour and a total of ~5.467.000 kg CO_2 annually for the DHBW case. These reductions confirm the ecological advantage of online instruction, particularly when infrastructure-heavy campus operations are replaced by decentralized, digital participation.

However, the emissions do not disappear entirely; they are shifted into the private sphere, as students and instructors consume electricity. Especially during colder months, household heating becomes a notable emission factor, along with the continuous use of electronic devices and internet connectivity. The latter also shows a noticeable impact contributing to approximately 0.068 kg CO_2 per student per hour. In the case of DHBW Stuttgart, this results in ~598,400 kg CO_2 annually. However while these values are still lower than those of on-campus formats, they introduce new challenges: the burden of energy consumption is transferred to individuals, raising questions of equity, data availability, and institutional responsibility.

The findings underline the efficiency potential of digital teaching, but also point to the need for further investigation into the hidden or indirect emissions associated with decentralized learning. Support measures - such as encouraging the use of green electricity or providing energy-efficient equipment - could help optimize the environmental performance of online formats even further.

3.4.4 Hybrid teaching as a context-sensitive solution

Hybrid teaching formats occupy a middle ground between fully in-person and fully online instruction. Their ecological performance depends significantly on how the hybrid model is implemented, particularly the balance between physical attendance and remote participation.

In the case of DHBW Stuttgart, two calculation methods were applied to assess the emissions of hybrid teaching under the assumption of a 50/50 distribution between on-site and online participation (OnCampusShare = 50%):

- The “Split” method uses a differentiated approach, accounting for fixed and variable energy shares in campus operations (70/30 for electricity and 80/20 for heating). This method reflects the reality that many building systems (e.g., heating and lighting) continue operating even with partial occupancy. → Result: ~0.77 kg CO_2 per student per hour, or ~6.773.243 kg CO_2 annually.
- The “Mix” method applies a purely proportional model based on the 50% share, assuming that energy use scales directly with occupancy. → Result: ~0.764 kg CO_2 per student per hour, or ~6.720.000 kg CO_2 annually.

Both results fall between the values for fully in-person teaching (~0.906 kg) and fully online teaching (~0.621 kg), demonstrating the intermediate ecological footprint of hybrid formats. However, the minor difference between the two hybrid methods also highlights how structural decisions, such as grouping on-campus days or managing building operations efficiently, can fine-tune ecological performance.
These findings suggest that hybrid teaching, if thoughtfully designed, can serve as a flexible and context-sensitive solution that balances didactic needs with sustainability goals. Particularly when attendance is clustered or building usage is actively managed, hybrid formats offer a promising compromise with measurable emission reductions.

3.4.5 Material use plays a minor, but format-sensitive role

Across all formats, material use (e.g. printed documents) accounts for a relatively small share of total emissions. However, it is most pronounced in face-to-face settings, where physical handouts and printed materials are more common. Although minor in quantitative terms, reducing unnecessary printing remains a low-effort, symbolic opportunity for demonstrating environmental awareness in educational settings.

3.4.5 General insights and strategic implications

The DHBW case study demonstrates the practical applicability of the abstract, KPI-based model and its ability to meaningfully differentiate teaching formats in ecological terms. The results show clear variation in the per-student CO_2 emissions across formats:

- In-person teaching results in the highest footprint at approximately 0.906 kg CO_2 per student per hour (or ~7,972,800 kg CO_2 annually).
- Online teaching offers the lowest emissions, with ~0.621 kg CO_2 per student per hour (or ~5.467.000 kg CO_2 annually). Compared to in-person instruction, this represents a reduction of around 31%.
- Hybrid formats fall in between, with emissions of ~0.764 kg CO_2 (Mix) and ~0.77 kg CO_2 (Split). This corresponds to a reduction of approximately 15% to 16% compared to in-person teaching. Relative to online teaching, hybrid formats emit about 22% to 24% more CO_2 per student-hour.

These results confirm that emission responsibility is distributed differently across formats and that optimization strategies must be format-specific:

- For face-to-face teaching, mobility remains the dominant emission driver, making transportation policy and scheduling key levers for emission reduction.
- In online teaching, the focus shifts to household energy efficiency, equitable access to digital infrastructure, and the promotion of renewable electricity use at home.
- For hybrid formats, the structural and operational setup - such as clustered on-campus days, room usage strategies, and dynamic building control - directly impacts the ecological balance. The small difference between the "Mix" and "Split" methods (~2%) highlights how underlying assumptions about infrastructure operation can influence the results.

Overall, the analysis illustrates how a data-informed, KPI-driven approach can support evidence-based decision-making in the transition toward more sustainable university teaching. By aligning ecological insights with didactic needs and institutional capacity, higher education institutions can develop context-sensitive teaching strategies that contribute to climate protection while preserving flexibility and quality.

KPI / Format	In-Person	Hybrid	Online
Mobility	High	Reduced	None
Electricity Campus	High	Medium*	None
Electricity Home	None	Medium*	High
Heating Campus	High	Medium*	None
Heating Home	None	Medium*	High
Data Transmission	None	Medium	Medium
Material Use	High	Reduced	Low

** Medium = reduced, but still significant due to fixed base loads (Split method: 70% electricity, 80% heating).*

Table 7: Summary Table of KPI Relevance

4 Pathways Toward More Sustainable Higher Education

4.1 Framework Conditions for Sustainable Higher Education

A sustainable transformation of university teaching requires not only changes at the level of individual formats but also favorable overarching conditions. Fundamental framework requirements include data transparency, adequate infrastructure, and institutional willingness to act. Reliable information on commuting behavior, building energy use, and digital engagement is essential for evidence-based decisions. Moreover, both digital and physical infrastructures must support low-emission teaching - ranging from efficient campus buildings to functioning digital learning platforms. Institutional sustainability efforts should also be aligned with national climate goals and supported by policy instruments such as funding incentives or sustainability audits. In addition, flexible curriculum structures and scheduling models can enable more climate-conscious teaching designs. Finally, sustainability must be a shared responsibility: raising awareness and encouraging participation among students and faculty significantly enhances the acceptance and impact of emission reduction strategies.

4.2 Measures to Reduce CO_2 Emissions for Each Teaching Formats

4.2.1 In-Person Teaching

In traditional in-person teaching, the largest share of emissions is typically attributable to student and staff commuting. Accordingly, effective mobility management is a central lever for emission reduction. Universities can implement compact or block teaching schedules to minimize the number of weekly commutes and incentivize sustainable travel behavior through subsidized public transport tickets, improved cycling infrastructure, or carpooling programs. Since students are regularly present on campus, improving building energy efficiency is also essential - e.g., through potential thermal renovation, demand-based heating control, LED lighting, and the use of certified green electricity. Reducing material consumption - by moving away from printed handouts toward digital workflows - can further support emission savings without affecting instructional quality.

4.2.2 Hybrid Teaching

Hybrid formats, with their flexible combination of digital and physical participation, pose both challenges and opportunities from a sustainability perspective. Their ecological impact depends heavily on the specific implementation. For example, if students can freely choose between attending in person or online, energy use on campus often remains high regardless of reduced occupancy. To counteract this, institutions should design structured hybrid schedules - such as grouping physical attendance into dedicated on- campus days - to allow for partial campus closures or reduced heating and electricity demand. Promoting remote participation for students with long commutes or limited access to low-emission transport can also reduce travel-related emissions. Didactically, hybrid formats should be developed to avoid redundancy - e.g., by ensuring digital resources are fully equivalent to in-person content. Additionally, universities can evaluate the technical energy efficiency of hybrid classrooms (e.g., for lighting, AV equipment) and transition to greener systems where possible. A consistent use of renewable energy across both physical and virtual infrastructures can significantly increase the climate benefit of hybrid teaching.

4.2.3 Online Teaching

In fully online teaching, emissions shift from campus infrastructure and commuting to the private household level. While overall CO_2 emissions are often lower, the burden of electricity and heating consumption is transferred to students' homes. Universities can respond by providing guidance for energy-efficient remote learning, including recommendations on heating routines, energy-saving device settings, or optimized use of power strips. Additionally, offering technical support or low-energy equipment (e.g., loaner laptops, energy-efficient monitors) may help lower emissions and improve equity. Promoting the use of green electricity tariffs at home can further enhance the sustainability of online formats. Since printed materials are rarely essential in virtual settings, universities should standardize paperless teaching practices to avoid unnecessary resource use.

5 Discussion, Conclusion, and Outlook

5.1 Summary of the Main Findings

This thesis developed and applied a KPI-based model to assess and compare the carbon footprint of three dominant teaching formats in higher education: in-person, hybrid, and online. Drawing on secondary literature and empirical data from DHBW Stuttgart, the analysis demonstrated that online teaching results in the lowest per-student CO_2 emissions (~ 0.554 $kgCO_2/h$), followed by hybrid (~ 0.73 – 0.736 $kgCO_2/h$), and in-person formats (~ 0.906 $kgCO_2/h$). Key emission drivers differ by format: in-person teaching is dominated by commuting and campus energy consumption, while online teaching shifts emissions to the private sphere, particularly home heating and electricity. Hybrid teaching showed emissions highly sensitive to its structural design - especially the balance between on-site and remote participation. Across all formats, material usage had comparatively minor but format-sensitive effects.

5.2 Significance for Future Development of Higher Education

These findings highlight the potential for higher education institutions to actively contribute to climate goals through strategic format design. By adjusting teaching structures - such as clustering attendance days, promoting remote participation, or optimizing building usage - universities can significantly reduce their ecological footprint without compromising educational quality. Moreover, the KPI-based framework developed here offers a practical tool for institutional planning, enabling flexible adaptation to local infrastructure and policy conditions. As higher education continues to evolve post-pandemic, sustainability should be embedded as a core design principle in academic operations.

5.3 Critical Reflection of Results and Limitations

While the study offers robust insights, several limitations remain. First, not all emission categories - such as lifecycle emissions of IT equipment or backend internet infrastructure - were included, due to their diffuse and format-independent nature. Second, the model relies on generalized assumptions and national averages, which limit precision and neglect regional variability. Third, behavioral aspects - such as students staying at home during in-person days - were assumed rather than measured.

Furthermore, the study focuses solely on ecological dimensions, omitting pedagogical, social, and economic factors that are also crucial for evaluating teaching formats holistically. Nonetheless, these constraints were consciously applied to ensure transferability, transparency, and clarity.

5.4 Positioning within the Current State of Research

This work builds upon and synthesizes prior studies on the carbon footprint of educational formats, such as those conducted at THM, San José State University, and in Chinese and UK contexts. It contributes by integrating these diverse perspectives into a standardized, transferable model that bridges theoretical analysis and practical applicability. In contrast to institutional carbon accounting tools like the EFEU calculator, this study focuses specifically on the functional emissions of teaching activities, offering a new lens for strategic format evaluation. The case study approach further grounds the model in real-world university operations, enhancing its empirical value.

5.5 Recommendations for Further Research

Future research should aim to refine the model by incorporating primary data on student and staff behavior, energy usage patterns, and other aspects of digital infrastructure. Including Scope 3 emissions related to IT production and waste could yield a more complete picture of digital teaching formats. Moreover, longitudinal studies capturing seasonal effects (e.g., heating demand) and institutional transitions (e.g., hybrid uptake over time) would add depth. Cross-national comparisons would also be valuable in assessing the influence of energy systems and mobility infrastructure. Finally, expanding the scope to include social and pedagogical outcomes would support a truly multidimensional sustainability assessment of teaching formats

References

Al Kez, D., Foley, A. M., Laverty, D., Del Rio, D. F., & Sovacool, B. (2022). Exploring the sustainability challenges facing digitalization and internet data centers. *Journal of Cleaner Production*, *371*, 133633.

Attar, M. et al. (2024). *The EFEU Carbon Footprint Calculator*. https://www.dhbw-stuttgart.de/fileadmin/dateien/Forschung/EFEU/EFEU-Report-The-EFEU-CFP- Calculator.pdf

Egger, R. et al. (2022). *Hybrid, flexibel und vernetzt?* https://link.springer.com/book/10.1007/978-3-658-37204-0

HHU Heinrich-Heine-Universität. (2022). *Glossar für Lehr-Lern-Formen und digitale Lehre an der HU*. https://www.elearning.hhu.de/fileadmin/E-Learning/Downloads/220824_Glossar_Lehre-V2.pdf

Kerres, M. (2013). *Mediendidaktik Konzeption und Entwicklung mediengestützter Lernangebote.* https://www.researchgate.net/publication/362651599_Mediendidaktik

Little, M., Codero, E. (2014). *Modeling the relationship between transportation-related carbon dioxide emissions and hybrid-online courses at a large urban university*. https://www.researchgate.net/publication/265969442_Modeling_the_relationshi p_between_transportation-related_carbon_dioxide_emissions_and_hybrid-online_courses_at_a_large_urban_university

Lopes Silva, D. A. (2021). *The environmental impacts of face-to-face and remote university classes during the COVID-1S pandemic.* *https://www.researchgate.net/publication/351438c5c_The_environmental_impa*

Mustafa, A. (2022). *Beyond the COVID-1S Pandemic: Can Online Teaching Reduce the Carbon Footprint of the Internationalisation of*

UK Higher Education?. https://www.mdpi.com/2813-141X/1/2/11

Polomik, T. (2025, August 28). *CableLabs Deepens Engagement With RDK-B to Accelerate Innovation.* CableLabs. *https://www.cablelabs.com/blog/cablelabs-rdk-b-engagement-innovation*

Schomburg, J. (2024). *CO_2-Fußabdruck von „klassischen“ und „neuen“ bildungstechnologischen Formaten in Hochschulen am Beispiel der Technischen Hochschule Mittelhessen.* https://www.springerprofessional.de/co2-fussabdruck-von-klassischen-und-neuen-bildungstechnologische/2c8cc534

Umweltbundesamt (UBA). Emissionen des Verkehrs. *https://www.umweltbundesamt.de/daten/verkehr/emissionen-des-verkehrs*

World Resources Institute C World Business Council for Sustainable Development. (2004). *The Greenhouse Gas Protocol: A corporate accounting and reporting standard (Revised edition)*. *https://ghgprotocol.org/sites/default/files/standards/ghg-protocol-revised.pdf*

Yin, Z. et al. (2022). *The impact of online education on carbon emissions in the context of the COVID-1S pandemic – Taking Chinese universities as examples.* https://pmc.ncbi.nlm.nih.gov/articles/PMC8913334/*cts_of_face-to-face_and_remote_university_classes_during_the_COVID-1S_pandemic*

ANNEXES

Annex 1

Layout of the Calculator with the Results for DHBW Stuttgart

Name	Input (Valu	Unit
Emission Factor (Campus - type	0.221	kg CO_2/kWh
Emission Factor (Home - type o	0.221	kg CO_2/kWh
Emission Factor (Data Transmis	0.045	Kg CO2/GB
Emission Factor (type of materi	0.753	kg CO_2/kg
Emission Factor (electricity mix	0.055	kg CO_2/kWh
Emission Factor (transport mix)	0.139	kg CO_2/km
Average Distance per Roundtrip	32	km
Average Data Transmission 1 hr	1.5	GB
Number of Students	8000	number
Teaching Hours	5	per day
Teaching Days	220	per year
Total Electricity Demand (Camp	1479021	kWh per year
Total Heating Demand (Campus	692320	kWh per year
Own Renewable Electricity Suppl	140000	kWh per year
Own Renewable Heating Supply (	0	kWh per year
Material Demand (Campus)	12000	kg per year
Home Electricity Use	1500	kWh per Student per year
Home Heating Use	4200	kWh per Student per year
OnCampusShare	50.00%	%
OnlineShare	50.00%	%
FixedShare (Heating)	80.00%	%
VariableShare (Heating)	20.00%	%
FixedShare (Electricity)	70.00%	%
VariableShare (Electricity)	30.00%	%

Output				
	In-Person	brid (Mix vs Spl	Online	
Per Student Pe	0.906	0.770 0.764	0.621	kg CO_2
All Students Pe	7974126.28	6773243.94 6720819.30	5467512.33	kg CO_2