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Research article

Towards context-independent indicators for an unbiased assessment of environmental sustainability in higher education: An application to Italian universities

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ABSTRACT

Higher education institutes (HEIs) are important drivers for the development and implementation of best practices for environmental sustainability. However, reliable indicators are needed to objectively evaluate the environmental performance of HEIs and their policies. The present paper aims at identifying suitable indicators for unbiased comparisons among different HEIs and for the identification of temporal trends in terms of environmental sustainability performance. At this aim, sustainability reports made publicly available by 24 Italian HEIs over a 10-year period were considered. Normalization of sustainability variables such as the annual electrical and thermal energy consumptions, related greenhouse gas emissions, and water consumption, against context-specific factors such as the number of users of each university, latitude, illuminance, heating degree days (HDDs) and cooling degree days allowed identifying the actual possible disturbance of the same variables. HDDs were found to positively affect the thermal energy consumption and the related CO_2 emissions. Based on this, a novel indicator was formulated where the actual value of thermal energy consumption and the related CO_2 emissions are divided not only by the number of users but also by the HDDs of the HEIs' locations. Indeed, this is a remarkable finding that, prior to confirmation with data from world HEIs, could be implemented in world university green ranking systems for improved and less biased sustainability assessments.

1. Introduction

In a historical period of great challenges for the environment such as the current one, science and technology require winning social resistance to behavioral changes and the adoption of new perspectives (Brink et al., 2023). Indeed, the implementation of actions towards environmental preservation and resource circularity needs strong directions from politics, but also the active involvement and participation of the whole society. The public acceptance that people's behaviors must be changed to achieve results in the field of environmental sustainability is the first hurdle to overcome (Bertossi and Marangon, 2022; Sterman, 2002). In this context, higher education institutions (HEIs) can play an important role (Brusca et al., 2018; Fischer et al., 2015; Pereira Ribeiro et al., 2021). Higher education has been considered by the United Nations as a crucial actor in the promulgation of sustainable development (Obrecht et al., 2022) and, in particular, in the achievement of the Sustainable Development Goals (Soliman and Mehanna, 2023; Sustainable Development Solution Network, 2020). As a matter of fact, by means of awareness campaigns (Leal Filho et al., 2019; Rieckmann, 2012) and the implementation of curricula on environmental preservation and sustainability (Horne et al., 2024; Lozano et al., 2015; Lozano and Barreiro-Gen, 2019; Wiek et al., 2011), academia has the potential to develop environmental consciousness in students (Al-Dmour, 2023).

Furthermore, HEIs themselves can provide students with examples of virtuous behaviors in terms of resource preservation, energy efficiency, waste management and circular approaches (Alshuwaikhat and Abubakar, 2008; Németh et al., 2023; Schiavon et al., 2021; Sharp, 2009). This could make students consider sustainable initiatives as more natural behaviors to implement in their daily life. More in general, HEIs are able to act at two different levels: first of all, by efficiently transferring

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concepts to students, the latter can in turn influence families and friends by bringing home the lessons learnt (De Feo et al., 2019); secondly, HEIs can directly influence the external audience by taking initiatives for scientific, technological and cultural transfer (Weinstein et al., 2013) and by building partnerships with local communities (Karatzoglou, 2013; Trencher et al., 2014) and the industrial sector (Stål and Babri, 2020). On both levels of action, HEIs do not only promote but also actively implement best practices oriented to energy efficiency, water saving, low carbon emissions, green public procurement and waste management (Bungau et al., 2023; Ralph and Stubbs, 2014). Specifically, best practice actions may consist in the implementation of simple initiatives, such as the replacement of paper towels with energy-efficient hand driers in restrooms (Coller et al., 2021), communication campaigns to improve the selective collection of waste (Rada et al., 2020), or the introduction of purified tap water dispensers to replace plastic bottles in vending machines (Fissi et al., 2021). The adoption of more structural policies, such as the improvement of building insulation with efficient opaque envelopes (Geng et al., 2013) or the introduction of renewable energy systems (Dursun, 2012; Wang et al., 2023) may also be involved, considering the targets of the Paris agreement (United Nations, 2015).

A factor further enhancing sustainability in HEIs is the sharing of information regarding sustainability actions and, more in general, the collaboration among various institutions. For this purpose, the Conference of Italian University Rectors held in Italy in 2016 led to the creation of the Italian University Network for Sustainable Development (RUS). The main goals of the RUSare to support the collaboration, to share information, experiences and best practices, and to spread the culture of environmental sustainability and social responsibility within and outside academia (RUS, 2023). In June 2024, the RUS was composed of 86 out of the 99 recognized public and private Italian universities. The RUS targets may be achieved by several means, such as.

- creating specialized working groups on different topics (climate change, energy, mobility, waste management, education, food, and industry engagement) composed of members of different universities;
- publishing position papers and guideline documents on practices and standardized approaches to assess the level of environmental sustainability of the affiliated universities;
- publishing periodical reports on the universities' performance in terms of environmental sustainability;
- developing joint initiatives, projects and awareness campaigns;
- fostering collaboration with public bodies and the engagement of stakeholders.

Besides key data such as the consumption of water, electrical and thermal energy, related emissions of GHGs and waste production, sustainability reports contain information on the initiatives that HEIs have implemented and that may partially explain the results obtained in the short and long term.

With regards to the improvements the HEIs can make in terms of environmental sustainability, a reliable assessment of their sustainability development can represent a starting point (Fischer et al., 2015; Pope et al., 2004; Shriberg, 2002; Waas et al., 2014). As a matter of fact, by knowing its sustainability status and the weaknesses emerged from an assessment, an institution can schedule initiatives for sustainability improvement (Bond et al., 2012). In the last decades, the sustainable development of HEIs has started to be measured according to different assessment schemes by worldwide recognized ranking systems. The development and diffusion of these rankings have fostered competitiveness among HEIs worldwide and such competition has in turn promoted the implementation of an increasing number of initiatives to achieve higher sustainability targets (Atici et al., 2021). However, weak points in the formulation of questions to the participating HEIs and possible improvements to the evaluation mechanisms that may lead to less biased rankings have been identified (Boiocchi et al., 2023a; Lauder et al., 2015; Ragazzi and Ghidini, 2017).

In the scientific literature, some examples of sustainability assessment of HEIs are available. For instance, Bautista-Puig and Sanz-Casado (2021) evaluated the sustainability status of 82 Spanish HEIs by considering only few selected parameters such as the research patterns, internationalization, the presence of sustainability action plans, and campus operation in terms of the mere institution of green offices. A further study within the context of Spanish HEIs by Larran Jorge et al. (2016) proposed a framework of 156 items to assess HEIs' sustainable development. In Saudi Arabia, Alshuwaikhat et al. (2016) assessed the sustainability of Saudi HEIs based on criteria such as teaching and curriculum on sustainability topics, research activities regarding sustainability, practical actions for improved sustainability within the campus, management and community concern about sustainability, and financial approach for sustainability. Sepasi et al. (2018) proposed an assessment tool for HEIs' sustainability framed according to: Environmental, Social, Educational, and Governance indicators. The tool was then applied to the University of California using data related to the year 2015. Finally, Barros et al. (2020) analyzed the sustainability of a Brazilian university focusing only on the environmental actions taken regarding specifically education, water, waste, electricity, and emissions. From these studies, various discrepant ways through which sustainability is measured emerge; in particular, different items are considered, and no standard criteria are adopted. The absence of normalization and the consequent impossibility of making fair comparisons was highlighted by Guerrero-Lucendo et al. (2022). Furthermore, the issue of being able to fairly compare the sustainability status of HEIs regardless of local context-specific factors remains unaddressed. Besides the numerosity of the academic community, context-specific factors for the consumption of natural resources are mainly related to the location of HEIs and their climatic conditions. Normalizing typical environmental sustainability variables against context-specific factors is crucial for an objective comparison among HEIs that are located in different geographical contexts with different environmental challenges. In a recent work (Boiocchi et al., 2023a), a number of hypotheses on the normalization of sustainability variables were proposed to achieve a fair assessment of sustainability in HEIs.

The present paper aims at filling the existing gap in the literature concerning the identification and use of appropriate indicators for an unbiased assessment of environmental sustainability in higher education. Using Italian HEIs as a database of environmental variables, the present paper proposes a systematic investigation to identify suitable context-independent indicators based on the normalization of typical environmental sustainability variables against local context-specific parameters. Based on the results of this investigation, sustainability indicators are proposed for possible use in environmental sustainability rankings worldwide to allow an unbiased evaluation of the environmental performance of HEIs, regardless of their location. The identification of context-independent indicators intrinsically allows applying the resulting ranking framework to other geographical contexts.

2. Materials and methods

The work presented in this article is structured according to the following steps: first, the collection and handling of data about all the possible sustainability parameters of Italian universities is carried out; secondly, indicators describing unbiasedly the sustainability status of universities are identified through an *ad-hoc* methodology, after the identification and quantification of context-specific factors. Using the identified performance indicators, the overall national trends are then analyzed. Perspective considerations on GHG emissions for environmental evaluations are finally provided.

2.1. Data collection and handling

To assess the status of environmental sustainability in Italian HEIs, an online search on sustainability data from reports published by Italian universities was first carried out. Specifically, besides considering those reports uploaded on the RUS website, other documents such as sustainability/social/energy reports and assessments were searched online coupled with the name of those Italian universities not publishing their report on the RUS website. Combining the reports from the RUS website and those from this online search, a significant number of Italian universities emerged having published at least one sustainability report. These reports contain information regarding the consumption of electrical energy, thermal energy, natural gas, and water as well as waste production and greenhouse gas (GHG) emissions from different sources (e.g., energy consumption and mobility) year by year. It is important to point out that not all the sustainability reports provided all these pieces of information. A database including all the sustainability variables reported by the various universities was then built up. Some missing information about few variables were deduced based on the available data. Specifically, thermal energy consumption was not always directly provided by all universities. In this case, an estimation was carried out based on the actual energy sources employed. This estimation can be simply made as expressed in Eq. (1).

$$E_{thermal}^{tot} = \sum_{i=1}^{N} \left(E_{thermal,i} \bullet V_i \right) \tag{1}$$

In Eq. (1), $E_{thermal,i}$ is the specific thermal energy generated per unit of volume of the energy source i used, V_i is the total volume of energy source i used by a university in a year, N is the total number of energy sources employed for thermal energy production, and $E_{thermal}^{tot}$ is the total thermal energy consumed by the university in a year. The typical thermal energy sources employed in HEIs were: methane, diesel and liquified petroleum gas. One university also employed geothermal energy, which is a renewable energy source.

As for GHG emissions, several universities did not provide the amount of CO_2 equivalents (CO_{2eq}) emitted linked to either electrical or thermal energy consumption. Estimations were carried out based on the energy source employed where the information about the latter was available. More in detail, the CO_{2eq} emitted due to thermal energy consumption could be estimated based on the energy source employed and the well-known specific emission factors related to the same energy source, as described by Eq. (2).

$$CO_{2eq}^{therEnergy} = \sum_{i=1}^{N} \left(EF_{CO_{2eq},i}^{therEnergy} \bullet V_i \right) \tag{2}$$

In Eq. (2), $EF_{CO_{2eq},i}^{therEnergy}$ is the CO_{2eq} emission factor of the thermal energy source i, while $CO_{2eq}^{therEnergy}$ is the total CO_{2eq} emitted due to thermal energy consumption by a university in a year.

With regards to the CO_{2eq} emissions due to electrical energy, the information about the energy mix was not available, hence no GHG emission estimation was made. An equivalent approach would have been adopted for the estimation of CO_{2eq} if the same type of information had been available in the case of electrical energy.

Besides retrieving missing information, some data from different universities needed to be homogenized for statistical analysis purposes. Specifically, information about electrical energy and water consumption directly provided in the various universities' reports was employed for further analysis only after changing the units of measurement where needed.

A subset of these variables to be further considered for the present study was then identified based on their availability. Specifically, data numerosity was considered sufficient if at least five universities reported a value for the variable considered for at least three years. In other words, at least five values per variable needed to be provided in three of the years analyzed, otherwise information on that variable was considered as not sufficient for any further study. Infrequent reporting throughout the years for several universities and/or a lack of information about the variable in most universities were the main reasons for insufficient data numerosity. According to this criterion, the following variables were selected.

1) Electrical energy consumption;
2) Thermal energy consumption;
3) Water consumption;
4) GHG emissions due to electrical energy consumption;
5) GHG emissions due to thermal energy consumption.

It is important to point out that the selected variables are only partly representative of the sustainability levels of HEIs. Nevertheless, including more variables would not add useful information due to the scarce amount of related data reported by HEIs.

2.2. Identification of suitable sustainability indicators

As disclosed in the introduction, in order to assess HEIs' sustainable development, a proper set of sustainability indicators needs to be identified. For this purpose, an ad-hoc methodology was followed. Starting from data sets made of yearly raw values for a sustainability variable, normalization was carried out with the aim of eliminating the effect of university context-specific factors on the sustainability variable itself. This is because these context-specific factors may have affected one or more sustainability variable values but did not depend on HEIs' choices. Therefore, aiming at assessing the sustainability of HEIs without biases, their effect must be eliminated (Boiocchi et al., 2023a). As a clear example, the number of people regularly attending a university influences the consumption of water and energy, but this is a factor upon which the university has little or no choice. Other examples of these factors include the weather conditions such as external temperature, exposure to solar radiation or – more generally – the geographical location. If the effect of these factors is not eliminated, a university may result as unsustainable compared to others simply because of a larger number of enrolled students that increase energy/water consumption or because it is located in a colder climate, which requires a larger amount of energy for heating.

In general, each of the sustainability variables selected as described in Section 2.1 could be affected by one or more context-specific factors. If the exact context-specific factors affecting each of these variables were known, normalization would be carried out straightforwardly. However, since the knowledge about the actual effect of these factors on each sustainability parameter is not known a priori but can only be supposed, different trial normalizations with candidate context-specific factors were carried out. A rule of thumb was then used to assess if the sustainability parameter was affected by the candidate context-specific factor used for normalization. Specifically, once the various sustainability variables were normalized against candidate factors, the concept of the coefficient of variation (CV) was exploited to evaluate if the factor against which the sustainability variable was normalized had affected the parameter itself. Based on the definition of CV, the higher the CV, the higher the data dispersion around the mean value, the lower the representativeness of the mean value in depicting the data set (Brown, 1998; Reed et al., 2002; Stepniak, 2011). When normalizing a sustainability parameter against a context-specific factor having an actual influence on the parameter itself, the CV of the normalized dataset is expected to decrease compared to the case when the normalization against that factor was not performed. This is because context-specific factors related to specific characteristics of HEIs tend to increase discrepancies among the absolute values of a sustainable variable, thus increasing dispersion around the mean value and increasing the related CV. Following this line of reasoning, year-by-year CVs for each year computed for datasets without normalization and with normalization were compared against each other. If the CV values of the normalized dataset overall decreased in comparison with the non-normalized case, the factor against which the variable was normalized was considered as a suitable normalization factor. A sustainability variable, normalized against all context-specific factors upon which it is found to be dependent, is considered a valid indicator for HEIs' sustainability to be used for further analyses such as sustainability assessment. It is important to note that, in this work, normalization is carried out by dividing each absolute value of a sustainability variable by a candidate context-specific factor on which the sustainability variable may be dependent. This implies assuming a linear dependency between the sustainability variable and the factor. However, other behaviors such as second-order or exponential dependency, for instance, may occur. For these reasons, one-by-one correlations between each sustainability variable and each candidate context-specific factor were additionally investigated not only through the computation of the Pearson coefficient to assess possible linear correlations, but also through the computation of the Spearman coefficient to evaluate other possible monotone correlations (Hauke and Kossowski, 2011). Beside this main purpose, these correlations served to additionally know whether the identified dependency between the sustainability variable and the context specific factor was positive or negative, namely whether the sustainability variable value increases or decreases with increasing values of the factor.

It is important to note that this method is based on the evaluation of the effect of candidate context-specific factors chosen based on the literature, expert-knowledge, common sense, intuition, and data availability for their quantification, as detailed in the next section. However, other factors more difficult to quantify may emerge as affecting the sustainability parameter and thus leading to a better sustainability indicator. Therefore, it is important to keep in mind that the research presented in this work represents only a step towards the identification of ideal sustainability indicators.

2.3. Identification and quantification of context-specific factors

For each sustainability variable, Table 1 summarizes the candidate context-specific factors against which they were normalized.

As presented in Table 1, the most frequent candidate context-specific factor for all the variables is the number of users. Reasons for including this factor have partly been disclosed in Section 2.2 and are also highlighted in a recent study (Ekim et al., 2023). In general, the number of users likely affects the consumption of electrical energy due to a larger number of people using informatic devices. A larger number of users generally implies larger rooms to be heated during cold seasons, which in turn increases thermal energy consumption. Similarly, a larger number of users is expected to increase water consumption due to an increased hygienic service attendance. On the other hand, climate conditions related to the location of the university described through the heating degree days (HDDs) could affect the amount of thermal energy consumption since more heating is needed in colder areas compared to warmer areas (De Rosa et al., 2014, 2015). Electricity could also partly be used for heating purposes, which may make HDDs relevant for electrical energy consumption (Yurtsever, 2022). On the other hand, the cooling degree days (CDDs) may affect yearly electrical energy consumption by determining the need for air conditioning during the warm months of the year (De Rosa et al., 2014, 2015). The natural illuminance is a further parameter expected to theoretically affect the amount of electrical energy consumed, since lights in HEIs tend to be switched on to compensate for the lack of natural light from the outside (Gago et al., 2015). Latitude is also a parameter upon which climate conditions and daylight exposure depend. A weak – yet non-negligible - correlation between latitude and electricity end-use was identified in the Brazilian residential sector (Ghisi et al., 2007). In an assessment on the impact of climate change on electricity consumption for cooling purposes (Romitti and Sue Wing, 2022), cities located at mid-latitudes were found to have an increased peak demand compared to cities located in tropics, underlying the important role of latitude on electricity consumption. In addition, in a recent study (Ekim et al., 2023), latitude was found to slightly affect the thermal energy demand of buildings.

Table 1
Candidate context-specific factors for each sustainability variable selected.

Sustainability variable	Candidate context-specific factor	Reference
Electrical energy consumption and related CO_2 emissions	Number of users	Ekim et al. (2023)
	Heating degree days	Yurtsever (2022)
	Cooling degree days	De Rosa et al. (2015, 2014)
	Natural illuminance	Gago et al. (2015)
	Latitude	Ghisi et al. (2007); Romitti and Sue Wing (2022)
Thermal energy consumption and related CO_2 emissions	Number of users	Ekim et al. (2023)
	Heating degree days	De Rosa et al. (2015, 2014)
	Latitude	Ascione et al. (2020)
Water consumption	Number of users	Ekim et al. (2023)

Since electrical and thermal energies usually directly affect the GHG emissions due to their production, the same factors may also affect the emission of GHGs related to the respective energy use. However, specific investigations need to be carried out also for these emissions since energy sources may variably reduce the importance of the context-specific factor investigated.

Information regarding the candidate context-specific factors presented in Table 1 was retrieved as follows. The number of users was computed as the sum of the following contributions: the number of students enrolled in bachelor's and master's degree programs, the number of academic staff (including professor, researchers and research grant recipients), the number of technical and administrative staff, students of specialization courses and PhD students. Such data were mostly taken from the statistical office website by the Italian Ministry of University and Research (Ministry of University and Research, 2023). It must be pointed out that, while the number of academic, technical and administrative staff was provided solar year by solar year, which is compatible with the reporting of sustainability variables, the numbers of regular students, students of specialization courses and doctoral students were provided academic year per academic year. In most Italian universities, the academic year starts in fall (usually in the end of September). In few universities the academic year may start in the middle of September. Anyhow, a month-weighted average of the number of students provided was used to estimate the number of students per solar year, as presented in Eq. (3).

$$N_{student}^{y} = \frac{M_{y}^{y-1/y} \bullet N_{student}^{y-1/y} + M_{y}^{y/y+1} \bullet N_{student}^{y/y+1}}{12} \quad (3)$$

In Eq. (3), $M_y^{y-1/y}$ and $M_y^{y/y+1}$ are the number of months of the solar year y in the academic years $y-1/y$ and $y/y+1$, respectively, whereas $N_{student}^{y-1/y}$ and $N_{student}^{y/y+1}$ are the number of students in the academic years $y-1/y$ and $y/y+1$, respectively. For the sake of simplicity, $M_y^{y-1/y}$ was set to 9, while $M_y^{y/y+1}$ was set to 3. For one case, the solar year by solar year contributions could be directly found in the sustainability report, Hence, in that case no calculation was made.

The illuminance for each city (expressed as lux) where the considered universities were located was taken from the Italian Agency for New Technologies, Energy and Sustainable Economic Development (ENEA, 2016). Specifically, the location-specific values of the annual average natural diffuse illuminance on the horizontal plane between 8am and 6pm were considered. Data about the latitude of the universities were approximated as corresponding to the latitude of the city where the main university headquarter is located and retrieved using Google Earth, while the yearly HDDs for each university employed in this work are calculated as the sum of the daily positive differences ($DIFF_{T,HDD}$) between the reference temperature for indoor environments conventionally (T_{in}^{HDD}) set at 20 °C in this work, and the daily average outdoor temperature (T_{out}^{i}) which depends on each location, computed throughout the days of a solar year N_{day}^{y}, as expressed in Eqs. (4) and (5). If the outer temperature is higher than T_{in}^{HDD} for a day and thus the difference is negative, the same difference is set to zero.

$$DIFF_{T,HDD}^{i} = \begin{cases} T_{in}^{HDD} - T_{out}^{i} & if\ T_{in}^{HDD} > T_{out}^{i} \\ 0 & if\ T_{in}^{HDD} < T_{out}^{i} \end{cases} \quad \forall i = 1, \ldots\ldots, N_{day}^{y} \tag{4}$$

$$HDD = \sum_{i=1}^{N_{day}^{y}} DIFF_{T,HDD}^{i} \tag{5}$$

On the other hand, the CDDs were defined in the opposite way to the HDDs: namely, the difference ($DIFF_{T,CDD}^{i}$) is computed between the local outdoor temperature (T_{out}^{i}) and the reference indoor temperature (T_{in}^{CDD}) set at 26 °C, as mathematically expressed according to Eqs. (6) and (7).

$$DIFF_{T,CDD}^{i} = \begin{cases} 0 & if\ T_{in}^{CDD} > T_{out}^{i} \\ T_{out}^{i} - T_{in}^{CDD} & if\ T_{in}^{CDD} < T_{out}^{i} \end{cases} \quad \forall i = 1, \ldots\ldots, N_{day}^{y} \tag{6}$$

$$CDD = \sum_{i=1}^{N_{day}^{y}} DIFF_{T,CDD}^{i} \tag{7}$$

Both HDDs and CDDs are expressed as K•day•year^{-1}. Data about the outdoor average daily temperatures used in this work related to the city where the main university headquarter is located were retrieved online.

3. Results and discussion

In this section, after an overview regarding the amount of reported data available for this research, results are presented regarding the identification of suitable sustainability indicators for electrical energy consumption, thermal energy consumption, water consumption and GHG emissions through the methodology explained in the previous sections. Pearson and Spearman coefficients for the correlation between each sustainability variable and the candidate context specific factors presented in Table 1 are provided in Supplementary Information (SI).

3.1. Analysis of data availability

To elucidate the amount of information provided in the environmental sustainability reports of the 24 universities, the yearly maximum number of sustainability variables that each university reported during the 10-year period between 2012 and 2021 was extracted. These data are presented in the SI (Fig. S1). The variables initially considered were: electrical energy consumption, thermal energy consumption, water consumption, GHG emissions from electrical energy, GHG emissions from thermal energy, GHG emissions from total energy consumption, municipal solid waste production and special waste production.

Year-by-year number of universities reporting each of the previously mentioned environmental sustainability variables between 2012 and 2021 is reported in Fig. S2. It is possible to observe that several Italian universities publicly reported data regarding electrical and thermal energy consumption and water consumption. On the other hand, fewer Italian universities reported data regarding GHG emissions. While missing data regarding GHG emissions due to thermal energy consumption could be easily computed according to Eq. (2) given that most universities detailly reported the thermal energy sources employed, the same did not occur for the GHG emissions due to electrical energy consumption, as previously mentioned in Section 2.1. More universities should make efforts in estimating GHG emissions due to electrical energy consumption or providing detailed information about the energy mix. Indeed, monitoring sustainability items such as GHG emissions is an important step towards an increased awareness of sustainable development of universities, which in turn can create the basis for improvements (Maulidevi et al., 2023). The number of universities publicly reporting data on municipal solid waste and special waste is considerably lower compared to the other variables and too low for statistical purposes. For this reason, the environmental sustainability variables further considered were limited to the ones reported in Table 1. The highest frequency of reporting occurred in the years 2017, 2018, and 2019. A fairly high frequency of reporting also occurred in 2016, 2020, and 2021. There is still a sufficient amount of data provided for the years 2014 and 2015. On the other side, reporting has been sparing for the years before 2014. The lower reporting rate in the years prior to 2016 and even more sparing for the years prior to 2014 can be largely attributed to the fact that the RUS, stressing and promoting the reporting on sustainable development by Italian universities, was founded only in 2016. When Italian universities started to systematically report on their sustainability actions, only data regarding few years back were retrieved. Furthermore, some universities did not join the RUS immediately upon its launch but few years later, which further delayed the first year of reporting. With regards to the lower amount of published data for the years 2020 and 2021 compared to the years 2017, 2018 and 2019, though the reporting can be considered satisfactory for statistical analysis, this is to be attributed to the scheduled frequency at which each university decides to publish sustainability reports, which is arbitrary and varies from one university to another. Only few universities publish sustainability reports every year, while many others publish reports every two years. Furthermore, there are internal technical and administrative issues that may delay the publication of a sustainability report by a university.

Besides considering the amount of data, it is also important to consider that the available data come from universities of different sizes located in various geographical locations in Italy, making the variation of the candidate context-specific factors presented in Section 2.3 significant, which in turn is expected to enable a thorough investigation on their effect on the sustainability variable to analyze. Therefore, despite some deficiencies, the amount of available data can be preliminarily considered sufficient to carry out the statistical analysis described in Section 2.

3.2. Indicators for electrical energy consumption

The year-by-year CV values for the electrical energy consumption without normalization and normalized against the candidate context-specific factors listed in Table 1 (i.e., the number of users, HDDs, CDDs, illuminance and latitude) are presented in Fig. 1.

As can be observed in Fig. 1, a significant reduction in the CV values is obtained when the values of electrical energy consumption are normalized with respect to the number of users. More specifically, for all the years considered, the CV becomes below 0.5, which describes a low dispersion of values around the mean. The CV reduction by normalization against the number of users was expected as the latter directly affects the use of electronic devices such as laptops and computers which abundantly consume electricity and the use of other energy-demanding services. On the other hand, normalizing against the illuminance did not yield any significant CV reduction compared to the non-normalized case. Although it was expected that a higher illuminance would reduce the need to have lights switched on and thus reduce the electrical energy demand linked to it, the results clearly suggest that the contribution of this context-specific factor is insignificant. The reasons for this can be partly attributed to the fact that in Italy the discrepancy among illuminance values in the universities located in different geographical positions is minimal. A discrepancy occurring during winter may be compensated in summer so that the overall yearly discrepancy is minimized. A further reason explaining the revealed insignificant effect of illuminance on the electrical energy consumption is that, in geographical locations with a higher illuminance, higher temperatures usually occur, which in turn increase the use of air conditioning and the

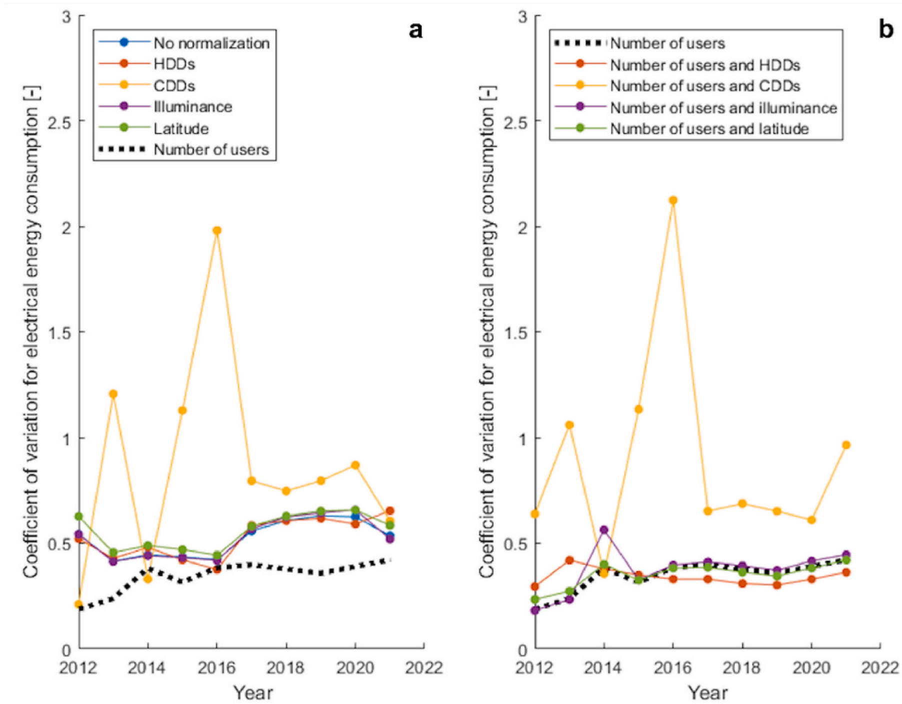

Fig. 1. Coefficients of variation for electrical energy consumption in case of: **(a)** no normalization (blue line) and normalization against number of users (dotted line), HDDs (red line), CDDs (orange line), illuminance (purple line), and latitude (green line); **(b)** normalization against number of users (dotted line), both number of users and HDDs (red line), both number of users and CDDs (orange line), both number of users and illuminance (purple line), and both number of users and latitude (green line). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

electrical energy consumed thereby. In this case, the higher electrical power consumption due to the higher need for air conditioning in summer may be compensated by the lower consumption due to a lower need for lights on in winter.

For the same possible reasons explaining the lack of influence of the illuminance on the electrical energy consumption, the role of latitude results negligible as well, as can be clearly deduced by comparing the CV values obtained without normalizing the electrical energy consumption by the various universities with those obtained by normalizing the same consumption against their respective latitude. The effect of HDDs is not completely clear. On one hand, the normalization of the electrical energy consumption against this factor alone did not reduce the CV values, while normalizing the electrical energy consumption against both the number of users and the HDDs yielded a slightly lower CV reduction compared with the CV reduction achieved through normalization against the number of users only. There seems to be only a weak - and perhaps casual - effect of the HDDs on the electrical energy consumption, confirmed by the low values for Pearson and Spearman coefficients (see Table S1 in SI) indicating poor correlation between electrical energy consumption and HDDs. In the absence of stronger evidence, HDDs are preliminarily not considered as a true context-specific factor for electrical energy consumption.

Summing up, for unbiased evaluations, the sustainability indicator related to the consumption of electrical energy in HEIs should be simply computed as a ratio between the actual energy consumption and the overall number of users. By evaluating this ratio, the year-by-year trend of this indicator shown in Fig. 2 is obtained as an average of all reporting universities.

As visible in Fig. 2, after a period of approximate stability in the average electrical energy consumption from 2014 to 2019, a drop in 2020 can be observed considering the average values related to all reporting universities. This can be attributed to the COVID-19 lockdown which drastically reduced the attendance days of students to universities. When the attendance to classes was restored in 2021, electrical energy consumption increased to a value slightly higher than those before the lockdown. In addition, it can be observed that the normalized electrical energy consumption in 2012 and 2013 were found lower than the following years. However, it is also important to notice that, as discussed in Section 3.1, average data for 2012 and 2013 should be considered much less statistically significant than those of later years due to a much lower number of universities reporting data on electrical energy consumption. In general, the obtained trends displayed in Fig. 2 reveal a lack of strategies towards more sustainable electrical energy consumption in Italian universities. Improvements can be achieved first

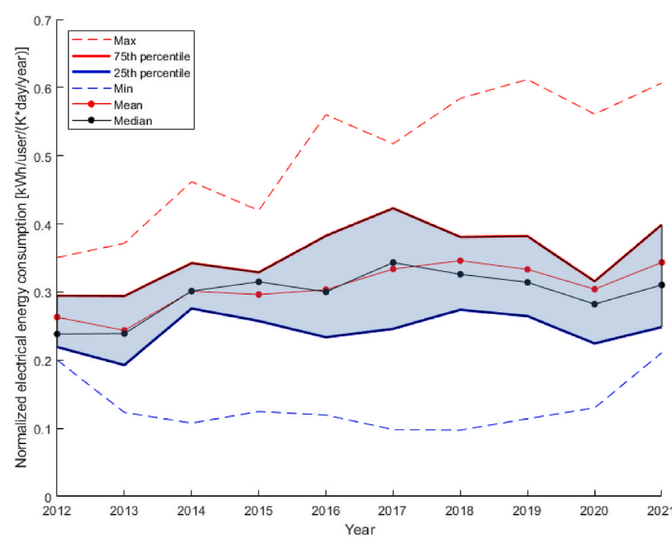

Fig. 2. Yearly trends of normalized electrical energy as averages of all reporting universities. The 25%–75% percentile interval is shown within the blue area, while minimum and maximum values are shown respectively with blue and red dashed lines. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

by establishing a comprehensive tracking system of the various electrical energy consumption contributors so that the major contributors can be easily identified. Then, mitigation strategies focusing on these can be formulated. Indeed, minimizing energy consumption and avoiding energy waste should always be a sustainability goal even when renewable energy sources are used. This is because renewable energy may not always be available in an unlimited amount for all infrastructures and users in an area (Abdul Basit et al., 2020; Halkos and Gkampoura, 2020).

3.3. Indicators for thermal energy consumption

Fig. 3 shows the year-by-year CV values for the thermal energy consumption in the non-normalized case and in the normalized cases against all the candidate context-specific factors presented in Table 1, such as the number of users, the latitude, and the HDDs. As can be seen, CV values significantly decrease when the normalization is made against the number of users and the HDDs. Furthermore, by comparing the CV values obtained when the thermal energy consumption was normalized against each of these two context-specific variables separately, it can be noted that the number of users has a more important effect than the HDDs, although normalizing further against the latter was needed to further reduce the values of CV for each year analyzed. Conversely, no significant effect by latitude was revealed from the normalization. Indeed, latitude could have affected the thermal energy consumption since universities located at higher latitudes are generally expected to have colder winters than those located at lower latitudes. Nevertheless, at the same latitude temperature conditions can still change in function of other factors such as – for instance – the horizontal distance from the sea and the altitude. On the other hand, HDDs offer a more precise description of the heating needs of HEIs, and this in turn influences more directly the thermal energy consumption.

These results suggest that an unbiased sustainability indicator for thermal energy consumption $I^y_{thermEnergy}$ related to the year y should be computed by dividing the raw value of consumed thermal energy of each university (TEC^y) by both the number of users in the same university (N^y_{users}) and the HDDs (HDD^y), as mathematically expressed in Eq. (8). Indeed, both these context-specific factors have shown to have an important effect on the sustainability variable considered and should be normalized against when carrying out unbiased sustainability assessments.

$$I^y_{thermEnergy} = \frac{TEC^y}{N^y_{users} \bullet HDD^y} \tag{8}$$

The suitability of the proposed indicator as the per-capita thermal energy consumption normalized against the HDDs for comparisons among different HEIs regardless of their geographical context is also visible in Fig. 4, showing the expected good linear correlation between per capita thermal energy consumption and heating degree days related to the year 2019 (providing one of the two most populated data sets).

Values for Pearson and Spearman coefficients, qualifying the good correlation between per capita thermal energy consumption and heating degree days not only for the most populated year (2019) but also for the other years considered in this work are provided in Table S2 in SI.

Fig. 5 shows the year-by-year thermal energy consumption indicator of Eq. (8) computed one-by-one as the average among all reporting Italian universities. As can be seen, while from 2014 to 2020 the normalized thermal energy consumption is constant at around 0.28 kWh•user^{-1}•K^{-1}•day^{-1}•year, a significant drop can be observed starting with 2021. Contrary to what happened for the electrical energy consumption, with a considerable increase from 2020 to 2021, the thermal energy consumption normalized against both the number of users and the HDDs shows a decrease in the mean and median values. This could be partly attributed to the fact that university energy

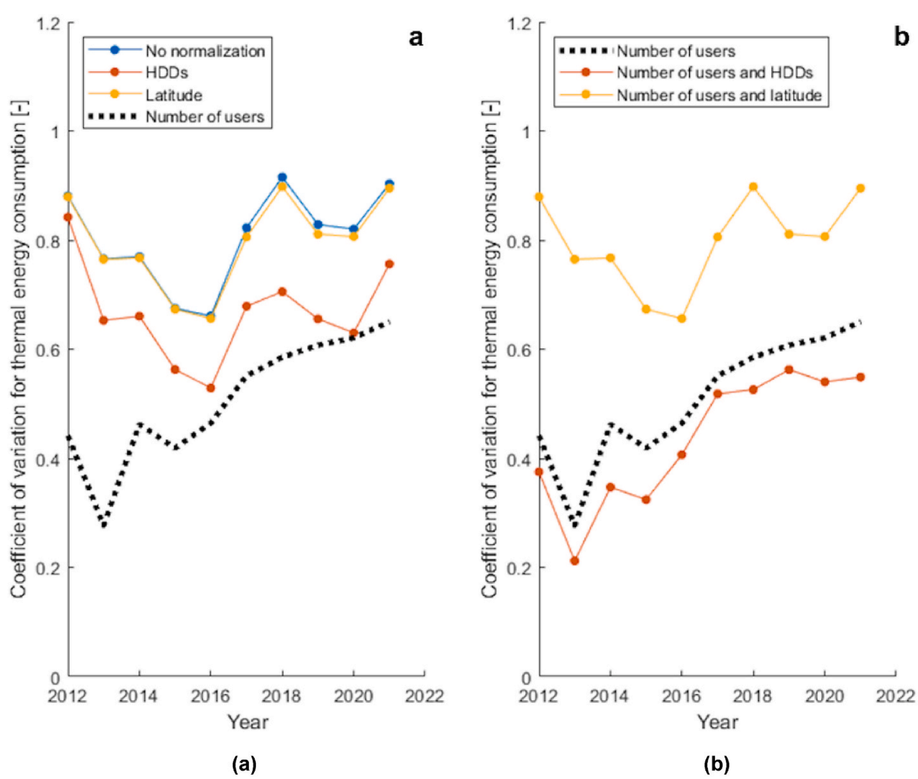

Fig. 3. Coefficients of variation for thermal energy consumption in case of: **(a)** no normalization (blue line) and normalization against number of users (dotted line), HDDs (red line), and latitude (orange line); **(b)** normalization against number of users (dotted line) and normalization against both number of users and HDDs (red line), and both number of users and latitude (orange line). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

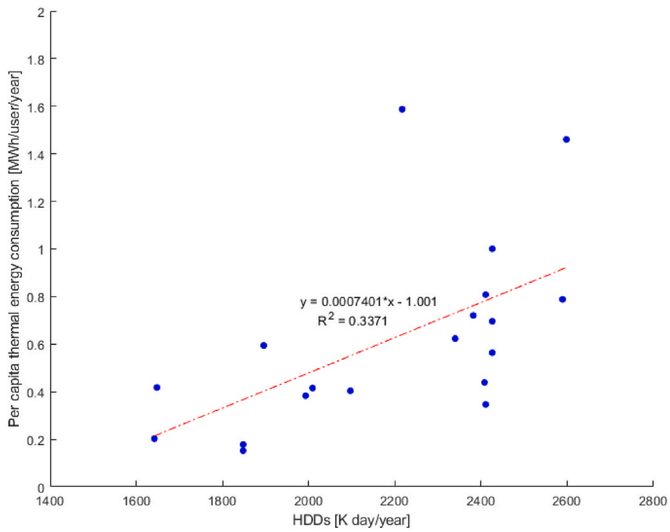

Fig. 4. Correlation between heating degree days (computed with a reference temperature of 20 °C) and per capita thermal energy consumption for the year 2019.

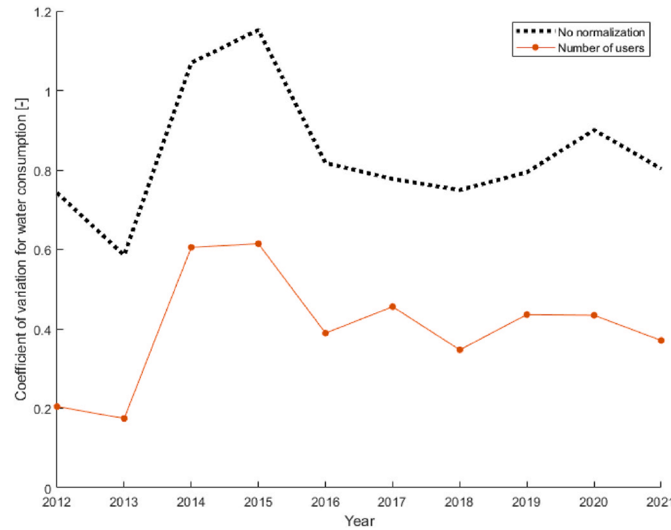

Fig. 6. Coefficients of variation for water consumption in case of: no normalization (dotted line) and normalization against the number of users (orange line). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

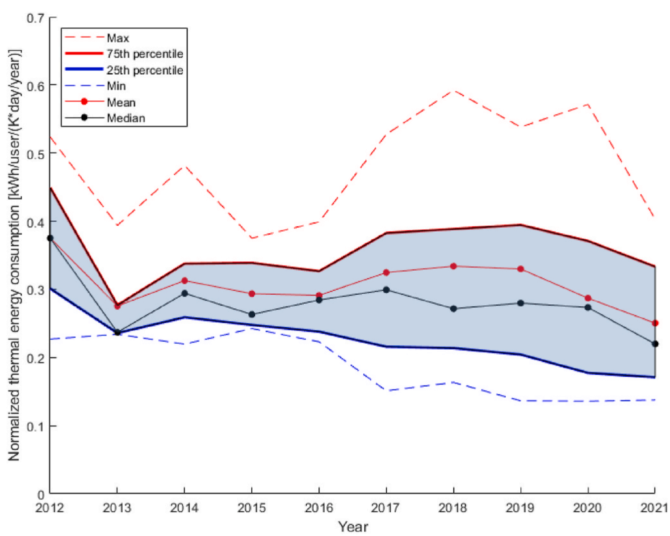

Fig. 5. Yearly average trend of thermal energy consumption normalized against both the number of users and the HDDs. The 25%–75% percentile interval is shown within the blue area, while minimum and maximum values are shown respectively with blue and red dashed lines. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

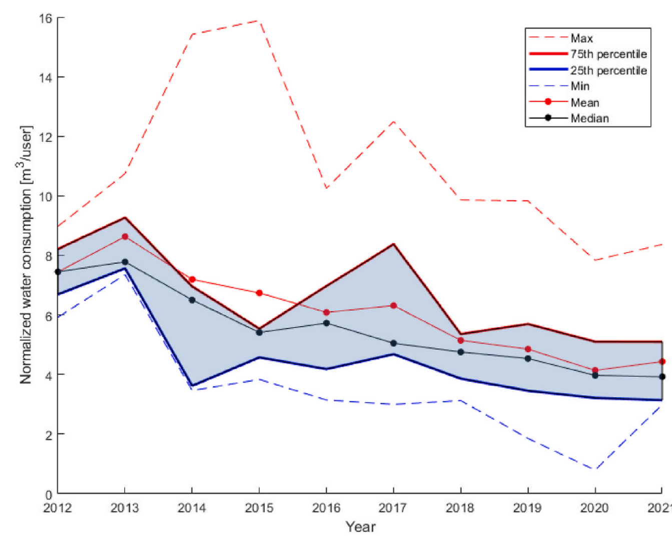

Fig. 7. Yearly average trend of water consumption normalized against both the number of users and the heating degree days. The 25%–75% percentile interval is shown within the blue area, while minimum and maximum values are shown respectively with blue and red dashed lines. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

managers made several efforts to optimize the heating system efficiency and the heat provision according to the actual university needs. Optimization of heating system and provision may have been carried out also for the next year, resulting in a similar thermal energy consumption.

3.4. Indicator for water consumption

By using the same approach adopted for energy consumption, the expected central role of the number of users for water consumption was confirmed, which is clearly demonstrated by a significant reduction of the CV values when water consumption volumes were normalized against the number of users in the respective universities (see Fig. 6).

From the mean values depicted with the standard deviation in Fig. 7, trends towards a more sustainable water consumption throughout the last decade can be clearly observed. As a matter of fact, there is a constant drop in the mean value of per-capita water consumption from one year to the next, except for the year 2021 where a rise of the mean value can be noted. However, the reason for this could be largely attributed to a water consumption peculiarly lower in 2020 due to the COVID-19 related lockdown which was not in force in 2021. Nevertheless, the per-capita water consumption in 2021 is still lower compared to the pre-COVID scenario. This result is interesting considered the introduction of hygienic measures for COVID-19 prevention (e.g., frequent hand washing) and that several Italian universities have installed tap water purifiers to disincentivize the purchase of PET water bottles by users as a plastic-free measure.

3.5. Indicators for GHG emissions

The present section is structured as follows: first the indicators for the GHG emissions due to electrical and thermal energy consumption are presented, secondly an overall analysis of the GHG emissions by energy use is carried out.

3.5.1. Indicator for GHG emissions due to electrical energy consumption

Considering the GHG emissions related to electrical energy consumption, the effect of illuminance and latitude on the CO_{2eq} emissions linked to electrical energy is not significant, as shown in Fig. 8a. This was expected since the mere electrical energy consumption showed the same undetectable effect (Fig. 1a). Nevertheless, the greater illuminance in some universities could have promoted the adoption of photovoltaic as renewable energy source for electricity, thus reducing CO_{2eq} emissions. On the other hand, the effect of the number of users shows up as only slightly relevant, given that only a minor reduction in the CVs could be obtained compared to the non-normalized case. Compared to the case of electrical energy consumption, the number of users seems to have a much less pronounced effect. Additionally, it can be observed that CV values for CO_{2eq} emissions due to electrical energy consumption (both for the normalized and the non-normalized cases) are generally larger than those for electrical energy consumption. This means that there is a larger scattering of CO_{2eq} emissions linked to electrical energy among Italian universities than for the electrical energy consumption itself, which is to be attributed to the large variability of the grid mix adopted by Italian universities. These results indicate the significance of the energy source on the related CO_{2eq} emissions rather than the mere amount of electricity consumed. Given the revealed effect of context-specific factors on the sustainability variable analyzed, a suitable indicator for GHG emissions due to electrical energy consumption should be computed as the ratio between these emissions and the number of users.

Fig. 9 shows the year-by-year normalized CO_{2eq} emissions due to electrical energy consumption computed as the average of the emissions from the various universities. As visible, a sensible decreasing trend since 2018 can be noted. By computing the incremental difference between the CO_{2eq} emissions from each university year by year, average reduction percentages compared to the previous year result as follows:

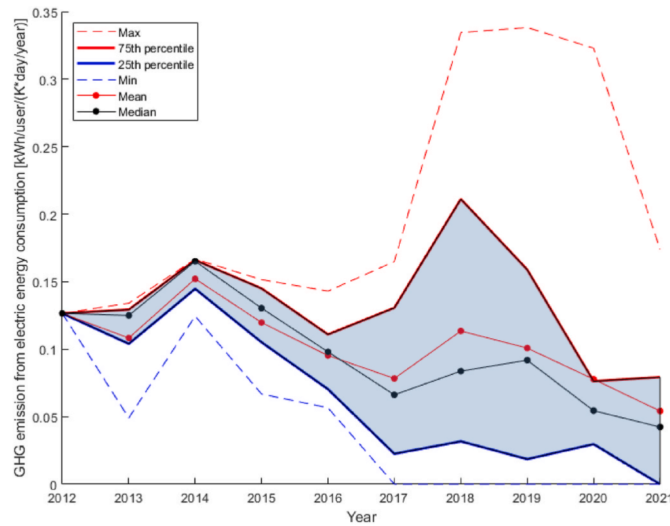

Fig. 9. Yearly trend of average CO_{2eq} emissions due to electrical energy for all reporting universities normalized against the number of users. The 25%–75% percentile interval is shown within the blue area, while minimum and maximum values are shown respectively with blue and red dashed lines. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

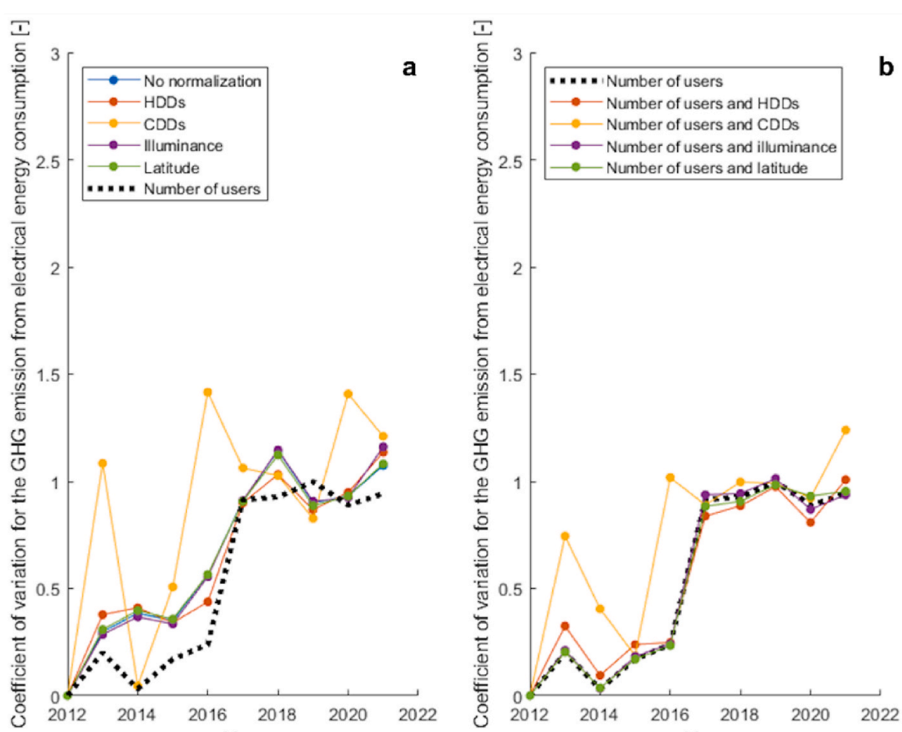

Fig. 8. Coefficients of variation for GHG emissions due to electrical energy consumption in case of: **(a)** no normalization (blue line) and normalization against the number of users (dotted line), HDDs (red line), CDDs (orange line), illuminance (purple line) and latitude (green line); **(b)** normalization against the number of users (dotted line) and normalization against both number of users and HDDs (red line), both number of users and CDDs (orange line), both number of users and illuminance (purple line), both number of users and latitude (green line). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

6.1% for 2019, 37.5% for 2020 and 22.8% for 2021. This result, coupled with the lack of decrease in the consumed electrical energy depicted in Fig. 2 (aside for the year 2020), clearly indicates that throughout the last 5 years at least some universities have been consistently making efforts to adopt more and more renewable energies to produce electrical energy. This effect can be seen in the trend of the minimum values in Fig. 9: from 2017 at least one university started using electrical energy totally from renewable energies. More specifically, the number of universities using 100% renewable energy sources for electricity compared to the number of universities reporting data on GHG emissions from electric energy consumption was: 2 out of 11 in 2017, 3 out of 14 in 2018, 4 out 16 in 2019, 3 out of 13 in 2020 and 4 out of 10 in 2021.

3.5.2. Indicators for GHG emissions due to thermal energy consumption

Fig. 10a shows the CVs obtained by dividing the CO_{2eq} emissions linked to thermal energy production with the number of users, the HDDs, and the latitude while Fig. 10b reports the normalization against number of users and HDDs and both number of users and latitude.

As visible in Fig. 10, similarly to the case of thermal energy consumption, CV values are significantly reduced when CO_{2eq} emissions are normalized against both the number of users and the HDDs, while normalization against latitude did not yield any significant reduction. For this reason, the suitable indicator here proposed to achieve unbiased sustainability assessment with respect to this variable ($I^y_{CO_{2eq,thermEnergy}}$) should be the amount of CO_{2eq} emitted for the production of thermal energy ($CO^y_{2eq,thermEnergy}$) divided by both the number of users and the HDDs, as described according to Eq. (9):

$$I^y_{CO_{2eq,thermEnergy}} = \frac{CO^y_{2eq,thermEnergy}}{HDD^y \bullet N^y_{users}} \quad (9)$$

Similar to the case of the mere thermal energy consumption, even in this case the linear dependency of the CO_2 emissions due to thermal energy consumption can be clearly proven using the available data, as depicted in Fig. 11 related to the most data-populated year (i.e. 2019). Pearson and Spearman coefficients, qualifying the correlation between the per capita CO_2 emissions due to thermal energy consumption and HDDs and latitude, are provided in Table S4 in SI.

By analyzing the time trend of this indicator displayed in Fig. 12, its behavior is similar to the trend of normalized thermal energy in Fig. 5. The reason for these similarities can be ascribed to the similar energy source employed by the various Italian universities, which is mainly

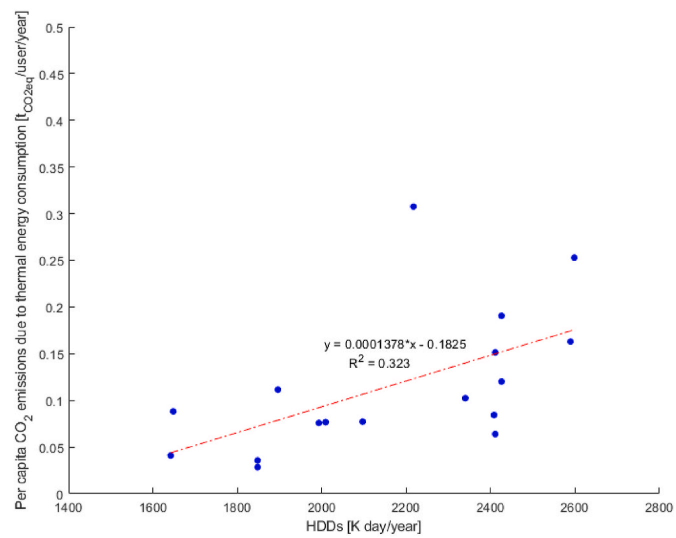

Fig. 11. Correlation between heating degree days (computed with a reference temperature of 20 °C) and per capita emitted CO_2 due to thermal energy consumption for the year 2019.

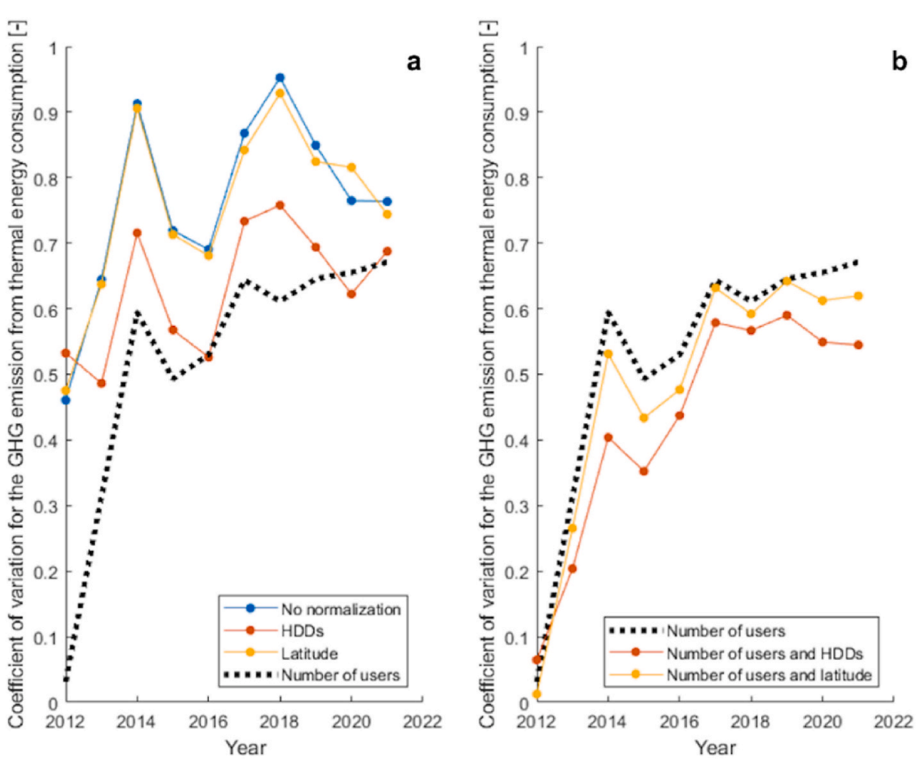

Fig. 10. Coefficients of variation for GHG emissions due to thermal energy consumption in case of: **(a)** no normalization (blue line) and normalization against the number of users (dotted line), HDDs (red line) and latitude (orange line); **(b)** normalization against the number of users (dotted line) and normalization against both the number of users and the HDDs (red line), and both the number of users and the latitude (orange line). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

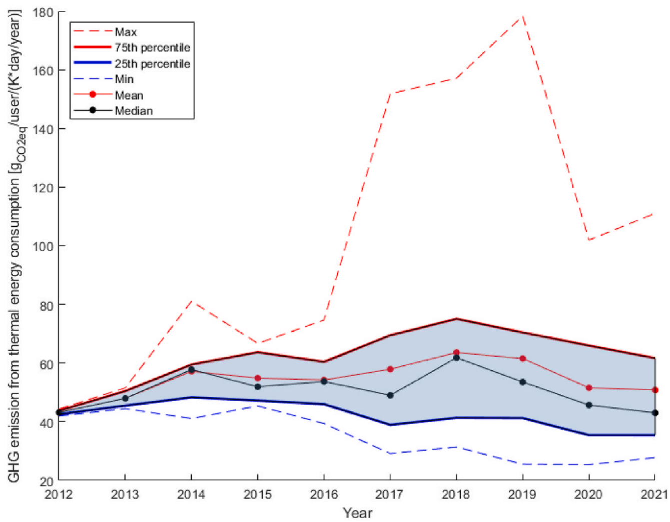

Fig. 12. Yearly trend of average CO_{2eq} emissions due to thermal energy for all reporting universities normalized against both the number of users and the HDDs. The 25%–75% percentile interval is shown within the blue area, while minimum and maximum values are shown respectively with blue and red dashed lines. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

natural gas. Only one university reported that part of its thermal energy was produced from geothermal sources. Indeed, while efforts toward a more optimized consumption seem to have been made in the last few years, too little effort has been made by Italian universities to adopt more carbon-neutral thermal energy sources.

3.5.3. Further considerations on GHG emissions by HEIs

When formulating strategies aimed to a carbon neutrality in HEIs, it is important to analyze the different contributions to GHG emissions, as done also in other works and contexts (Boiocchi et al., 2023b; Maktabifard et al., 2022; Samara et al., 2022). With regards to the average per-capita CO_{2eq} emitted due to energy consumption as displayed in Fig. 13, a decreasing trend since 2018 can be observed mainly due to the decreasing trend in the contribution by electrical energy consumption, specifically from 61.4% in 2016 to 46.8% in 2021. This is due to the increasing adoption of renewable sources to produce electricity by

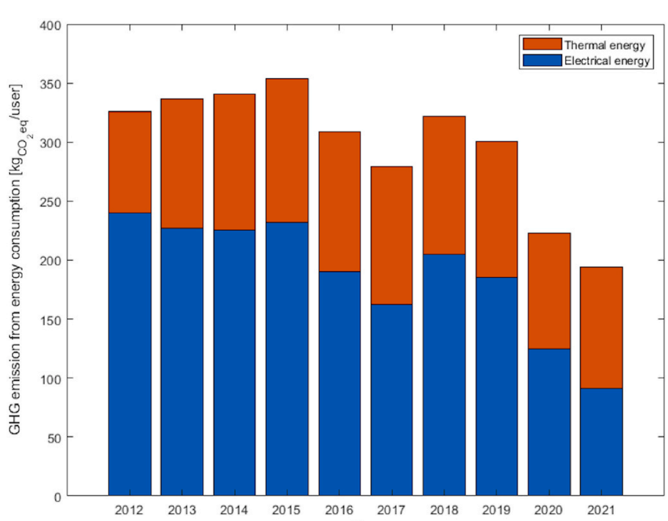

Fig. 13. Trend of per-capita GHG emissions due to thermal and electrical energy consumption by the Italian HEIs considered in the present paper between 2012 and 2021.

various HEIs.

Within this frame, it is important to avoid a too simplified vision of the responsibility of HEIs in terms of GHG emissions. Strategies aimed to a carbon-neutral university should go beyond the role of energy consumption. For instance, the management of residual municipal solid waste may play a visible role in GHG emissions, even if some guidelines decided not to take it into account (RUS, 2023). To this concern, the University of Trento was selected because of the following characteristics referred to residual municipal solid waste management: (a) data were available both as actually collected amount and as amount virtually expected in case of optimal selective collection; (b) the fate of waste was known. Moreover, the GHG emissions from electricity consumption of the same university are set to zero thanks to a contract that allows buying electricity exclusively from renewable sources since 2021. Table 2 displays two scenarios: the one referring to the last pre-pandemic year (2019) and the one referring to the first post-pandemic one (2022). As visible in Table 2, zeroing CO_2 contribution by electricity put more in evidence the role of waste management

Table 2
Details on the calculations of GHG emissions from residual municipal waste management versus energy consumption for the selected case study.

2019	Value	Reference
Volume of residual municipal solid waste paid	1888 m^3/y	University of Trento (2019)
Residual municipal solid waste density	0.113 t/m^3	Data from invoices
Amount of residual solid waste collected	213.3 t/y	–
Percentage of waste to incineration	36.2%	Trento Province Agency for Environmental Protection (2021)
Percentage of waste to landfilling	63.8%	Trento Province Agency for Environmental Protection (2021)
GHG emission factor for incineration	0.52 kg_{CO2eq}/kg	Ecoinvent (2021)
GHG emission factor for landfilling	0.61 kg_{CO2eq}/kg	Ecoinvent (2021)
Estimated GHG emissions from residual solid waste	123 kg_{CO2eq}/y	–
Estimated GHG emissions from electricity consumption	13,788 t_{CO2eq}/y	University of Trento (2019)
GHG emissions from thermal energy	4939 t_{CO2eq}/y	University of Trento (2019)
Ratio between GHG residual waste and GHG energy consumption	<1%	–
2022	**Value**	**Reference**
Volume of residual municipal solid waste paid	1578 m^3/y	University of Trento (Internal source)
residual solid waste density	0.113 t/m^3	Data from invoices
Amount of residual municipal solid waste collected	178.3 t/y	–
Percentage of waste to incineration	61%	Trento Province Agency for Environmental Protection (2023)
Percentage of waste to landfilling	39%	Trento Province Agency for Environmental Protection (2023)
GHG emission factor for incineration	0.52 kg_{CO2eq}/kg	Ecoinvent (2021)
GHG emission factor for landfilling	0.61 kg_{CO2eq}/kg	Ecoinvent (2021)
GHG emissions from residual solid waste	99 kg_{CO2eq}/y	–
GHG emissions from electricity consumption	0 t_{CO2eq}/y	University of Trento (Internal source)
GHG emissions from thermal energy	4540 t_{CO2eq}/y	University of Trento (Internal source)
Ratio between GHG residual waste and GHG energy consumption	2.2%	–

compared to the overall role of energy consumption. The minimal volume of residual municipal solid waste in 2019 was expected as 462 m^3 which was four times lower than the amount collected in the same year. Thus, the role of residual municipal solid waste could be reduced to a negligible contribution, compared to the energy consumption, even after 2022, if selective collection were optimized. The future is difficult to forecast; however, the expected decrease in the role of thermal energy consumption thanks to efficiency improvements might keep relatively visible the role of residual municipal solid waste management even in case of its optimization. Given all of this, it is advisable to include waste in the GHG emissions calculation of HEIs (at least in terms of residual municipal solid waste, because a calculation including all the separated streams of municipal solid waste and the special waste is surely highly complicated). Another contribution that could be relevant is the one given by the mobility of HEIs' users.

4. Conclusions

The present paper aimed at the identification of context-independent indicators for the evaluation of environmental sustainability of HEIs, regardless of their geographical context. To this end, the current availability of environmental sustainability data in reports published by a sample of 24 Italian HEIs over a 10-year period (2012–2021) was first analyzed. The following main variables were selected: electrical and thermal energy consumption, related CO_2 emissions and water consumption.

Afterwards, context-specific factors were identified to normalize the main variables: number of users, HDDs, CDDs, latitude and natural illuminance. Year-by-year CV values for the main variables not normalized and normalized against context-specific factors were compared against one another to identify valid context-independent indicators that could be used for the unbiased assessment of the environmental sustainability of HEIs worldwide. It was found that, while electrical energy consumption, the related CO_2 emissions and water consumptions needed normalization only against the number of users in the institutions, a novel context-independent sustainability indicator related to thermal energy consumption was identified as the ratio between the per capita thermal energy consumption and the HDDs. The same normalization was found to be needed for the per capita CO_2 emissions linked to thermal energy. As a confirmation, positive correlations between HDDs and per capita thermal energy or related CO_2 emissions could be identified. This is a remarkable finding proved with real data that, following confirmation with worldwide HEIs' data, should be implemented in world university sustainability rankings such as the GreenMetric World University Ranking system, which handles energy usages and related GHGs regardless of their purpose (e.g., electrical or thermal) and performs normalization only against the number of users, but not against the HDDs. The effect of HDDs on thermal energy consumption and the related CO_2 emissions was clearly demonstrated from the results presented in this work. Thus, HEIs located in areas with harsher winters are not penalized due to the increased need for thermal energy. This work also highlights the need for more detailed information on the grid mix used by HEIs, which is required to correctly estimate the GHG emissions from electrical energy consumption in case they are not provided. In addition, there is a need for standardized reporting modalities, which would allow a direct and faster evaluation of both general sustainability achievements and the implementation of specific policies.

Regarding the limitations of the present work, this paper analyzed one-by-one correlations between sustainability variables and context-specific factors. However, further investigations considering composite context-specific factors incorporating the contextual effect of multiple environmental conditions can be made to improve further the identification of sustainability indicators. An additional limitation of the present work is that consumptions and related CO_2 emissions by specific activities were not considered separately from other contributions. Thus, HEIs with large energy/water-demanding laboratory facilities may apparently underperform compared to other institutions having a lower research profile. To overcome this problem, sustainability reports should clearly state the presence of these kinds of activities and, possibly, present separate consumption data for research-related activities.

In the future, besides increasing the availability of more detailed information, it would be desirable to obtain larger amounts of data regarding waste management in HEIs, such as the generation of residual municipal solid waste, its composition, and the production of special waste from specific activities. Indeed, preliminary considerations on the role of residual municipal solid waste in terms of carbon emissions pointed out that its relative incidence on the overall GHG emissions could increase. Finally, as a next step, scientific research should compare environmental sustainability indicators with metadata such as the environmental policies implemented by each university. This cross-check would enable explaining better the behaviors and trends of indicators that currently remain unexplainable (e.g., the decrease in water consumption after the restoration of regular classes following the end of COVID-19 lockdown). To do this, information should be explicitly made available to the public and included in sustainability reports.

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CRediT authorship contribution statement

Riccardo Boiocchi: Writing – original draft, Methodology, Formal analysis, Data curation, Conceptualization, Investigation. **Luca Adami:** Writing – review & editing, Visualization, Validation, Supervision, Investigation, Formal analysis, Data curation, Conceptualization. **Elena Cristina Rada:** Writing – review & editing, Methodology, Data curation. **Marco Schiavon:** Writing – review & editing, Writing – original draft, Supervision, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Luca Adami reports financial support was provided by University of Trento Department of Civil Environmental and Mechanical Engineering. Luca Adami reports a relationship with University of Trento Department of Civil Environmental and Mechanical Engineering that includes: funding grants. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2024.121658.

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