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Energy Efficiency and Decarbonization Resulting from the Transition to Virtual Space

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Abstract: It is a serious challenge for humanity to find an appropriate response to stop the accelerating rise in global temperature caused by atmospheric carbon dioxide emissions. After a methodological review of the literature, online and in-person modelling of education, work, and conferences, and relying on the results of life-cycle studies, we sought the answer to what reasonable solutions are available for decarbonization and energy reduction. During the research, the organizational carbon footprint of a selected office, educational institution and conference, and then the carbon footprint created by a person in 1 h, were examined. The two-day online education significantly reduced the daily commute load in transport by 402 tons of CO_2 equivalent per year. Still, the energy demand of home learning subtracts 136 tons from this, so the real benefit was 266 tons above in an institution educating nearly 3500 students. In a workplace of 180 people, where 52% of employees commute, 90% teleworking saved 222 tons of carbon dioxide emissions in one month, taking into account the carbon footprint of working from home. In the case of conferences, the online solution reduces the carbon footprint due to the absence of travel and catering. Comparing the three areas, for the in-person case, the conference's carbon footprint per person per hour was the highest (11.91 kg CO_2 eq.). This value for education was 1.15 kg CO_2 eq.; for work, it was the lowest with a value of 0.90 kg CO_2 eq. Moving to an online space resulted in the most significant savings for the conference (11.55 kg CO_2 eq.), followed by working (0.54 kg CO_2 eq.), and minor savings were achieved in hybrid education (0.13 kg CO_2 eq.). The sensitivity analysis highlighted the impact of transport on carbon footprint in all three cases. However, the life cycle cost analysis showed that moving to a virtual space reduces the life cycle cost of de-carbonization by 42%.

Academic Editors: Domicián Máté and Hora Cristina

Received: 3 February 2025
Revised: 21 February 2025
Accepted: 27 February 2025
Published: 28 February 2025

Citation: Mannheim, V.; Szalay, Z.; Sándor, R.B.; Terjék, A.; Avató, J.L.; Sasvári, P.; István, Z.; Szilágyi, A.; Kaczkó, O.S.; Szita, K.T. Energy Efficiency and Decarbonization Resulting from the Transition to Virtual Space. *Energies* **2025**, *18*, 1206. https://doi.org/10.3390/en18051206

Keywords: energy efficiency; carbon footprint; life cycle assessment; in-person modelling; online modelling; life cycle costing; education; work; conference

1. Introduction

1.1. Research Background

Nowadays, one of humanity's most significant challenges is finding a solution to halt the rise in global temperatures due to carbon dioxide emissions. The climate system becomes increasingly unpredictable and dangerous as the temperature increases every tenth of a degree. The global average temperature in 2022 exceeded the pre-industrial (1850–1900) average by about 1.15 (±0.12) °C, according to the 2023 data set published by the World Meteorological Organization (WMO) [1]. 2022 was Europe's second-warmest year. Extreme heat waves, droughts, and devastating floods affected millions and cost billions of dollars in 2022. The sixth report of the Intergovernmental Panel on Climate Change (IPCC) [2] outlines the risks that may arise due to climate change under different scenarios. According to the Conference of the Parties 21 (COP 21) [3], we must limit global warming to 1.5 °C [4]. The European Green Deal (EGD) [5] defines transformative change.

The "Fit for 55" legislative package [6] enables all sectors of the European Union (EU) economy to achieve this goal. It sets the EU on the path to achieving its climate goals in a fair, cost-effective and competitive way. All EU member states are committed to making the EU climate-neutral by 2050 [7]. It creates new opportunities for innovation, investment, and job creation, reducing emissions and external energy dependence [8,9].

Climate change, pollution, and energy dependence support the need for decarbonization research topics. At the same time, decarbonization has been the focus of investigations due to climate policy objectives and digitization has become increasingly important due to COVID-19 and worldwide lockdowns. The latter saves time and reduces travel energy, but Information and Communication Technology (ICT) also requires energy. A significant question is the size of the carbon footprint of modern digital technology and the potential for reducing carbon emissions through the use of digital technologies in education, work, and conferences.

1.2. Literature Review

Information technology integration in the workplace began in the 1990s, and telecommuting emerged in the early 2000s. However, globalization and information communication technologies have further increased the trend of telecommuting. The COVID-19 pandemic has led to a significant increase in remote work, catalyzing innovation in work models. Remote work has become prevalent in many sectors and has taken various forms due to the spread of digital technologies [10].

Digital technology is essential for work and research. It provides access to global information and enables collaboration through file sharing and joint editing. Daily communication through emails and platforms like TEAMS is standard in the modern work environment. Innovative developments in ICT significantly reduce the environmental impact of technology.

The environmental impact of energy consumption from home office work can be characterized based on a life cycle assessment. The energy consumption of IT devices and lighting is assumed to be consistent across geographical areas, but the carbon footprint depends on the energy mix of the specific country or region [11,12]

The ICT Footprint project [13] aimed to help organizations calculate their carbon footprint, providing methodological recommendations and educational materials. ICT accounts for 8–10% of Europe's electricity consumption and 4% of its carbon dioxide emissions. Many leading IT service providers lack an adequate system for measuring environmental impact [13]. Analyzing the carbon footprint of ICT is crucial due to the increasing use of technologies in businesses, organizations, and daily routines, and is vital for reducing the global carbon footprint.

Some scientific publications [14–16] on the environmental impact of virtual work and its life cycle have been published, but this leads to uncertainty about the comparability of data. Vartiainen published a comprehensive study [17] on the impacts of virtual work, demonstrating its effects through case studies. Lehmann and Hietanen's study [18] examines work trends and provides a methodological foundation for mapping the environmental impacts of remote work using a life cycle approach.

Alneyadi and his co-authors [19] conducted a comparative analysis of digital and presence work, focusing on the digital environment's impact on knowledge. The study emphasized the importance of technology integration, including reading skills and creative expression. The study's small sample size limits the ability to make generalizations based on the findings.

A pivotal study by Geneidy et al. [20] analyzed the carbon footprint of a multinational knowledge organization, revealing that 79% of emissions come from indirect sources, mainly travel-related activities classified as Scope 3 emissions. The authors developed three scenarios for the post-COVID-19 world. In the first two, travel-related emissions remained significant despite reduced business travel and remote work. Only in the third scenario did these emissions decline, with heating becoming the top contributor. The study measures carbon footprints and outlines effective mitigation strategies for knowledge organizations aiming to lower their environmental impact [20].

Existing studies [21–25] on telecommuting primarily focus on CO_2 emissions associated with reduced transportation. Other environmental metrics related to telecommuting are not as well-studied, justifying the focus on emissions. The pandemic's impact on mobility can serve as a starting point for understanding the broader environmental effects of telecommuting [26]

A study by Shi et al. [27] found that the emissions of English teleworkers are significantly higher than those of non-teleworkers. When working from home 3–5 days a week, transport resulted in 3% less emissions, but there was a 17% increase in carbon dioxide emissions compared to traditional work. The emissions were influenced by factors such as the heating area, the heating time of the heating system, and the desired temperature.

The overall effect of telework on the ecological footprint is not apparent. According to Lachapelle et al. [28], telecommuting may increase production and income, resulting in increased consumption habits and higher energy demands, potentially leading to a larger total ecological footprint. The impact of telecommuting on emissions reduction from reduced commuting may be offset by increased consumption and higher energy demands.

Increased use of telecommunications and heating of homes has a negative effect on the climate. Companies may not be developing strategies to reduce office space and energy consumption. IT equipment has shown dynamic energy consumption in recent years. For example, internet use has a carbon footprint related to the energy consumption of data and cloud centres, ranging between 28 and 63 g of CO_2 equivalent per gigabyte by Obringer et al. [29].

Heated areas, the number of heating hours, wall insulation, heating system efficiency, and carbon dioxide intensity impact the emissions of buildings accommodating workplaces. Video conferences are identified as the internet service with the most significant energy demand, but technological development is leading to more energy-efficient solutions. Telecommuting can reduce mobility and greenhouse gas emissions, mainly caused by commuting from home to work. Telework or hybrid work is often cited as reducing carbon dioxide emissions due to lower commuting rates from home to work [30].

There is limited knowledge on the carbon footprint of higher education. A study by Li et al. [31] examined the state of research in this field, focusing on key publication sites, central researchers, productivity and citations, common keywords and research directions, and the most active research regions worldwide. The study also analyzed changes in these indicators over the past decade.

Bibliometric studies cover various areas of carbon footprint reduction in higher education institutions. These areas include researcher travel, student carbon footprint reduction efforts, emissions from campus buildings, environmental impact from daily commuting, campus electronic equipment, the carbon footprint of students living in dormitories, and perceived footprint reduction through online education. However, these studies do not address the impact of the carbon footprint of higher education institutions on stakeholders.

Li et al.'s bibliometric analysis [31] revealed various test methods and solutions to reduce carbon footprint. It encouraged sustainable consumption, transitioning to a low-carbon economy, increasing the sustainability of project procurement, prioritizing environmentally friendly energy sources, and promoting sustainable lifestyles.

Filho et al. [32] analyzed the decarbonization efforts of universities up to 2050, identifying fossil-fuel burning as the primary source of carbon emissions. Decarbonization at the global level requires establishing systems that reduce carbon emissions to environmentally sustainable levels.

Efforts to reduce carbon emissions have economic implications, which are still debated in some studies. Accepted methods to reduce carbon emissions include reducing energy consumption, using renewable energy sources, increasing energy efficiency, and limiting performance. The COVID-19 pandemic led to a shift to digital platforms in higher education, significantly impacting energy consumption and mobility-related loads.

The pandemic also provided an opportunity to examine the impact of distance education on carbon footprint. Many universities (De Montfort University, University of British Columbia) have been assessing their carbon footprint, with studies published in scientific journals. Different methods [33,34], such as the consumption-based carbon footprint definition and input–output analysis, have been used to determine the carbon footprints of institutions.

Models that can be used for the decarbonization assessment of conferences usually include computational tools and simulation models that allow the estimation of the carbon footprint and climate impacts of online conferences and the evaluation of the effects of decarbonization measures.

For example, a carbon footprint calculation that considers the climate impacts of the entire life cycle of online conferences, including event preparation, energy use, travel costs, and infrastructure, can be used for sustainability assessment. These models can compare the emission levels of different conferences, identify the areas with the highest emissions, and recommend decarbonization measures. The energy consumption of offline and online conferences is used to compare the carbon footprints [35].

1.3. Research Goal and Hypothesis

During the research, parallel investigations of three areas: education, work, and conferences were conducted. The first step investigated the literature and methodological reviews regarding the given topic and modelling for in-person and online versions. In the framework, a life cycle assessment approach was used to identify options for decarbonization.

The energy consumption required for work and its main elements, such as IT devices, heating/cooling energy demand, and lighting, are examined when modelling online versions. Regarding work types, an economic evaluation of decarbonization based on life cycle cost (LCC) analysis was performed. We applied the LCC to the scopes (1,2,3) defined by the ISO 14064 standard [36].

The research aims to model the online/digital transformation of some offline organizational activities in a way that can be used to reduce their CO_2 emission impact and natural load. However, the question arises: How can the decarbonizing effect of digitization be modelled and measured?

Our initial hypothesis is that the transition to online versions strongly reduces the carbon footprint of in-person organizations for education, work, and conferences.

Regarding education, we examined the kind of ecological loads we must deal with in the operation of a university campus. The work aimed not to analyze online education's methodological and social aspects. A prominent topic was how online education, which is spreading more and more in higher education, can affect the environmental impact of education. In the field of education, the research focuses on three main areas:

- To determine the carbon footprint of university education and a university campus and to find possible emission reduction areas.
- To examine the impact of the online education format on carbon footprint.

In examining in-person and home office work types, we assumed as a hypothesis that using heating, lighting, and IT equipment during home office work, as a rebound effect, neutralizes the impacts of the absence of travel.

The primary goal of the conference research was to compare a two-day in-person conference with an online conference by conducting complete life cycle assessments that evaluate carbon footprints and energy consumption values. After conducting literature research on the carbon footprint of education, workplaces, and conferences, and calculating decarbonization solutions, the calculations' results were compared and discussed, and the conclusions were determined.

2. Materials and Methods

2.1. Research Methodology

Decarbonization can be characterized based on the difference (ΔCF) between the carbon footprint of the presence (CF_j) and online, digital (CF_D) solutions [37]:

$$\Delta CF = CF_j - CF_d$$

When determining the carbon footprint, we follow the methods of counting the emissions that determine the emissions of the areas of influence (SCOPE) according to the standard. We aggregate the carbon footprints determined in this way. The calculation is the same for offline and online solutions. The formula used in the calculation is as follows:

$$CF_M = \sum (i = 1)^n \ CF_i$$

where

CF_M: workplace carbon footprint
CF_i: factors involved in the formation of the carbon footprint
CF_{direct}: direct emissions
Detailed as follows:

$$CF_M = \sum CF_{direct} + \sum\_ \ CF_{indirect} + \sum\_ CF_{other}$$

where

CF_{direct}: direct emissions related to energy use

$CF_{indirect}$: indirect emissions linked to energy (electricity)
CF_{other}: other indirect
Other CF consists of emissions of the following elements:

$$\sum CF_{other} = CF_{transport} + CF_{foreign\ travel} + CF_{business\ partner} + CF_{meals} + CF_{waste} + CF_{water}$$

Using LCA software 2.0.2, in addition to choosing different impact assessment methods, the potential of greenhouse gases can be determined for the entire life cycle (cradle to grave), and the carbon footprint can be given by aggregating them. According to the CML method and IPCC/ARC6 standard, the software is suitable for determination.

2.2. Methodology for Decarbonization Calculation of Examined Areas

The research examines the significant reduction in carbon footprints associated with education, work, and conferences resulting from the transition to virtual formats. The carbon footprint calculation methodology followed the Greenhouse Gas Protocol and the ISO 14064 standard for organizational carbon footprints. We applied the given standard across all three analyzed areas and employed two different life cycle assessment software for precise estimation.

In the case of education, the carbon footprint of the university campus for the years 2021 and 2022, over a reference period of ten months, was determined. Regarding work, the calculation is based on data measured during two specific periods of the workplace environment (February 2020 and February 2021). The analyses of education and online work were conducted during the COVID-19 pandemic. Therefore, it is essential to note that during this period, the building's heating and lighting systems operated at a lower efficiency.

The carbon footprint was calculated for conferences based on an international conference held in 2019. Furthermore, we carried out a separate, in-depth study on the life cycle assessment of conference catering services.

We considered food and beverages within the cradle-to-grave analysis, with life cycle stages defined based on the weight of the portions served. Transport was completely excluded from this study, as the food ingredients do not originate from the same place.

The first methodology step calculates the carbon footprint values for the entire duration, extending it to the three areas by clearly defining the system boundary of the LCA and performing a detailed inventory analysis. As the second methodology step, one hour per person is used as a functional unit to compare the different event areas' carbon footprints.

The LCC analysis was performed only for work types. Finally, a sensitivity analysis methodology to all three examined areas was applied. Table 1 summarizes the main parameters and applied research methodology tools for the three examined areas.

Table 1. Methodology for modelling of decarbonization based on the reference period and number of participants.

	Education	**Work**	**Conference**
Reference year (in-person case)	2022	2020	2019
Reference year (online case)	2021	2021	
Reference period	10 month	Month: February	2 day event (15 h) Month: September

Table 1. *Cont.*

	Education	Work	Conference
Number of examined participants (for both cases)	155 employees 3350 students	180	200
Commuting (in-person case)	2500 persons	95	160
Commuting (online case)	2500 * persons	18	-
Examined travel distance [km] (in-person case)	350,000	20–250	20–13,700
Examined travel distance [km] (online case)	140,000	1–50	-
Applied software	OpenLCA 2.0.2		Sphera, GaBi 9.0
Applied data base	Ecoinvent 3.9.1		GaBi 10.6
Functional unit	1. Carbon footprint value in tons over 1 year. 2. Carbon footprint value per person and hour.		
LCIA methods	ISO 14064		CML 2016 excl. biogenic carbon IPCC AR6, GWP 100, excluding biogenic carbon

* The number of commuting students remains the same, but the frequency of their travel from home to university has changed.

Table 2 presents the scenarios and scopes for the applied methodology for education.

Table 2. Scenarios and scopes for modelling of education.

Education	
Scenario 1 (S-1) (In-Person Education)	**Scenario 2 (S-2) (Online/Hybrid Education)**
Students and lecturers visit the university on average four times a week.	Theory classes are online and students visit the university twice weekly. (Different frequency trips home and back).
Direct scopes (Scope 1)	
Natural gas consumption for heating, official university cars, HFC32.	
Indirect scopes (Scope 2)	
Office lighting, heating/cooling, and power consumption of IT tools.	
Other scopes (Scope 3)	
Travelling of students and workers, computer usage, online consumption, water consumption, and waste management.	

The examined university campus consists of the main building, dean's offices, classrooms, and laboratories. It is more than 100 years old.

- Building B: Mainly a laboratory, a few classrooms, and teachers' rooms. It is an old building, more than 100 years old.
- Building C: Faculty rooms and departmental offices. It is about 50 years old.
- Building G: Three large lecturers, small classrooms, IT labs, and teaching rooms. Newly built, approximately 15 years old.

A canteen and a dormitory building are also connected, but these are not part of the analysis. The campus serves the educational needs of most of the Kálmán Kandó Faculty of Electrical Engineering and the Károly Keleti Faculty of Economics.

The proposed possible solutions have been classified into three groups:

- Energy supply and energy-saving solutions.
- The reduction in emissions that can be achieved through the organization of transport and education.
- Solutions that support environmental education.

Table 3 presents the three scenarios and three scopes for the work. The S-3 scenario is based on the actual data of S-1 and S-2. The comparison is performed in a complete system, i.e., it considers the elements of working at home that were taken into account when working at the workplace (heating, energy use, etc.). The LCA-based approach to the carbon footprint and the analysis and comparative evaluation of the S-1, S-2, and S-3 scenarios made it possible to determine hot spots and decarbonization paths.

Table 3. Scenarios and scopes for modelling of the work.

Work		
Scenario 1 (S-1) (In-Person Work)	**Scenario 2 (S-2) (Home Office Work)**	**Scenario 3 (S-3) (Hybrid Work)**
100% of the employees come to work, and there is no option for home office work.	90% of employees work at home, and only 10% must be at the workplace.	Home office work is possible, which affects 20% of employees, so 80% come to work.
Direct scopes (Scope 1)		
Gas consumption, company cars, and HFC32.		
Indirect scopes (Scope 2)		
Office lighting, power consumption of IT tools, cooling/heating, and power demand of kitchen equipment.		
Other scopes (Scope 3)		
Business trips, employee commuting, employee meals, waste, and wastewater streams.		

Regarding work, life cycle cost analysis was investigated using the following three scenarios:

Scope 1: gas consumption cost, costs of company cars, loss of air conditioners.

Scope 2: costs for office lighting, power consumption of IT devices, cooling/heating, and power demand of kitchen equipment.

Scope 3: costs for business trips, employee commuting, and employee meals, waste cost and water consumption cost.

The calculation of conference types is based on data collected from a two-day international science conference held in October 2019 in Hungary. The functional unit used for measurement was kilograms of CO_2 equivalent per person per hour. The following scenarios were examined:

- In-person conference: This scenario is based on accurate and measured values, including travel to the conference site and registration packages.
- Online conference: This scenario omits travel and registration packages, focusing solely on virtual attendance.

Figure 1 summarizes the methodological analysis steps of the in-person conference as an example.

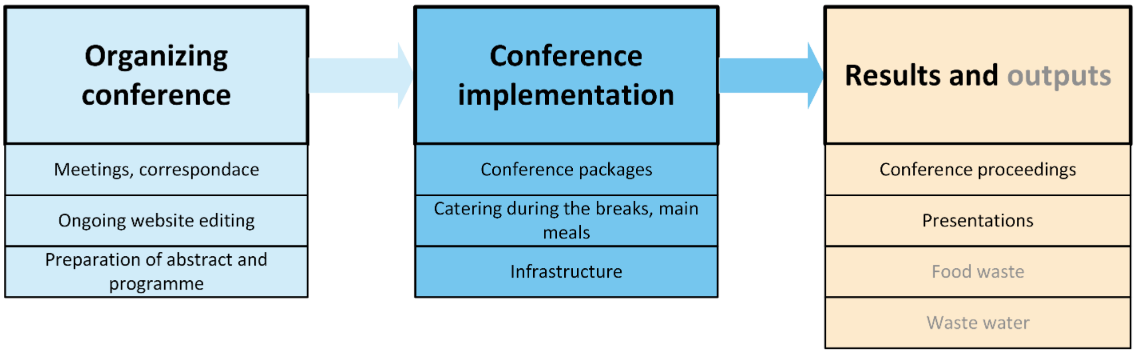

Figure 1. Methodology of examination for in-person conference.

2.3. Allocation and System Boundary

All environmental loads were allocated by mass allocation to the tested products and the generated waste. The material and energy flows used are related to the examined product output. The energy requirement was determined as a function of the energy content.

Equipment and machinery fell outside the system boundary. While we did not find transport emissions to be as substantial, we took into account waste management and home heating for in-person education, as well as computer use for online education, all within the system boundary. Due to the unavailability of reliable data, we placed certain factors such as purchased equipment, the embodied CO_2 content of the building and procurement, meals, building maintenance, and cleaning outside the system boundary.

During the LCC, we assumed that the system boundary established during the LCA analysis and the functional unit determining the basis for the comparison was the same. Construction and maintenance costs of buildings were not considered when determining the LCC. IT equipment and internet-related costs were also not the focus of the study since these areas were not considered during the environmental studies. Therefore, operation-related costs were primarily taken into account.

2.4. Life Cycle Inventory (LCI)

The life cycle inventory is based on data between 2019 and 2022 and follows the technique described in the ISO 14040:2006 and 14044:2006 standards [38,39]. It includes the material and energy supply of all the examined processes. Table 4 shows the life cycle inventory for the three examined areas for in-person and online cases.

Regarding work examination, the data collection was carried out for the office building, which forms the basis of the reference model, and for the input–output currents defined in the model. The data affecting the carbon footprint development were taken into account based on the measured data of the relevant offices (operations, IT, HR), with an allocation that considers the actual area and personnel data.

Regarding conference main dishes, we aimed to create an accurate list of resources for preparing and cooking products. The Hungarian Saint Anna Restaurant (in Berkenye) provided key kitchen data for our analysis of lunch and dinner served during the in-person conference. We received specific information about material and energy use for each main course, including electricity for cooking, gas consumption, and water warming. We measured ingredients, electricity for storing items, and drinking water for cleaning and cooking.

The material flows analyzed for the online case were aligned with those from the in-person event to ensure consistency. During the preparation and cooking phase, the LCI includes wastewater from washing raw materials and dishes and the necessary water input flows [38,39].

Table 4. Methodology of life cycle inventory (LCI).

	Education	Work	Conference
Cut-off flows	Building maintenance, equipment acquisition.	Building maintenance, equipment acquisition.	Kitchen equipments, extra materials, additives, energy for heating/cooling.
Water input flows	Estimated data based on the bill.		Tap water for the food preparation phase, cooking, dishwashing and hand washing.
Wastewater output flows	Estimated data based on the bill.		Wastewater from dishwashing, handwashing, and tank flushing by toilet use.
Areas of considered energy flow inputs for in-person case	Energy consumption of the given university. Natural gas consumption for heating. Lighting, heating/cooling, and power consumption of IT tools.	Heat pump, natural gas for heating, office lighting, and power consumption of IT tools.	Power consumption of IT tools, lighting with neon tubes, electricity and natural gas for cooking and water warming.
Areas of considered energy flow inputs for online case	Energy consumption at home. Lighting, heating, and power consumption of IT tools.	Energy consumption at home. Lighting, heating, and power consumption of IT tools.	Laptop's power consumption, home room lighting, natural gas consumption for cooking, gas consumption, and water heating for dishwashing, and handwashing at home.
Energy consumption (in-person case) [kWh/month]	24,000	30,900	1365 (only considering equipment energy consumption)
Energy consumption (online case) [kWh/month]	18,000	11,300	259 (only considering equipment energy consumption)
Catering (in-person case)	Central Statistical Office and household data.		Data from Saint Anna Restaurant (in Berkenye, Hungary)
Catering (online case)	Central Statistical Office and household data		Data measured on a household scale.
Heating for in-person case	Measured data at the examined university.	Measured data at the given office.	Not considered (assuming of the month of September).
Heating for online case	Measured data of the university. Central Statistical Office data for households.	Measured data of office. Central Statistical Office data for households.	Not considered (assuming of the month of September).
Other inputs for in-person case	-	-	Hand towel sheets, toilet paper, and liquid soap
Other inputs for online case	-	-	Toilet paper, and soap.
Other outputs (in-person case)	Communal waste.	Communal waste.	Paper waste, cooking oil waste, food waste from all life cycle stages, used tea bags from catering, and lemon peel. (Regarding food waste, we estimated that 15% of the soup, 26% of the main course, and 5% of the dessert would be wasted).
Other outputs (online case)	Communal waste.	Communal waste.	Used cooking oil, food waste from the food preparation stage, used tea bag, and lemon peel.

3. Results

3.1. Comparing the Environmental Impact of Education

In terms of education, the current state of in-person instruction was evaluated under Scenario 1, which involves the campus operating continuously with students and lecturers visiting the university an average of four times a week. In contrast, Scenario 2 analyzed a hybrid education model as an online model, where theory classes are conducted online and students come to the university twice a week. Additionally, direct, indirect, and other scopes (Scopes 1–3) were introduced to calculate the carbon footprint based on subchapter 2.2.

Figure 2 compares the carbon footprint of in-person and online education based on the examined scopes. If we only look at the emissions of Scope 1, the annual value of attendance education is 1827 tons of CO_2 eq., and the difference is 266 tons.

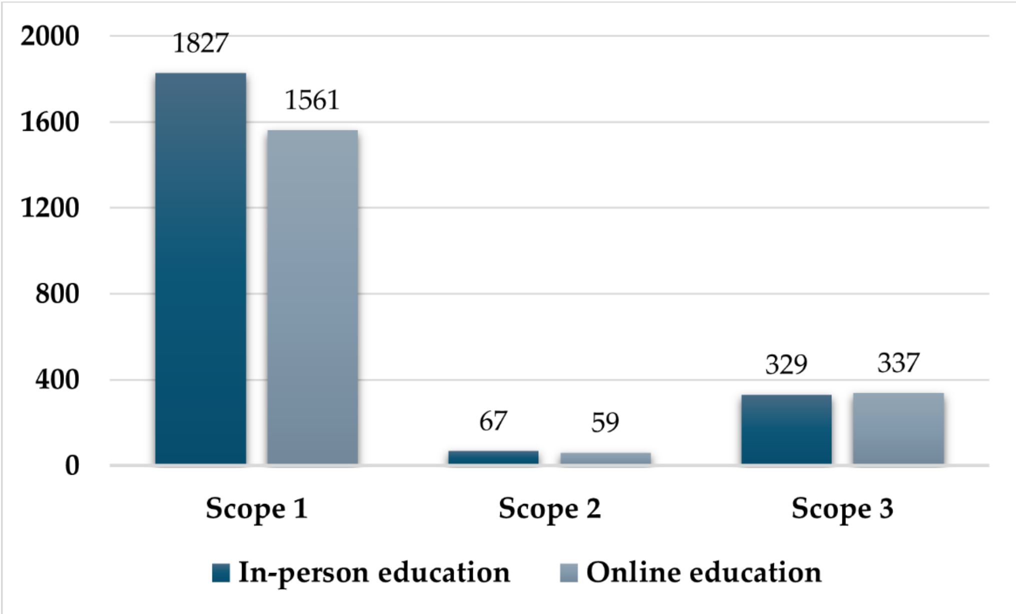

Figure 2. Comparison of the carbon footprint for in-person and online education.

In the case of in-person education, the total campus's carbon footprint for the given year (2022) is 2223 tons of CO_2 eq. Likewise, if online education had been introduced twice a week (online case), it could have been 12% less, i.e., 1957 tons, saving 266 tons per year. Figure 3 shows the comparison of the carbon footprint of in-person and online education according to Scope 3.

Figure 3 shows that 96% of the environmental impacts are caused by student travel during in-person education. The subsequent impact is the travel of teachers and researchers to work. These travel values are reduced in the hybrid solution, but not by as much. Gas consumption hardly changed during the closure, and electricity consumption showed a 10–15% decrease in the spring of 2021. Online consumption regards the extra heating and lighting required during online education. Home computer use regards the computer and internet use needed to process online educational materials. One factor that dominates is the students' use, which is worth breaking down further. The contribution of official trips to lecturers and university water consumption is negligible, below 0.5%.

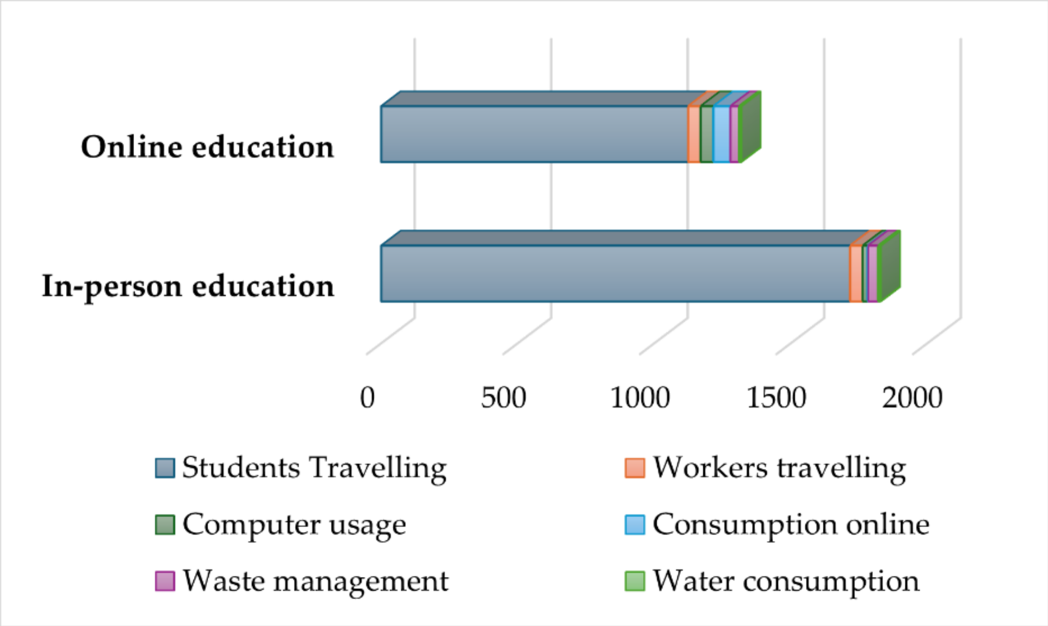

Figure 3. Comparison of the carbon footprint of in-person and online education according to Scope 3 in tons per year.

3.2. Comparing the Environmental Impact of Work

In terms of education, three scenarios and direct, indirect, and other scopes were introduced to calculate the carbon footprint based on subchapter 2.3.

If we examine scenarios S-1, S-2, and S-3 individually, the pie charts in Figures 4–6 illustrate the parameters' percentage distribution. The impact of HFC32 is negligible and has, therefore, been omitted from the diagrammatic representations. We have plotted gas and water consumption together for all three scenarios, of which water consumption represents 97–98%. We have also plotted the impacts of eating and waste together. While the eating–waste ratio for the S-1 and S-2 scenarios is 91–9%, for the S-3 hybrid working environment, this ratio is 96–4%.

Figure 4 shows that employee commuting is the most significant contributor to a company's carbon footprint, accounting for about 55% of total emissions for in-person office work. This is followed by lighting, which contributes 14%, IT equipment usage, 8%, and heating and cooling, which contributes 7.5%.

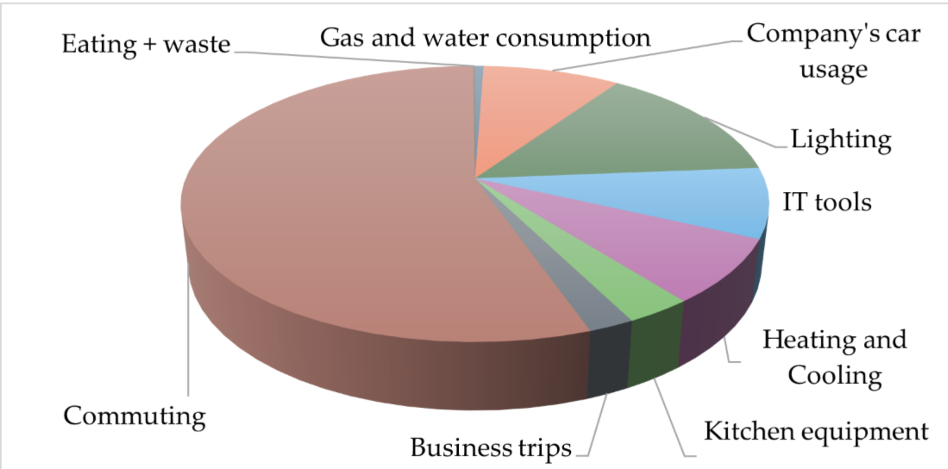

Figure 4. Percentage distribution in the case of scenario S-1.

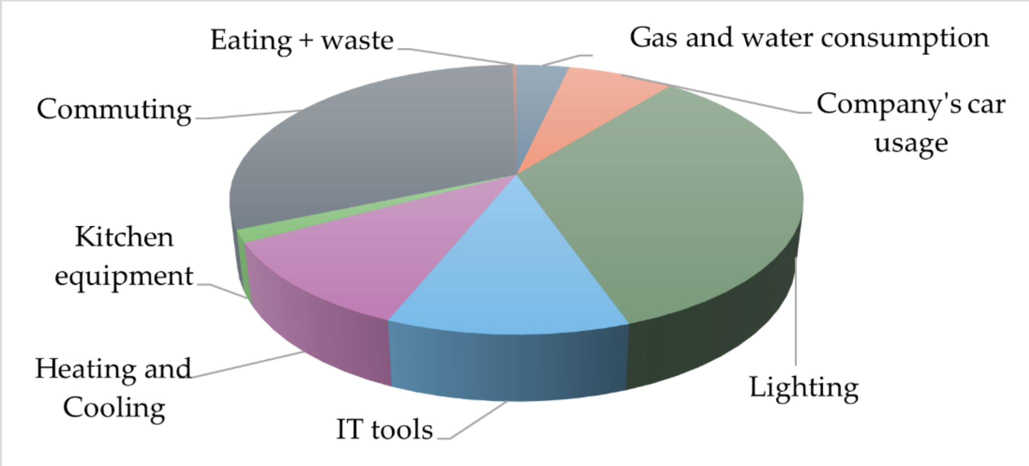

Figure 5. Percentage distribution in the case of scenario S-2.

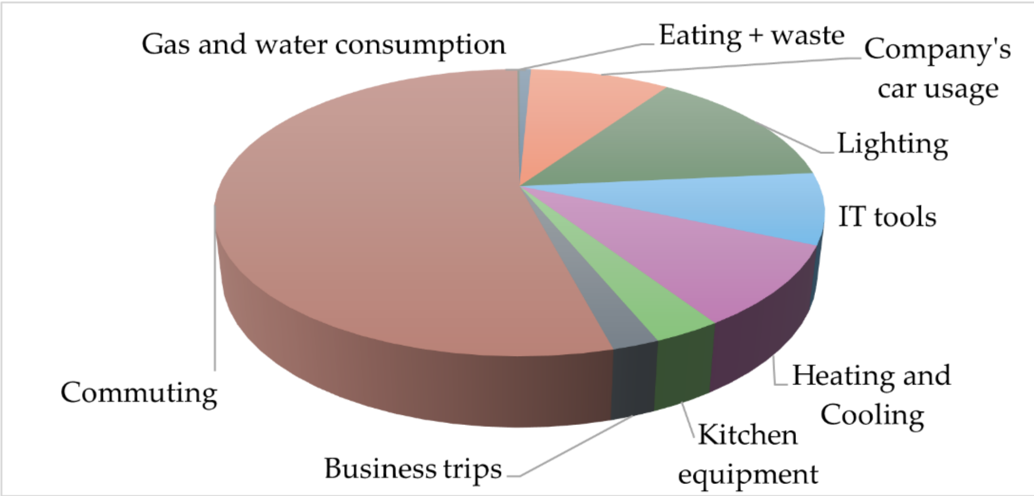

Figure 6. Percentage distribution in the case of scenario S-3.

Regarding 90% of home office work, as shown in Figure 5, lighting and water consumption cause the most significant load at 34% each. The load caused by commuting is relatively high compared to working from home, which is 31%. The load from the company car is 7%. The load from IT tools and heating–cooling ranges between 11 and 12%. The amount of kitchen loads is almost negligible, as the total load caused by food, waste, and kitchen utensils is only 2%. We considered the value of business trips to be zero in this scenario.

Figure 6 shows that employee commuting is the most significant contributor to a company's carbon footprint, accounting for 54% of total emissions for hybrid work. It is followed by lighting, which contributes 14%, IT equipment usage, which contributes 8%, and heating and cooling, which contributes 9%. There are no significant differences between the S-3 and S-1 scenarios.

Figure 7 summaries the carbon footprint values for the three work scenarios in kg CO_2 equivalents per month based on the consumption elements.

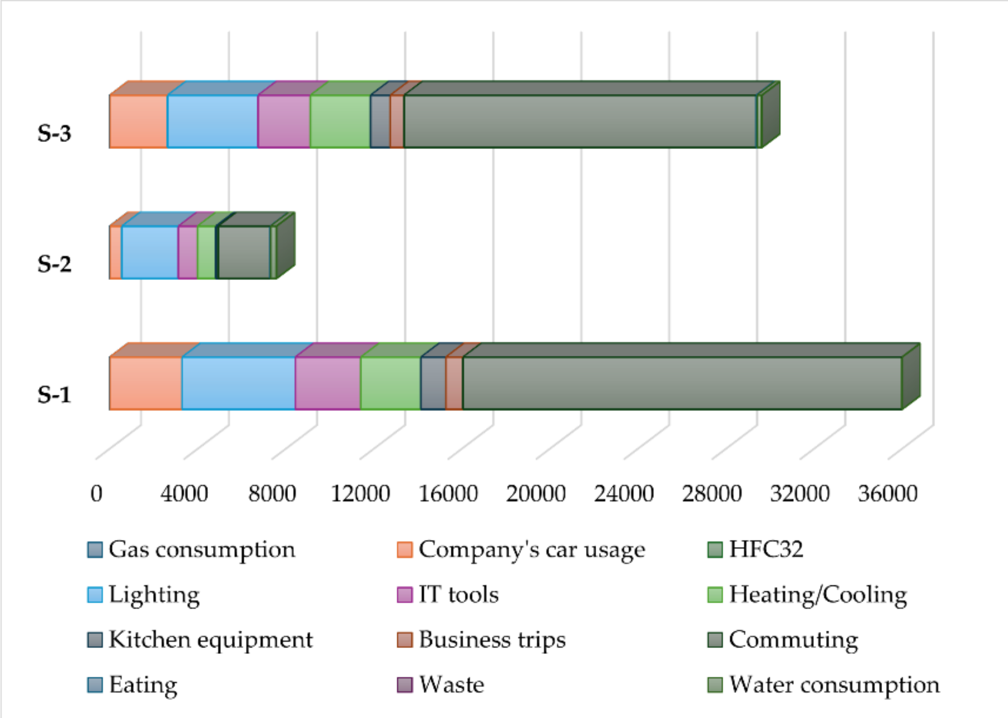

Figure 7. Carbon footprint values for the three work scenarios in kg CO_2 equivalents per month based on the consumption elements.

3.3. Life Cycle Cost (LCC) Analysis for Work Types

The LCC analysis was performed based on the methodology and scopes previously described for different work types. Homework costs include heating, lighting, water consumption, and meals. External costs are determined based on the CO_2 quota (the employer is not currently charged for this cost element). After the calculations, the life cycle cost based on the various alternatives is summarized in Figure 8.

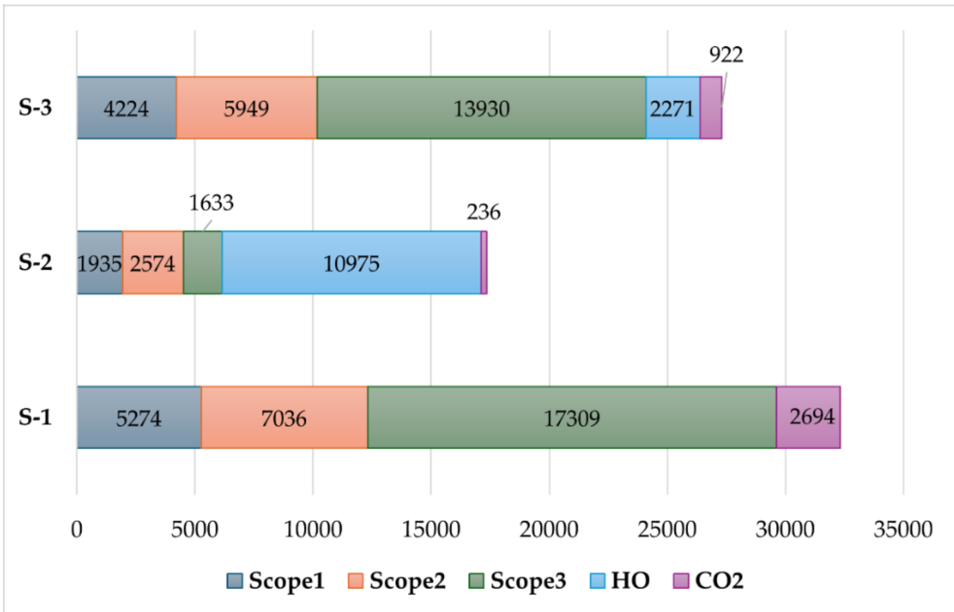

Figure 8. Life cycle cost per one month in EUR.

Based on Figure 8, the life cycle cost of the S-1 alternative is projected for one month at EUR 32,313, the S-2 alternative for one month at EUR 17,353, and the S-3 alternative for one month at EUR 27,296.

The digital transition—due to working from home—resulted in a 42.2% reduction in life cycle costs. From the employer's point of view—where the employer does not cover the cost of working from home—there is a further reduction in costs, the value of which is a 79.2% saving. If we project the analysis onto the functional unit used in the LCA study (one person per hour), the trend does not change based on Figure 9.

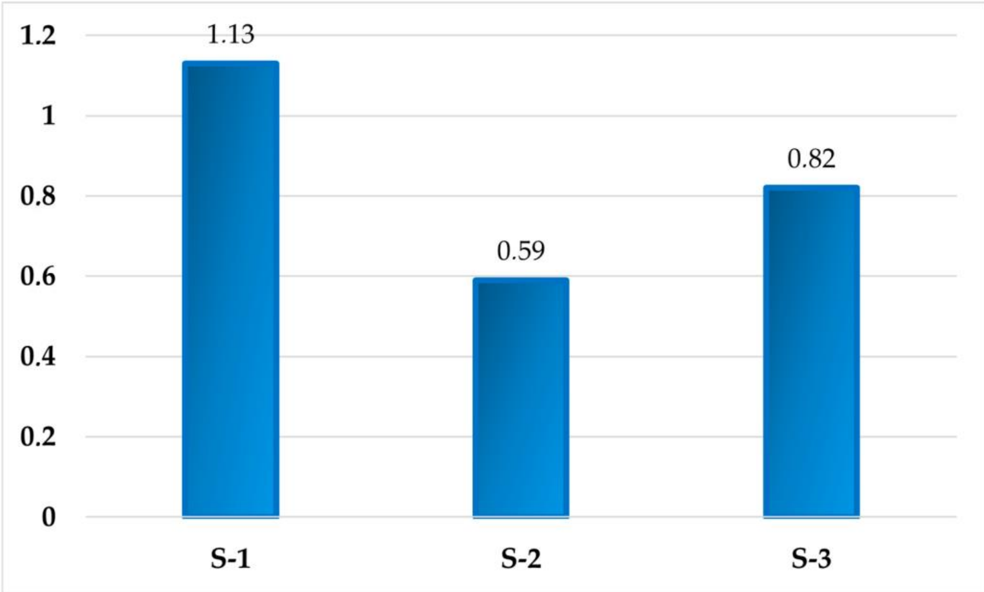

Figure 9. Life cycle cost per person and hour in the EU.

An interesting indicator of LCC studies is the specific cost of the carbon footprint, which depicts the costs associated with each alternative compared to the value of CO_2 emitted (see Figure 7).

Figure 9 shows that although the life cycle cost has decreased due to working from home, the decrease is less than the reduction in the carbon footprint.

Since the employer does not assume the costs of the employee, in the case of work performed at home, the cost reduction is still noticeable from the employer's point of view. For the employer, if 90% of the employees work at home, the cost is only EUR 0.22/person/hour.

3.4. Comparing the Environmental Impact of Conferences

The carbon footprint results of the conference types are calculated for one person and one hour. Figures 10 and 11 present the percentage distribution of decarbonization values for in-person and online conferences. The main meals, which included two lunches and one dinner during the two-day event, were combined in the illustration. The organization and management have a negligible effect compared to the other parameters examined, so they were not depicted for the two cases. Conference trips are examined in the case of an in-person conference, which includes travels by plane, train, and car.

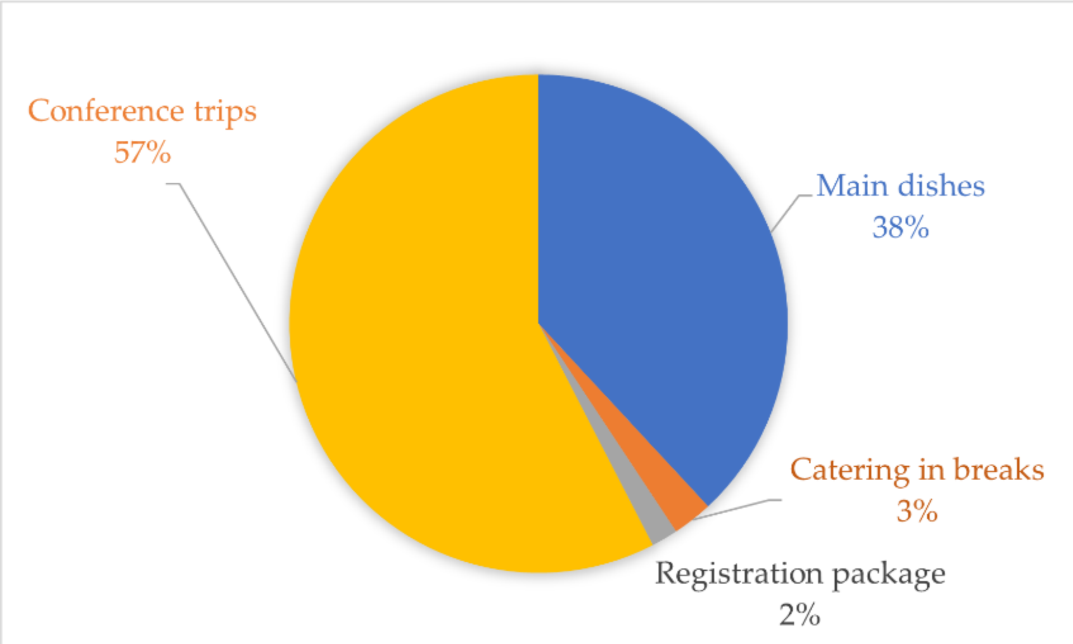

Figure 10. Percentage distribution of carbon footprint for in-person conference based on the CML 2016 LCIA method (functional unit: one person/one hour).

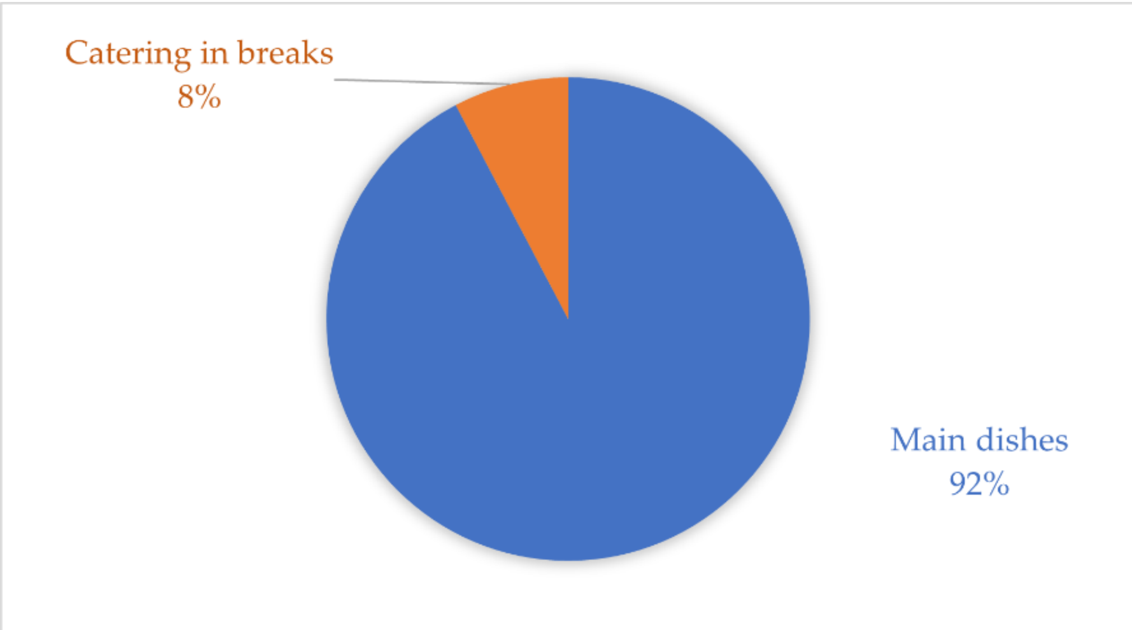

Figure 11. Percentage distribution of carbon footprint for online conference based on the CML 2016 LCIA method (functional unit: one person/one hour).

In the case of an in-person conference, conference trips account for 57% of the environmental load, and the conference main dishes account for 38% of the impact. In the case of an online conference, the main dishes account for 92% of the environmental impact, and the catering service accounts for 8% of the burden.

The research results indicate that the carbon footprints of in-person and online conferences are comparable. For in-person conferences, travel contributes significantly to the carbon footprint, accounting for 11.912 kg of CO_2 equivalent per person per hour, representing 57% of the total environmental impact. Over the entire duration of the conference, this travel impact totals 178.68 kg CO_2 equivalent per person. The environmental impact of meals, including lunches, dinners, and catering, is the second largest contributor, totaling 8.413 kg CO_2 eq and per person per hour, constituting 41% of the total impact.

When disregarding the environmental impacts of meals and travel, the decarbonization value is 0.3627 kg CO_2 eq. per person per hour. However, this amount only includes the impacts of conference preparation, organization, implementation, and registration packages for in-person conferences.

4. Discussion

The results of the study are consistent with previous research findings [40,41], according to which the carbon footprint in all three areas studied is reduced as a result of moving to virtual space. In agreement with previous research [40,42] based on the results of the study, it can be concluded that moving to a virtual space has a positive impact on commuting-related energy use and emissions in addition to reducing the carbon footprint.

At the same time, the less efficient energy consumption of working from home and the use of IT at home have a rebound effect on reducing carbon footprint savings. Emails and team meetings were assumed to increasing the carbon footprint, as there is still much uncertainty regarding their carbon footprint. If, in a life cycle approach, it is assumed that sending an email results in 5 g of carbon dioxide emissions, an additional attachment results in 50 g of carbon dioxide emissions [43].

Our examined education model allows for two days of online learning while maintaining attendance for the remainder. Research in education highlights that commonly recommended environmental measures—such as thermal insulation, renewable energy, and energy-efficient lighting—are crucial.

In 2022, the total carbon footprint for the in-person campus was 2223 tons. For Scope 1 emissions, in-person education produces 1827 tons of CO_2 equivalent annually. Implementing online education twice a week could have reduced this by 12%, resulting in 1957 tons. 96% of the environmental impact during in-person education is due to student travel, followed by the travel of teachers and researchers. Many students in Hungary travel between 40 and 250 km to attend universities in Budapest, often returning home every two weeks. The calculated carbon footprint aligns with similar previous studies [19,31,32], showing that our examined campus has the lowest emissions. The solar panels on campus can cover its electricity demand, but their effectiveness during summer, when the institution is closed, needs further evaluation.

Transportation is a key area that influences our second objective: analyzing educational organization and online learning. The literature review and our analysis show that traffic and commuting significantly contribute to emissions. Our analysis reveals an outlier rate of over 80%, partly due to rural students' frequent trips home. The average emission of 4.18 kg per capita daily is notably lower than the national average of 18.4 kg, suggesting a realistic $4\times$ multiplier. Implementing two days of online education reduces transport-related CO_2 emissions by 402 tons annually.

However, the energy demand of at-home learning accounts for 136 tons, yielding a net saving of 266 tons. Gas consumption did not change much during the closure, while electricity consumption dropped by 10–15% in spring 2021. Online education also increases heating and lighting needs and energy used by home computers and internet access. Most emissions come from students, with negligible contributions from official trips by lecturers and university water consumption, accounting for less than 0.5%.

Significant changes in this habit may require longer blocks of online classes, which come with the challenge of reorganization and should offer clear professional advantages.

While every reduction counts, fundamentally altering educational approaches may not be sufficient. The shift to e-learning, accelerated by the COVID-19 epidemic, presents significant methodological challenges. It requires careful preparation, consideration of students' socialization needs, and reassessment of instructors' roles to provide adequate support. Ultimately, the effectiveness of online education varies by content, with technical fields requiring more in-person instruction.

While hybrid models reduce some travel emissions, the impact remains significant.

For energy efficiency, the focus should be on modernizing the two leading educational buildings, A and B, which are over 100 years old and cannot have external insulation. Options include replacing windows and upgrading the HVAC system.

Building AC has the highest heating and cooling demands, while Building G has a more efficient system. Renewable energy sources, particularly solar, should be considered due to the campus's potential [44]. A small power plant could generate nearly 400 kW with an annual production of approximately 400 MWh, exceeding the campus's consumption, although the system's embodied carbon must be assessed [45].

Regarding work, some studies, including ours, show that commuting influences the carbon footprint, with the most amount accounting for about 55% of total emissions in a typical office. It was followed by lighting (14%) and IT equipment usage (8%).

With 90% home office work, lighting and water consumption are 34% of each, commuting is 31%, and the company car contributes 7%. The impact of kitchen-related activities is minimal at 2%.

In the hybrid work scenario, commuting remains the most significant contributor at 54%.

For home office work costs, LCC analysis evaluated heating, lighting, water consumption, and meals. External costs are tied to CO_2 quotas, which the employer currently does not cover. Based on the LCC results, the shift to home working resulted in a 42.2% reduction in life cycle costs; from the employer's perspective, the savings rose to 79.2%.

While working from home does increase energy use for heating, lighting, and IT, it significantly decreases emissions from commuting. Thus, remote work generally leads to considerable environmental gains. The main advantage of teleworking lies in reduced commuting emissions, though outcomes can vary based on transportation modes, work schedules, and community infrastructure.

If remote work occurs within existing frameworks designed for full-time office work, sustainability improvements may be minimal, and carbon footprints could worsen. Though telecommuting offers clear benefits, the outcomes depend on various factors, such as implementation strategies and the balance between remote and office work.

To enhance home office work's positive impacts, policy measures should address commuting, mobility, energy use, and occupational profiles. While telework can reduce carbon emissions, it may also lead to increased home energy consumption and potential social isolation. Efforts to decarbonize offices include energy audits, improving energy efficiency, and using renewable energy.

Achieving decarbonization and climate targets requires collaboration between employers and employees.

In our previous studies [46–48], we developed life cycle models for vegan, vegetarian, and traditional diets and conference types using SWOT analysis and the SAP-LAP model. Our findings show that meal preparation has a higher carbon footprint than cooking due to the production impacts of raw materials.

Conference results show that the carbon footprints of in-person and online conferences are comparable. In-person conferences have a significant environmental impact, with travel accounting for 57%. Travel for in-person events generates about 11.912 kg of CO2 equivalent per person per hour, totaling approximately 178.68 kg for the entire conference. Meals add another 8.413 kg of CO_2 equivalent per person per hour, making up 41% of the total impact. For online conferences, meals dominate, representing 92% of the impact, while catering contributes only 8%.

Excluding travel and meals, the decarbonization value is 0.3627 kg of CO_2 equivalent per person per hour, reflecting the impacts of conference organization and registration for in-person events.

Reducing travel can significantly lower emissions, and hybrid or online conference formats further aid decarbonization. At the same time, catering also contributes substantially to conference emissions. Choosing sustainable dietary options and serving snacks instead of full meals can help mitigate this issue.

When comparing the three areas, the carbon footprint per person per hour for the in-person conference was the highest at 11.91 kg CO_2 equivalent. For educational activities, the carbon footprint was 1.15 kg CO_2 equivalent, while for work-related activities, it was the lowest at 0.90 kg CO_2 equivalent. Transitioning to an online format resulted in the most significant reductions in carbon footprint, with the conference showing a decrease to 11.55 kg CO_2 equivalent. For work, the reduction was to 0.54 kg CO_2 equivalent; for hybrid education, there were minor savings at 0.13 kg CO_2 equivalent.

Table 5 summaries the carbon footprint per person per hour for the three areas.

Table 5. Comparing the carbon footprint for the three areas (functional unit: 1 person/1 h).

	In-Person	**Online/Hybrid**	**20% Home-Office**
Education	1.15	1.02	
Work	0.90	0.37	0.77
Conference	11.91	0.36	

During a sensitivity analysis, we analyzed how changes in various input parameters affect the environmental impact projected over the entire life cycle. In all three cases, changes in transport inputs have the most significant impact on the carbon footprint. In the carbon footprint of commuting, changes in car travel (type, age, performance, fuel consumption, distance travelled by car) also have a sensitive effect on the carbon footprint. Switching to public or shared transport and reducing business trips by car or plane have a beneficial effect. In the case of international conferences, the carbon footprint of plane trips is also prominent. Reducing commuting to work by 90% resulted in a nearly 90% reduction in the carbon footprint. Of course, the extent of the reduction is greatly influenced by the mode of travel, fuel, and kilometres travelled.

Overall, online connectivity helps decarbonize all three areas (education, work, and conferences) from an environmental perspective. However, neglecting attendance is unrealistic in several respects, especially in education, which lowers standards. Therefore, it is necessary to pay attention to these problems so that the quality of teaching and work is also maintained in addition to improving energy efficiency.

5. Conclusions

This research study aimed to develop better scenarios for more sustainable education, work, and conferences by calculating the energy consumption and carbon footprint associated with in-person and online versions.

A comparison of the three cases showed that the international conference's carbon footprint per person per hour was 11.91 kg CO_2 eq. At the same time, education accounted for only 10% of the total and working in an office accounted for only 7.5%. The shift to digital space resulted in a 60% reduction in the conference and work areas' carbon footprint and a 12% reduction in hybrid education.

Digitalization can significantly increase energy efficiency and reduce carbon emissions in buildings, transport, and energy networks. It is especially evident when international conferences are moved online, with much more significant savings than education and work. Home office and virtual work also reduce emissions from commuting.

From the viewpoint of digital document management and cloud service, optimizing data centres can reduce paper use and energy demand. Intelligent systems and renewable resources help improve energy efficiency, balancing weather-dependent renewable sources (solar and wind energy). At the same time, it is important to pay attention to the sustainability of data centres and the proper management of electronic waste.

The digital transition—due to working from home—resulted in a 42.2% life cycle cost reduction. From the employer's perspective—where the employer does not assume the cost of working from home—there is an additional cost reduction, the value of which is a 79.2% saving.

We hypothesized that shifting to online opportunities reduces the decarbonization efforts of such events. Our results confirmed this research hypothesis.

Author Contributions: Methodology, review, writing and editing, funding, V.M.; conceptualisation, review, writing and editing, Z.S.; resources, writing and editing, R.B.S.; data curation, writing and editing, J.L.A.; diagrams, writing and editing, A.T.; funding acquisition, P.S.; diagrams, writing and editing, Z.I.; investigation, visualization, review, A.S.; writing and editing, investigation, O.S.K.; original draft preparation, supervision, funding acquisition, investigation, review, K.T.S. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding author.

Acknowledgments: The study was created with the support of the National Media and Communications Authority (NMHH) based on research agreement No. NKE/9939/2023 between the National Public Service University and the LCA Centre Association.

Conflicts of Interest: Bay Zoltán Nonprofit Ltd. is engaged in applied research, not an industrial company in Hungary. Renáta Bodnárné Sándor (R.B.S.) works as a scientific associate, i.e., researcher status, at this company. ÉMI Nonprofit Llc. is engaged in quality control innovation research. Anita Terjék (A.T.) works as a scientific senior associate, i.e., researcher status, at ÉMI Nonprofit Llc. These authors contributed to this research work as researchers. We did not receive any financial support from these named employers. We have no commercial relationships with the named research institutions. The other authors declare that the research was conducted without commercial relationships; therefore, there is no potential conflict of interest.

Abbreviations

COP	Conference of the Parties
EGD	European Green Deal
EU	European Union
ICT	Information and Communication Technology
IPCC	Intergovernmental Panel on Climate Change
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LCC	Life Cycle Cost
SDGs	Sustainable Development Goals
WMO	World Meteorological Organization

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