ACTA IMEKO
ISSN: 2221-870X
March 2026, Volume 15, Number 1, 1 – 11

Sustainability comparison between a traditional electronics measurement laboratory and an immersive metaverse laboratory: An extended life cycle assessment analysis

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ABSTRACT
University laboratories are essential for engineering education but often require significant resources in terms of energy, equipment, and space. This paper presents a comparative Life Cycle Assessment of two models: a traditional measurement laboratory with 20 physical workstations and an immersive digital twin-based laboratory (*IM-MetaLAB*) supported by one high-performance workstation and 20 virtual reality headsets. The study extends the Life Cycle Assessment framework to the triple bottom line, jointly addressing environmental, economic, and social dimensions.
Results highlight substantial advantages of the immersive model. Energy demand decreases from 18,000 to 7,000 kW h/year, with associated emissions reduced by more than 60 %. Over a seven-year horizon, electronic waste is reduced from 500–600 kg to about 200 kg. Economically, capital expenditures drop from approximately 100,000 € to 25,000 €, while annual operating costs fall from 17,000 € to 5,000 €, yielding a per-student exercise cost four times lower. Socially, immersive access enables remote 24/7 participation, improves completion rates (70 % vs 56 %) and average grades (27.4/30 vs. 25/30), and eliminates commuting emissions ($\approx 24\,\mathrm{tCO_2/year}$ for 40 students).
The immersive laboratory thus proves to be a sustainable, cost-effective, and pedagogically effective alternative to the traditional activities, showing how digital twin and virtual reality technologies can support both innovation in teaching and institutional sustainability goals.

Section: RESEARCH PAPER

Keywords: life cycle assessment (LCA); triple bottom line (TBL); digital twin; virtual reality in education; sustainability in higher education

Citation: F. Bonavolontà, V. Verde, R. Schiano Lo Moriello, A. Liccardo, Sustainability comparison between a traditional electronics measurement laboratory and an immersive metaverse laboratory: An extended life cycle assessment analysis, Acta IMEKO, vol. 15 (2026) no. 1, pp. 1–11. DOI: 10.21014/actaimeko.v15i1.2199

Section Editor: Francesco Lamonaca, University of Calabria, Italy

Received: September 13, 2025; **In Final Form:** January 22, 2026; **Published:** March, 2026.

Funding: The research activity involving the development of the digital twin of the instruments has received funding from the project ”Augmented Reality Measurement Instrumentation Project for Remote Teaching Applications” (MISURANDO), which received a 3-year funding under the call for University Research Funding (FRA) DR/2022/2055 of 17/05/2022. The research activity involving the development of the Metaverse has received funding from the project ”EXTENDABLE - network of EXTENDed reAlity-enaBLEd laboratories for remote practical training” CUP E53D23014680001 funded by EU under the NextGenerationEU plan through the Italian ”Bando Prin 2022-D.D. 1409 del 14-09-2022” by MUR.

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1. INTRODUCTION

The educational laboratory has always represented a cornerstone in the university training of technical-scientific disciplines. Since the beginning of modern engineering courses, experimental activity has been considered essential to strengthen theoretical knowledge. It translates concepts into practical skills by exposing students to real-world measurement issues [1]. In the field of electrical and electronic measurements, this operational space offers the opportunity to directly interact with instruments such as signal generators, multimeters, oscilloscopes, and power supplies, fostering the understanding of phenomena related to electrical quantities and signal transmission, and thus making the transition from the conceptual to the applicative level tangible. In the measurement laboratory, through experimental activity, the student faces real problems that theory alone cannot fully convey: background noise, measurement uncertainty, connection errors, the need for calibration and adjustment of instruments, and the management of complex experimental data. It is within this space that the integral growth characterizing the professional identity of the engineer in the context of electrical and electronic measurements takes shape.

However, the traditional model of measurement laboratories today shows increasing limitations, attributable to three fundamental dimensions: economic, environmental, and social. The effects of these criticalities clearly emerge when considering a typical measurement laboratory, as shown in the following example:

- From an economic perspective, setting up a 120 m^2 classroom with twenty complete workstations requires an initial investment exceeding 100,000 € [2], [3], to which annual operating costs of about 17,000 € for maintenance and periodic replacement of equipment must be added. This makes the traditional model unsustainable in the long term.
- From an environmental perspective, the simultaneous operation of twenty workstations, together with air conditioning and lighting, results in an average consumption of 18,000 kW h/year, corresponding to about 4.5 t of CO_2 [4]. Added to this is the generation of waste electrical and electronic equipment (WEEE), estimated at 500–600 kg every seven years for a single laboratory, in a global context which, in 2019, saw the generation of 53.6 million tons of WEEE, less than 20 % of which was correctly recycled [5].
- From a social perspective, the need to physically attend the facility at predetermined times limits the flexibility of learning and generates additional emissions related to commuting. For a class of 40 students, commuting accounts for about 24 t of CO_2 per year, further aggravating the overall ecological footprint [6].

Taken together, these elements show how the traditional laboratory model is no longer adequate in relation to current needs of economic, environmental, and social sustainability, making a radical rethinking of teaching and infrastructural methods necessary.

The use of digital technologies for laboratory teaching is not a recent phenomenon. Since the last decade of the previous century, remote laboratories have been used [7] [9], allowing students and teachers to access real instrumentation located within university campuses via the Internet [10], [11]. These first experiences achieved some success [12], mainly for the possibility of making equipment accessible remotely, but they showed significant limitations: interfaces were often not very engaging, the experience was reduced to remote control of physical instruments, and the collaborative and immersive dimension that characterizes the in-presence laboratory was entirely missing [13].

With the spread of virtual reality technologies, a different perspective has opened: the possibility of creating immersive three-dimensional environments in which students could not only interact with simulated instruments but also move within the space, collaborate with each other, and reconstruct the social context of the laboratory [14] [18]. In this scenario, the shift from simple static simulations to true digital twins marked a radical change. Digital twins are not mere graphic replicas: they are connected to real physical devices, with near real-time data updates, allowing observation and manipulation of instrument behavior with an unprecedented level of fidelity [19], [20]. This has enabled a learning experience that integrates the concreteness of measurement with the flexibility of the virtual environment.

At the same time, the social and institutional context has also pushed in this direction. The growing attention to sustainability, understood both as cost reduction and as environmental impact containment, has made clear the need for alternatives to the traditional physical laboratory. A further impulse was generated by the COVID-19 pandemic [21], which accelerated the digitalization of teaching and made the use of solutions capable of ensuring training continuity at a distance more urgent [22].

The most recent proposals of immersive laboratories are situated in this context, in which virtual reality, digital twins, and IoT protocols converge in hybrid environments intertwining the real and the virtual. An example is the IM-MetaLAB, developed at the University of Naples Federico II and presented in [16], which integrates a central workstation, VR headsets, and digital twins connected to real instrumentation, offering a training experience accessible both in presence and remotely [23], [24].

Beyond possible comparisons between the traditional physical laboratory and the new immersive environments—particularly with reference to their educational effectiveness, i.e., the ability to reproduce, integrate, or even surpass the in-presence experience, and to their inclusive potential, aimed at broadening access and reducing barriers—the question raised by the authors is whether, and to what extent, the immersive model can be configured as a more sustainable alternative to the traditional in-presence laboratory.

To answer this question, the Life Cycle Assessment (LCA) methodology was adopted, integrated with the triple bottom line model (planet, profit, people), which makes it possible to jointly assess environmental, economic, and social impacts throughout the entire life cycle (ISO 14040/44).

In this perspective, two teaching scenarios were compared involving either a traditional laboratory or an immersive metaverse laboratory. The objective is not only to estimate the direct impacts of each model but also to consider the indirect ones often overlooked—such as emissions related to student commuting—in order to identify which solution can represent a more sustainable path for the future of engineering education.

2. METHODOLOGY

2.1. The LCA approach

The LCA, as established by ISO 14040 and 14044 standards, is structured into four fundamental phases: the goal and scope definition, which clarifies the purpose of the study, the system boundaries, and the functional unit; the life cycle inventory (LCI), which involves collecting data related to input and output flows (materials, energy, emissions, waste); the life cycle impact assessment (LCIA), in which these data are translated into environmental impact indicators (e.g., climate change, resource consumption, acidification); and finally the interpretation, which integrates and discusses the results, identifying the critical points and possible improvement strategies.

Figure 1 summarizes the main life cycle phases considered in this study, adapted to the specific case of traditional and immersive laboratories. The scheme integrates the canonical LCA phases (raw materials, production, use, end-of-life) with elements peculiar to the educational context, such as student commuting and the management of WEEE, highlighting the comparative perspective between the two models.

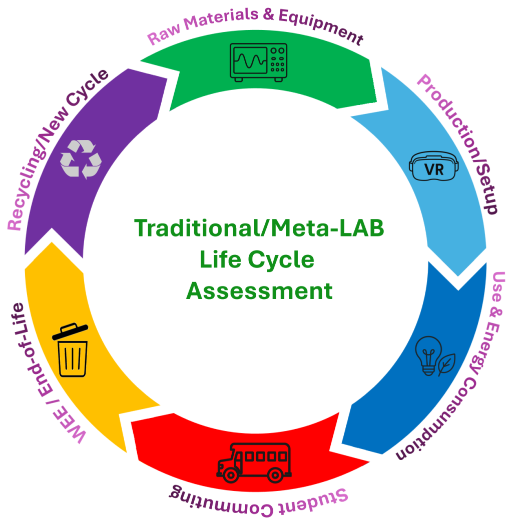

Figure 1. The life cycle framework adopted in this study, adapted to the comparison between the traditional laboratory and the immersive IM-MetaLAB. The scheme includes raw materials, production, use and energy consumption, student commuting, end-of-life, and recycling/new cycle.

Traditionally, LCA was conceived as a tool for environmental analysis, mainly applied to industrial products. In recent years, however, the need has emerged for a broader approach, capable of also including the economic and social dimensions of sustainability. One such approach is the triple bottom line (TBL) model, introduced by Elkington in the 1990s [25], which integrates the three key dimensions of sustainable development: planet (envi-ronment), profit (economy), and people (society).

Applying LCA in a TBL perspective therefore means extending the analysis to a Life Cycle Sustainability Assessment (LCSA) [26], which combines three complementary tools: LCA for the environmental component, Life Cycle Costing (LCC) for the economic component, and Social LCA (SLCA) for the social impacts. This extension is particularly relevant when the object of study is not a product in the strict sense, but a complex educational service, as in the case of the university laboratory.

Indeed, the laboratory is not limited to the life cycle of its infrastructures and equipment, but generates broader effects: on the environmental level (energy consumption, electronic waste, direct and indirect emissions such as those from transport), on the economic level (investment costs, operation and maintenance, returns in terms of efficiency and accessibility), and on the social level (skills development, access to education, digital inclusion, impacts on the academic community).

For these reasons, in the present study, LCA has been extended according to the TBL approach, so as to capture more completely and consistently the peculiar nature of the laboratory at the university, understood not only as technical infrastructure, but as an educational and cultural service with multilevel impacts.

2.2. Objectives and scope

The main objective of this study is the comparison between two models of university laboratories for electrical and electronic measurements, in order to evaluate their overall sustainability according to the extended approach of LCA integrated with the triple bottom line. In particular, the following scenarios are compared:

- Scenario A traditional laboratory, consisting of 20 physical workstations set up in a 120-m^2 classroom;
- Scenario B immersive laboratory (IM-MetaLAB) [27], based on a central workstation and the use of 20 VR headsets connected to digital twins.

The system boundaries include not only the technical and environmental aspects related to the equipment (purchase, useful life, energy consumption, and generation of WEEE), but also the economic components (initial investments and recurring operating costs) and the social and educational components (acces-sibility, delivery methods, digital inclusion). This choice makes it possible to coherently consider both the direct impacts (energy consumption, equipment maintenance, waste disposal) and the indirect ones, often overlooked, such as emissions from student commuting or barriers linked to physical attendance.

The selection of these two scenarios is motivated by the fact that they currently represent the most concrete and realistic alter-natives available for laboratory teaching in the university context: on the one hand, the consolidated traditional model, on the other, the emerging immersive paradigm, made possible by the integration of virtual reality, digital twins, and Internet of Things (IoT) protocols.

2.3. Functional unit

Within LCA, the functional unit represents the reference parameter that allows system inputs and outputs to be related in comparable terms, ensuring consistency and significance in the analysis (ISO 14040/44). The choice of the functional unit is particularly delicate when the object of study is not a tangible product, but a complex service, as in the case of university laboratory teaching.

In this study, the adopted functional unit is defined as the training of 40 students in one academic year, with at least 10 practical exercises. This definition reflects a standardized educational output, which does not depend on the technology used (traditional or immersive), but on the expected learning outcome, and makes it possible to compare the two models in relation to the same service provided.

In this way, the environmental, economic, and social impacts are expressed in terms of the same functional unit, allowing a direct comparison between heterogeneous scenarios. For example, energy consumption and costs are normalized with respect to the training of a homogeneous group of students, while social impacts can be interpreted in terms of accessibility, completion rate of exercises, and perceived learning quality.

This choice therefore makes it possible to go beyond the mere technical dimension of the laboratory, anchoring the evaluation to the educational service actually delivered, which constitutes the ultimate purpose of the system under analysis.

2.4. Data collection

The data collection was designed to meet the quality requirements established by ISO 14040/44 (see [26]) in terms of temporal, geographical, and technological representativeness, completeness, consistency, and transparency. As stated above, all data were normalized with respect to the functional unit (training of 40 students in one academic year with at least 10 exercises), so as to ensure comparability between scenarios. When information was not directly available, a conservative criterion was adopted and the sensitivity of the results to the most influential assumptions was tested.

The main sources include:

- Manufacturers' datasheets: they provide primary foreground data for the traditional scenario (rated power, masses, useful life), and are used for energy consumption and WEEE estimation [2], [3].
- Literature on remote and immersive laboratories: it allows parameterization of annual usage hours, replacement cycles, and teaching practices, as well as validation of technological assumptions [7], [9], [10], [12], [14], [19].
- International reports: they provide emission factors, benchmarks, and contextual data for environmental characterization and European comparability [4], [5], [6].
- VR headset specifications: they provide primary data for the immersive scenario (average consumption, mass, lifetime), used in the LCI for consumption and end-of-life flows [28].
- Energy studies on data centers and networking: they estimate the indirect overhead of computing and networking associated with the use of cloud services and digital twins, included in the LCI as a specific additional contribution [29].

Datasheets and specifications cover the direct flows of the devices, international reports provide the characterization factors and benchmarks, scientific literature anchors the scenarios to realistic teaching practices, while studies on data centers include the indirect impacts of the immersive architecture. This framework ensures source traceability, scenario comparability, and interpretative robustness across the three dimensions of the triple bottom line.

3. LIFE CYCLE INVENTORY

The Life Cycle Inventory (LCI) phase represents the quantitative core of the LCA analysis. In this phase, data are collected and systematized concerning all input resources (materials, energy, equipment) and output flows (waste, emissions, costs) along the entire life cycle, always referred to the defined functional unit. The objective is to build a solid and transparent basis of values that allows, in the subsequent phase, the impact assessment (LCIA).

As stated above, two scenarios, related to traditional and immersive laboratories, are analyzed in the following; for each scenario, the technical characteristics and investment costs, the estimated energy consumption, and the generation of electronic waste (WEEE) at end-of-life are considered and described.

3.1. Scenario A – Traditional Laboratory

3.1.1. Instrumentation and investment costs

Each workstation is equipped with a set of fundamental instruments for electronic measurements:

- oscilloscope ($\approx 90\,\mathrm{W}$, unit cost 2000 €),
- function generator ($\approx 50\,\mathrm{W}$, unit cost 1500 €),
- bench power supply ($\approx 60\,\mathrm{W}$, unit cost 500 €),
- digital multimeter ($\approx 5\,\mathrm{W}$, unit cost 200 €).

Figure 2 provides a visual overview of the traditional measurements laboratory: (a–b) students at the bench during oscilloscope-based activities; (c) lab layout.

The total cost of a single workstation is therefore:

$$C_{\text{workstation}} = (2000 + 1500 + 500 + 200)\ € \approx 4200\ €.$$

Multiplied by twenty workstations, the total cost of the instrumentation alone amounts to approximately:

$$C_{\text{instrumentation}} = 20 \times 4200\ € \approx 84{,}000\ €.$$

Ancillary setup costs (laboratory benches, cabling, safety accessories, and shared instruments) must be added to this amount, which account for an additional 15–20 %. This leads to a total value close to 100,000 , which represents the typical initial investment for such a laboratory (Table 1). The average useful life of the equipment is about 7 years, in line with what is reported in the literature.

3.1.2. Energy consumption

The total power absorbed by a single workstation is:

$$P_{\text{workstation}} = (90 + 50 + 60 + 5)\,\mathrm{W} \approx 205\,\mathrm{W}.$$

For twenty workstations, the value is:

$$P_{\text{instruments}} = 20 \times 205\,\mathrm{W} \approx 4.1\,\mathrm{kW}.$$

To this power demand, the requirements for the heating, ventilation, and air conditioning (HVAC), as well as the lighting of a 120-m^2 classroom must

Figure 2. Traditional measurements laboratory: (a) students at the bench; (b) oscilloscope-based activity; (c) lab layout.

also be added, which is estimated to be around 6 kW. The total required power is therefore:

$$P_{\text{total}} = P_{\text{instruments}} + P_{\text{HVAC}} \approx 10\,\text{kW}.$$

Considering an average use of 750 hours/year, the theoretical energy consumption is:

$$E = P_{\text{total}} \times t = 10\,\text{kW} \times 750\,\text{h/year} \approx 7500\,\text{kW h/year}.$$

Under intensive use conditions, the actual demand rises to 15,000–20,000 kW h/year, reflecting longer exercise cycles and multiple student shifts [30] (Table 2).

3.1.3. Electronic waste (WEEE)

The average weight of a single workstation at end-of-life is about 44 kg, resulting in a theoretical total of:

$$m_{\text{total}} = 20 \times 44\,\text{kg} = 880\,\text{kg}.$$

However, considering partial replacement and gradual decommissioning of equipment, the actual flow of WEEE generated amounts to 500–600 kg every 7 years (Table 3).

The traditional scenario is,thus, characterized by a high initial investment, substantial energy consumption including both equipment and auxiliary services, and a significant generation of electronic waste at end-of-life.

3.2. Scenario B – Immersive Laboratory (IM-MetaLAB)

Figure 3 provides a visual overview of the IM-MetaLAB immersive laboratory: (a) overall immersive scenario; (b) instrument bench in the virtual environment; (c) interaction with the digital multimeter.

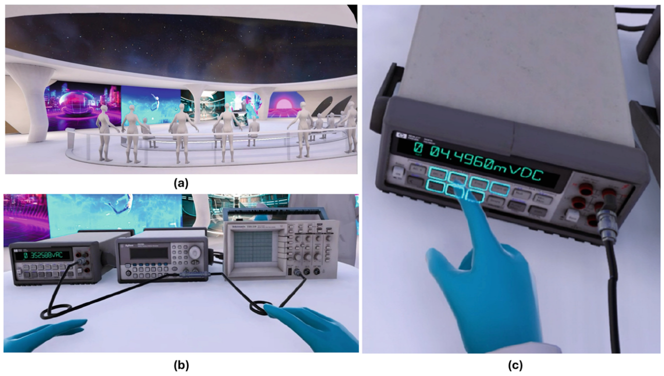

Figure 3. IM-MetaLAB immersive laboratory: (a) overall immersive scenario; (b) instrument bench in the virtual environment; (c) interaction with the digital multimeter.

Note. Schematic redrawn by the authors based on: F. Bonavolontà, A. Liccardo, R. S. L. Moriello, E. Caputo, A. Monaco, *IM-MetaLAB: First step towards a new metaverse laboratory for teaching fundamental concepts in instrumentation and measurement*, International Conference on Extended Reality, Springer, 2025, pp. 215–223. No third-party image elements have been reproduced.

3.2.1. Instrumentation and investment costs

The immersive configuration includes a central workstation and 20 VR headsets:

- high-end workstation (power consumption ≈ 1.2 kW, unit cost 15,000 €, useful life ≈ 7 years),
- VR headsets (≈ 10 W each, unit cost 400 €, mass ≈ 1 kg, useful life 3–4 years).

The total cost is:

$$C_{\text{total}} = 15{,}000\ € + 20 \times 400\ € = 23{,}000\ €.$$

Including accessories and supporting infrastructure (software licenses, peripherals, cabling), the initial investment amounts to about 25,000 €. This value is significantly lower (about one quarter) compared to the traditional laboratory (Table 1).

3.2.2. Energy consumption

The workstation consumes about 1.2 kW. For an average use of 900 hours/year, the direct consumption is:

$$E_{\text{workstation}} = 1.2\,\text{kW} \times 900\,\text{h/year} \approx 1080\,\text{kW h/year}.$$

The value of 900 hours, slightly higher than the 750 hours considered in the traditional scenario, reflects the greater flexibility of the immersive laboratory, which allows remote and distributed access to [31]. Students can in fact use the headsets even outside the standard classroom shifts, making a higher overall usage time plausible.

The VR headsets have a unit consumption of about 10 W. Considering 20 devices and 900 hours/year, the result is:

$$E_{\text{headsets}} = 20 \times 10\,\text{W} \times 900\,\text{h/year} = 180\,\text{kW h/year}.$$

The overhead due to cloud and networking services must be added to these values, estimated by Patterson et al. (2021) [29] as a factor of 4–5 compared to the consumption of the workstation, i.e., about 5000–6000 kW h/year. The total energy demand of the immersive scenario is therefore between 6000 and 7000 kW h/year (Table 2). The factor of

Table 1. Comparison of instrumentation and investment costs in the two scenarios.

	Scenario A – Traditional Laboratory	Scenario B – Immersive Laboratory (IM-MetaLAB)
Main components	Oscilloscope (90 W, 2000 €) Function generator (50 W, 1500 €) Bench power supply (60 W, 500 €) Digital multimeter (5 W, 200 €) *Total per workstation:* 4200 €	Workstation (1.2 kW, 15,000 €) 20 VR headsets (10 W, 400 € each, lifetime 3–4 years)
Number of units	20 complete workstations	1 workstation + 20 headsets
Estimated initial investment	20 × 4200 € = 84,000 € + 15–20% accessories (benches, cabling, shared instruments) ≈ 100,000 € total	15,000 € +(20 × 400 € = 8000 €) = 23,000 € + accessories/software ≈ 25,000 € total
Average useful life	≈ 7 years (instrumentation)	Workstation ≈ 7 years; headsets 3–4 years

4–5 applied to estimate cloud and networking overhead is a conservative value derived from general-purpose data-center workloads, as discussed in [28]. It explicitly includes both computational processing and the near-real-time synchronization required for digital-twin updates. A ±20 % sensitivity analysis was conducted on this parameter, confirming that the immersive scenario maintains a positive energy balance advantage across the whole range.

3.2.3. Electronic waste (WEEE)

The workstation generates about 20–25 kg of WEEE at end-of-life in 7 years. The VR headsets have a shorter useful life (3–4 years), so over 7 years two replacement cycles are expected: 1 kg × 20 headsets × 2 cycles = 40 kg.

The total WEEE for the immersive scenario is therefore about 200 kg every 7 years, i.e., a reduction of about 60 % compared to the traditional laboratory (Table 3).

The immersive scenario presents a significantly lower initial investment, lower energy consumption (despite the cloud overhead), and a considerably reduced amount of electronic waste compared to the traditional model (Table 1).

4. LIFE CYCLE IMPACT ASSESSMENT (LCIA)

The Life Cycle Impact Assessment (LCIA) translates the results of the LCI (inventory) into impact indicators, consistently with the defined functional unit and system boundaries. Below, we detail criteria, assumptions, formulas, and results for the three dimensions of the triple bottom line (environmental, economic, social), including a focus on student commuting.

4.1. Environmental dimension

Definitions and method. The climate impact is expressed in CO_2 equivalent (CO_2e) and calculated from annual electricity consumption E using an emission factor of the European electricity mix. We adopt the EEA 2022 average value of $0.25\,\mathrm{kgCO_{2e}/kW\cdot h}$ (European Environment Agency), consistent with the reference literature [4].

Input data. Annual consumption Scenario A (traditional): ≈ $18\,000\,\mathrm{kW\cdot h/year}$; Scenario B (IM-MetaLAB): ≈ $7000\,\mathrm{kW\cdot h/year}$.

Emission calculation. Annual operational emissions are obtained as:

$$CO_2e = E \times \text{emission factor}.$$

Applying $0.25\,\mathrm{kgCO_{2e}/(kW\cdot h)}$:

$$\text{Traditional}: \ (18{,}000 \times 0.25) \ => \ \mathbf{4{,}500}\,\mathrm{kgCO_{2e}/year},$$
$$\text{IM-MetaLAB}: \ (7{,}000 \times 0.25) \ => \ \mathbf{1{,}750}\,\mathrm{kgCO_{2e}/year}.$$

The energy difference is ≈ $11\,000\,\mathrm{kW\cdot h/year}$, equivalent to ≈ $2750\,\mathrm{kgCO_{2e}/year}$ avoided. Over a 7-year horizon, this corresponds to ≈ $19.25\,\mathrm{tCO_{2e}}$, rounded to ≈ $20\,\mathrm{tCO_{2e}}$ avoided.

Other environmental flows. WEEE over 7 years: Scenario A ≈ $500\,\mathrm{kg}$; Scenario B ≈ $200\,\mathrm{kg}$, with a reduction of about 60 % in the immersive scenario. These amounts derive from unit masses and respective estimated useful lives in the LCI. Uncertainties were examined through a ±20 % sensitivity analysis applied to electricity emission factors, usage hours, and cloud-network overhead coefficients. The comparative advantage of the immersive scenario remained consistent across the tested range.

4.2. Economic dimension

Definitions. CAPEX (Capital Expenditure) indicates capital expenditure (e.g., purchase of instrumentation, setup). OPEX (Operating Expenditure) indicates recurring operating costs (e.g., energy, maintenance, licenses, replacements).

Summary results. Initial CAPEX: Scenario A ≈100,000 € (higher) vs Scenario B ≈25,000 €. Annual OPEX: Scenario A ≈17,000 € vs Scenario B ≈5,000 €.

Normalized teaching cost. The average cost per exercise per student is calculated by normalizing to the same functional unit:

$$Cost_{\text{exercise}} = \frac{AnnualizedCAPEX + OPEX}{N_{\text{students}} \times N_{\text{exercises}}}.$$

Based on the collected data, orders of magnitude are obtained: > 40 for the traditional and < 10 for the immersive. (The "Annualized CAPEX" component derives from the technical useful life and amortization practices commonly adopted in academia.)

Table 2. Comparison of annual energy consumption in the two scenarios.

	Scenario A – Traditional Laboratory	**Scenario B – Immersive Laboratory (IM-MetaLAB)**
Instrument power	205 W per workstation 20 workstations = 4.1 kW	Workstation 1.2 kW VR headsets: 20 × 10 W = 0.2 kW
Auxiliary services	Air conditioning + lighting ≈ 6 kW	Cloud + networking overhead equivalent to 4–5× workstation consumption (≈ 5000–6000 kW h/year)
Total power	≈ 10 kW (instruments + HVAC)	≈ 1.4 kW (workstation + headsets) + cloud overhead
Theoretical consumption	10 kW ×750 h/year = 7500 kW h/year	Workstation: 1.2 kW ×900 h = 1080 kW h/year Headsets: 180 kW h/year
Actual consumption	Intensive use: 15,000–20,000 kW h/year	Total: 6000–7000 kW h/year

Table 3. Comparison of WEEE in the two scenarios.

	Scenario A – Traditional Laboratory	**Scenario B – Immersive Laboratory (IM-MetaLAB)**
Mass per unit	≈ 44 kg per complete workstation	≈ 1 kg per VR headset 20–25 kg per workstation
Number of units	20 workstations (complete instrumentation)	20 headsets (2 cycles in 7 years) + 1 workstation
Theoretical total mass	$20 \times 44\,\mathrm{kg} = 880\,\mathrm{kg}$	Workstation ≈ 25 kg + $(20 \times 1\,\mathrm{kg} \times 2) = 40\,\mathrm{kg}$ Total ≈ 65 kg
Estimated actual mass	≈ 500–600 kg every 7 years (considering partial replacements)	≈ 200 kg every 7 years (considering headset replacement cycles)
Percentage difference	—	≈ 60% less than the traditional scenario

4.3. Social dimension

Criteria and indicators. The social dimension is interpreted in terms of teaching and accessibility. We use two operational proxies: (i) completion rate of exercises, (ii) average grade achieved. These indicators do not exhaust learning quality, but provide quantitative signals comparable across scenarios.

Results (and caveats). Experimental data reported in the literature indicate: completion rate 70 % (immersive) vs. 56 % (traditional) [27]; average grade 27.4/30 vs. 25/30.

These data refer to a single academic-year cohort of approximately 40 students participating in an introductory measurement course that included ten practical laboratory sessions. The dataset was selected because it corresponds to the functional unit defined in Section 2.3. These results should therefore be interpreted as indicative rather than fully representative of all possible learning contexts.

These differences are consistent with the greater flexibility of access and with immersive/distributed support.

4.4. Student commuting

Why include it? Student commuting is an indirect impact often neglected in comparisons between teaching models, yet relevant on an annual basis: international studies indicate a contribution of up to 7 % of total university emissions [32]. Its inclusion is consistent with the extended system boundaries adopted in this study.

Method and formulas. For each student, annual commuting emissions are estimated as:

$$\mathrm{CO_2}\ (\text{student}) = D_{\text{annual}} \times f_{\text{emission}},$$

with annual distance $D_{\text{annual}} = d_{\text{daily}} \times N_{\text{days}}$. In the example: $d_{\text{daily}} = 20\,\mathrm{km}$ (round trip), $N_{\text{days}} = 110$, thus $D_{\text{annual}} = 2200\,\mathrm{km}$. The emission factor per passenger f_{emission} depends on the mode of transport (private car, bus, train) and the context (urban/interurban). Literature values range from ~ 0.12 to $0.27\,\mathrm{kgCO_2/km \cdot pax}$ (EEA; see [6]).

Adopted estimate and sensitivity. Assuming a prudential value at the upper end of the range to cover mixed use and congestion (e.g., $f_{\text{emission}} \approx 0.27\,\mathrm{kgCO_2/km}$), we obtain per student:

$$2200\,\mathrm{km} \times 0.27\,\mathrm{kgCO_2/(year \cdot km)} \approx \mathbf{0.6}\,\mathrm{tCO_2/year}.$$

For a cohort of 40 students: $\approx 24\,\mathrm{tCO_2/year}$. Scenario A includes this contribution, Scenario B reduces it to nearly zero thanks to remote/hybrid access.

Effect on the overall comparison. Adding commuting to laboratory energy emissions, the traditional scenario rises from $\sim 4.5\,\mathrm{tCO_2/year}$ to $\sim 28.5\,\mathrm{tCO_2/year}$, while the immersive remains $\sim 1.75\,\mathrm{tCO_2/year}$ (energy) with commuting ≈ 0. The gap thus widens substantially.

Note on uncertainties and transparency. Results are sensitive to electricity mix (EEA factors vary by country/year), usage profiles (hours/year), and transport emission factors. For this reason, we report assumptions and formulas, and suggest sensitivity analyses on (a) usage hours (±20 %), (b) electricity factor (0.18–$0.35\,\mathrm{kgCO_2/(kW \cdot h)}$), (c) commuting factor (0.12–$0.27\,\mathrm{kgCO_2/km}$). The qualitative robustness of the comparison (advantage of the immersive model) holds across the entire range.

5. DISCUSSION

The analysis clearly highlights that the two laboratory models present profoundly different sustainability profiles (Table 4).

Environmental dimension. The traditional laboratory shows high electricity consumption (≈ 18,000 kW h/year) and a considerable production of electronic waste (500–600 kg every 7 years). Added to this are the indirect emissions linked to student commuting, amounting to ≈ 24 tCO_2/year for a cohort of 40 students. The immersive scenario drastically reduces these impacts: consumption is ≈ 7,000 kW h/year, direct operational emissions are 1.75 tCO_2/year, and WEEE is about 200 kg/7 years. Furthermore, thanks to remote access, transport-related emissions are almost eliminated. This results in an overall gap that, on an annual basis, goes from ≈ 28.5 tCO_2 in the traditional scenario to ≈ 1.75 tCO_2 in the immersive scenario.

Economic dimension. From a cost perspective, the traditional laboratory requires an initial investment four times higher than the immersive one (100,000 € vs. 25,000 €) and entails annual operating expenses about three times greater (17,000 € vs. 5,000 €). Normalizing costs to the functional unit (40 students, 10 exercises), the average cost per exercise per student exceeds 40 € in the traditional scenario, compared to less than 10 € in the immersive scenario. This highlights not only an absolute saving, but also greater efficiency in the use of economic resources.

Social dimension. The social impact mainly concerns accessibility and learning outcomes. The traditional scenario imposes logistical constraints (classroom, schedules, physical presence) that limit participation and exacerbate the ecological footprint. The immersive scenario, on the other hand, enables 24/7 remote access, including students who are distant or have mobility difficulties. Experimental data confirm this difference: the completion rate increases from 56 % to 70 % and the average grade from 25/30 to 27.4/30. This suggests a measurable improvement in teaching effectiveness, while not entirely replacing the tactile and manual experience of the physical laboratory.

To provide an integrated view of the results obtained, Figure 4 shows the main indicators normalized with respect to the traditional laboratory (set at 100 %). It is immediately evident that the immersive model stands between 25 % and 40 % of the reference for energy consumption, operating costs, electronic waste, and invested capital, with an even sharper reduction in total CO_2 emissions (≈ 6% of the traditional value, thanks to the elimination of commuting). In a positive countertrend, the average grade indicator exceeds 100 %, suggesting an additional educational benefit. This representation confirms, in a synthetic manner, the advantage of the immersive laboratory across all dimensions of the triple bottom line.

Critical synthesis and limitations. The comparison therefore shows a clear superiority of the immersive laboratory in terms of integrated sustainability (environmental, economic, social) [33]. However, it is important to recognize the limitations: (i) the immersive simulation does not fully reproduce the physical manipulation of instruments; (ii) commuting estimates depend on local factors (means of transport, average distance, sustainable mobility policies); (iii) consumption associated with cloud services and data centers may vary significantly depending on the provider and geography. Despite these uncertainties, the order of magnitude of the gap remains robust: in every sensitivity scenario, the immersive laboratory shows lower impacts.

Future perspectives. The spread of haptic and multisensory technologies will progressively make the virtual laboratory more realistic, reducing the perceptual gap with the traditional one. A hybrid model therefore appears plausible, in which the physical experience with real instrumentation is integrated with low-impact immersive exercises, combining sustainability and educational realism.

6. CONCLUSIONS

The comparison carried out through the extended LCA approach, integrated with the triple bottom line model, shows that the immersive IM-MetaLAB scenario represents a significantly more sustainable solution compared to the traditional laboratory. In particular, substantial advantages emerged in terms of reduced energy consumption, CO_2 emissions (both direct and indirect, including commuting), electronic waste, and overall management costs. At the same time, an improvement in the social dimension was observed, thanks to greater accessibility, flexibility, and inclusiveness of the learning experience, with positive effects on educational outcomes.

While recognizing that the physical laboratory retains an irreplaceable pedagogical value, especially for hands-on practice and direct contact with real instrumentation, the results suggest that immersive solutions should not be seen as a substitute, but rather as a strategic integration of the traditional model. In this perspective, hybrid scenarios appear plausible, in which in-person exercises and metaverse-based activities coexist, combining sustainability, effectiveness, and educational realism.

Future developments may focus on three main directions. On the one hand, technological refinement, with the introduction of haptic and multisensory devices capable of bridging the perceptual gap with the physical experience. On the other hand, the expansion of evaluation metrics, including more detailed indicators of educational effectiveness and social impact. Finally, large-scale experimentation, extending the model to different disciplinary and institutional contexts, in order to validate its generalizability and consolidate its role as a paradigm for sustainable engineering education in the future.

AUTHORS' CONTRIBUTION

Francesco Bonavolontà: conceptualization, methodology, writing original oraft preparation. Maria Teresa Verde: data curation, formal analysis, writing review & editing. Rosario Schiano Lo Moriello: validation, visualization, investigation, writing review

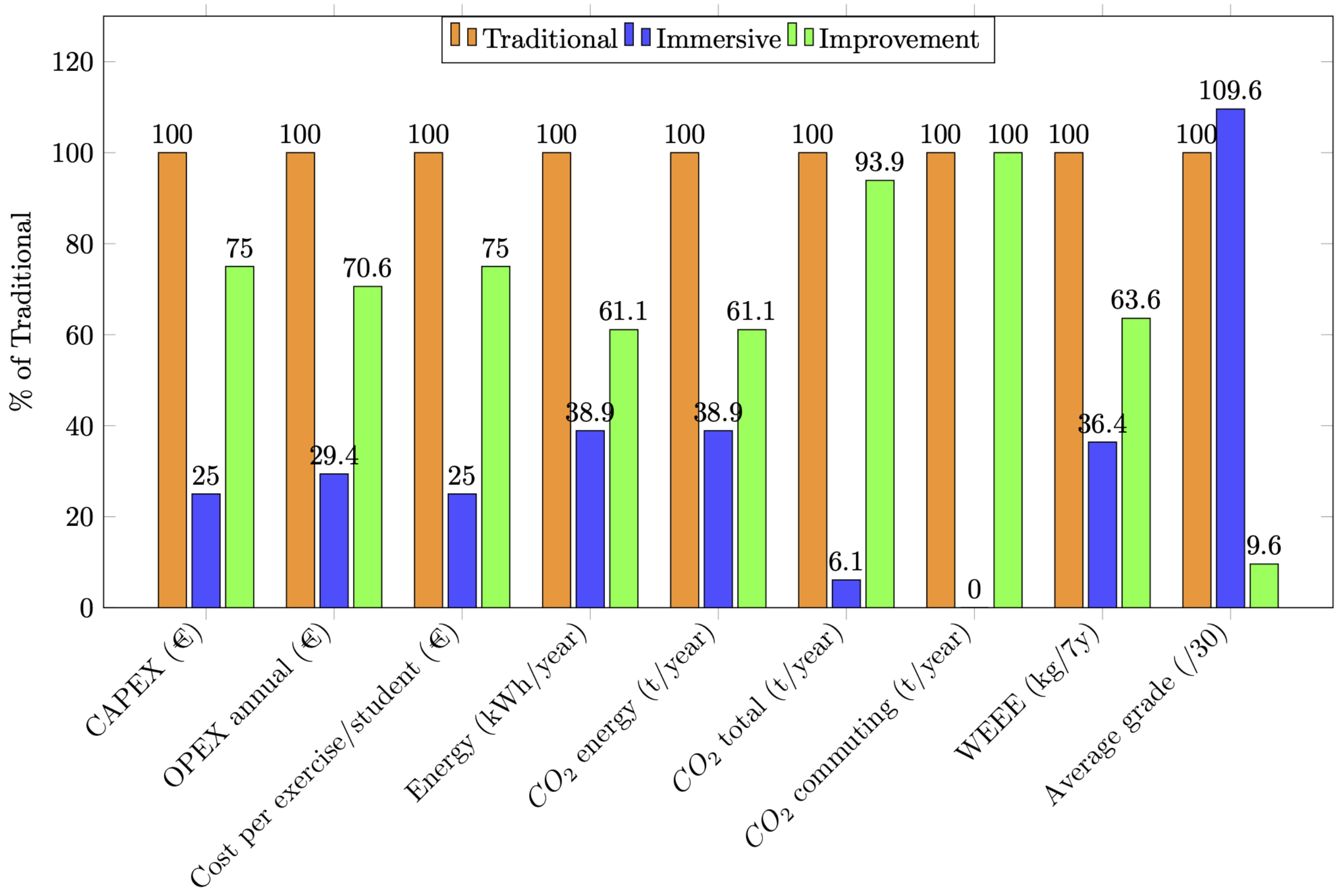

Figure 4. Indicators normalized with respect to the traditional laboratory (100 %). The immersive model reduces costs, consumption, emissions, and WEEE to less than 40 % of the reference, while improving the average grade indicator beyond 100 %. Green bars allow to appreciate the improvement brought by the immersive laboratory.

Table 4. Summary comparison between traditional and immersive laboratory across the three sustainability dimensions.

	Scenario A – Traditional	**Scenario B – Immersive (IM-MetaLAB)**
Energy consumption	18,000 kW h/year	7,000 kW h/year
CO_2 emissions (energy)	4.5 t CO_2/year	1.75 t CO_2/year
CO_2 emissions (commuting)	24 t CO_2/year	≈ 0 t CO_2/year
WEEE (7 years)	500–600 kg	≈ 200 kg
Initial investment (CAPEX)	≈ 100,000 €	≈ 25,000 €
Operating costs (OPEX)	≈ 17,000 €/year	≈ 5,000 €/year
Average cost per exercise/student	> 40 €	< 10 €
Completion rate	56 %	70 %
Average student grade	25/30	27.4/30
Accessibility	Limited to presence and schedules	Remote, flexible, 24/7

& editing. Annalisa Liccardo: supervision, project administration, funding acquisition.

REFERENCES

[1] L. D. Feisel, A. J. Rosa, The role of the laboratory in undergraduate engineering education, Journal of engineering Education, vol. 94, 2005, no. 1, pp. 121–130.
DOI: 10.1002/j.2168-9830.2005.tb00833.x

[2] Keysight Technologies, Infiniivision 2000 x-series and 3000 x-series oscilloscopes, Online [Accessed 19 March 2026]
https://www.keysight.com/it/en/assets/7018-02733/data-sheets/5990-6618.pdf.

[3] Tektronix, The arbitrary/function generator, Online [Accessed 19 March 2026]
https://download.tek.com/document/75W_25002_0_11x17_MR.pdf.

[4] European Environment Agency (EEA), Greenhouse gas emission intensity of electricity generation, Online [Accessed 21 January 2026]
https://www.eea.europa.eu/ims/greenhouse-gas-emission-intensity-of.

[5] V. Forti, C. P. Baldé, R. Kuehr, G. Bel, The global e-waste monitor 2020, Online [Accessed 21 January 2026]
https://ewastemonitor.info/.

[6] European Environment Agency (EEA), Passenger and freight transport demand – emissions dataset, Online [Accessed 11 October 2025]

https://www.eea.europa.eu/ims/passenger-and-freight-transport-demand.
[7] A. Baccigalupi, C. De Capua, A. Liccardo, Overview on development of remote teaching laboratories: from LabVIEW to web services, 2006 IEEE Instrumentation and Measurement Technology Conference Proceedings, IEEE, 2006, pp. 992–997. DOI: 10.1109/IMTC.2006.328272
[8] P. Daponte, C. De Capua, A. Liccardo, A technique for remote management of instrumentation based on web service, Online [Accessed 18 March 2026] https://www.imeko.org/publications/tc4-2004/IMEKO-TC4-2004-122.pdf.
[9] C. Landi, A. Liccardo, N. Polese, Remote laboratory activities to support experimental session for undergraduate measurements courses, 2006 IEEE Instrumentation and Measurement Technology Conference Proceedings, IEEE, 2006, pp. 851–856. DOI: 10.1109/IMTC.2006.328232
[10] L. Angrisani, F. Bonavolontà, M. DArco, A. Liccardo, A flexible remote laboratory with programmable device under test, Measurement, vol. 156, 2020, p. 107584. DOI: 10.1016/j.measurement.2020.107584
[11] A. Baccigalupi, M. D'Arco, A. Liccardo, M. Vadursi, Test equipment for DAC's performance assessment: Design and characterization, IEEE Transactions on Instrumentation and Measurement, vol. 59, 2010, no. 5, pp. 1027–1034. DOI: 10.1109/TIM.2010.2041019
[12] F. Bonavolontà, M. D'Arco, A. Liccardo, O. Tamburis, Remote laboratory design and implementation as a measurement and automation experiential learning opportunity, IEEE Instrumentation & Measurement Magazine, vol. 22, 2019, no. 6, pp. 62–67. DOI: 10.1109/MIM.2019.8917906
[13] C. De Capua, A. Liccardo, R. Morello, On the web service-based remote didactical laboratory: further developments and improvements, 2005 IEEE Instrumentationand Measurement Technology Conference Proceedings, IEEE, 2005, vol. 3, pp. 1692–1696. DOI: 10.1109/IMTC.2005.1604458
[14] M. Pradana, H. P. Elisa, Metaverse in education: A systematic literature review, Cogent Social Sciences, vol. 9, 2023, no. 2, p. 2252656. DOI: 10.1080/23311886.2023.2252656
[15] F. Bonavolontà, D. L. Carnì, F. de Pandi, F. Lamonaca, A. Liccardo, Reconfigurable measurement setup for laboratory activities in augmented reality, Measurement: Sensors, 2024, p. 101321. DOI: 10.1016/j.measen.2024.101321
[16] F. Bonavolontà, A. Monaco, E. Caputo, A. Liccardo, IM-MetaLAB: the first digital laboratory for teaching the fundamental concepts of instrumentation and measurement in metaverse, Scientific Reports, 2025. DOI: 10.1038/s41598-025-29553-7
[17] P. Onu, A. Pradhan, C. Mbohwa, Potential to use metaverse for future teaching and learning, Education and Information Technologies, vol. 29, 2024, no. 7, pp. 8893–8924. DOI: 10.1007/s10639-023-12167-9
[18] R. S. L. Moriello, A. Liccardo, F. Bonavolonta, E. Caputo, A. Gloria, G. De Alteriis, On the suitability of augmented reality for safe experiments on radioactive materials in physics educational applications, IEEE Access, vol. 10, 2022, pp. 54 185–54 196. DOI: 10.1109/ACCESS.2022.3175869
[19] A. Liccardo, F. Bonavolontà, R. S. L. Moriello, F. Lamonaca, L. De Vito, A. Gloria, E. Caputo, G. De Alteriis, Digital twins based on augmented reality of measurement instruments for the implementation of a cyber-physical system, Acta IMEKO, vol. 11, 2022, no. 4, pp. 1–8. DOI: 10.21014/actaimeko.v11i4.1397
[20] E. Caputo, R. S. L. Moriello, F. de Pandi, A. Liccardo, V. Gallicchio, M. Quarto, Exploiting augmented reality and internet of things for gamma ray experiments in educational field, 2021 IEEE International Instrumentation and Measurement Technology Conference (I2MTC), IEEE, 2021, pp. 1–6. DOI: 10.1109/I2MTC50364.2021.9459881
[21] X. Lv, J. Ma, T. M. Brinthaupt, S. Zhao, X. Ren, Impacts of university lockdown during the coronavirus pandemic on college students academic achievement and critical thinking: A longitudinal study, Frontiers in Psychology, vol. 13, 2022, p. 995784. DOI: 10.3389/fpsyg.2022.995784
[22] A. Liccardo, P. Arpaia, F. Bonavolontà, E. Caputo, F. de Pandi, V. Gallicchio, A. Gloria, R. S. L. Moriello, An augmented reality approach to remote controlling measurement instruments for educational purposes during pandemic restrictions, IEEE Transactions on Instrumentation and Measurement, vol. 70, 2021, pp. 1–20. DOI: 10.1109/TIM.2021.3101314
[23] F. Bonavolontà, E. Gambino, M. T. Verde, A. Liccardo, D. Agrelli, C. Amalfitano, E. Pignoli, A. Monaco, P. Adamo, Revolutionizing agrifood training: The MetaLAM virtual laboratory for multielement analysis, International Conference on Extended Reality, Springer, 2025, pp. 171–180. DOI: 10.1007/978-3-031-97763-3_12
[24] F. Lamonaca, A. Liccardo, D. L. Carnì, E. Bilotta, A. M. Palermo, G. Spadafora, Network of extended reality-enabled laboratories for remote practical training: Didactic in between virtual and real living environment, 2024 IEEE International Workshop on Metrology for Living Environment (MetroLivEnv), IEEE, 2024, pp. 403–408. DOI: 10.1109/MetroLivEnv60384.2024.10615399
[25] J. Elkington, I. H. Rowlands, Cannibals with forks: The triple bottom line of 21st century business, Alternatives Journal, vol. 25, 1999, no. 4, p. 42.
[26] A. Ciroth, M. Finkbeiner, M. Traverso, J. Hildenbrand, W. Kloepffer, B. Mazijn, S. Prakash, G. Sonnemann, S. Valdivia, C. M. L. Ugaya et al., Towards a life cycle sustainability assessment: making informed choices on products, Online [Accessed 21 January 2026] https://www.unep.org/resources/report/towards-life-cycle-sustainability-assessment-making-informed-choices-products.
[27] F. Bonavolontá, A. Liccardo, R. S. L. Moriello, E. Caputo, A. Monaco, IM-MetaLAB: First step towards a new metaverse laboratory for teaching fundamental concepts in instrumentation and measurement, International Conference on Extended Reality, Springer, 2025, pp. 215–223. DOI: 10.1007/978-3-031-97769-5_17
[28] Meta Platforms, Inc., Meta quest 2 technical specifications, Online [Accessed 11 October 2025] https://www.meta.com/quest/products/quest-2/tech-specs/.
[29] D. Patterson, U. Berkeley, A decade of machine learning accelerators: Lessons learned and carbon footprint, Online [Accessed 21 January 2026] https://www.cs.ucla.edu/wp-content/uploads/cs/PATTERSON-10-Lessons-4-TPU-gens-CO2e-45-minutes.pdf.
[30] C. A. Jara, F. A. Candelas, S. T. Puente, F. Torres, Hands-on experiences of undergraduate students in

automatics and robotics using a virtual and remote laboratory, Computers & Education, vol. 57, 2011, no. 4, pp. 2451–2461.
DOI: 10.1016/j.compedu.2011.07.003

[31] I. Gustavsson, K. Nilsson, J. Zackrisson, J. Garcia-Zubia, U. Hernandez-Jayo, A. Nafalski, Z. Nedic, O. Gol, . . more authors, On objectives of instructional laboratories, individual assessment, and use of collaborative remote laboratories, IEEE Transactions on learning technologies, vol. 2, 2009, no. 4, pp. 263–274.
DOI: 10.1109/TLT.2009.42

[32] L. Ozawa-Meida, P. Brockway, K. Letten, J. Davies, P. Fleming, Measuring carbon performance in a uk university through a consumption-based carbon footprint: De Montfort University case study, Journal of Cleaner Production, vol. 56, 2013, pp. 185–198.
DOI: 10.1016/j.jclepro.2011.09.028

[33] M. T. Verde, F. Bonavolontà, A. Liccardo, F. Lamonaca, E. Di Stasio, G. Raimondi, A smart combination of IoT and blockchain enabling technologies to measure and improve workplace safety in dairy farm, Acta IMEKO, vol. 12, 2023, no. 4, pp. 1–7.
DOI: 10.21014/actaimeko.v12i4.1634