scientific reports

OPEN

# Assessing microclimate thresholds for heritage preventive conservation to achieve sustainable and energy efficiency goals in a changing climate

**Francesca Frasca**[1]✉, **Elena Verticchio**[2], **Emanuela Bosco**[3], **Edgars Kuka**[4], **Daniel Sang-Hoon Lee**[5], **Cecil Krarup Andersen**[5], **Chiara Bertolin**[6] & **Anna Maria Siani**[1]

**This research addresses the issue of the heritage preventive conservation in the perspective of energy sustainability, for contributing to the achievement of the Sustainable Development Goals (SDGs) and towards the EU Green Deal. The study analyses and compares four cases associated with different microclimate thresholds as suggested by the standard EN 16893:2018 (Cases 1–3) and as derived from the outputs of three degradation models for preserving paper, wood, and canvas paintings (Case 4). Weather-based indices (degree and gram days) were calculated to estimate trends in the potential energy demand of collection facilities in three European cities belonging to different Köppen-Geiger climate zones (Cfb, Csa, and Dfb), under recent past (1981–2010) and near/far future climate scenarios (2021–2050 and 2071–2100) from two Shared Socioeconomic Pathways (SSP2-4.5 and SSP5-8.5). The findings suggest that adapting facilities' management strategies to focus on collections preservation can facilitate the achievement of 5 out of 17 SDGs, offering a viable alternative to costly energy retrofits and encouraging the development of shared solutions for similar facilities in the same climate zone. The results can contribute to inform the revision of EN 16893 and to face major challenges such as the preservation of paper collections in southern latitudes.**

**Keywords** SDGs, Changing climate, Heritage preventive conservation, Standard, Degradation models, Collections facilities

The preventive conservation of cultural heritage is defined as "measures and actions aimed at avoiding or minimizing future damage, deterioration and loss and, consequently, any invasive intervention"[1]. The definition implicitly includes the role of such measures in safeguarding collections from the impacts of the changing climate[2,3]. However, in the context of the achievement of the Sustainable Development Goals (SDGs) and the European Green Deal, it does not consider the challenges related to the energy efficiency of collections facilities, meant as all spaces housing, exhibiting, and storing cultural collections. The "European Cultural Heritage Green Paper", issued by Europa Nostra and ICOMOS, has acknowledged the potential of cultural heritage as a vital resource to drive transformative climate action (SDG 13) and to influence energy patterns hence supporting the green transition[2]. However, the progress toward climate neutrality and sustainable goals has been slowed down by insufficient research on the impact of climate change[4] on energy demand of collections facilities, and consequently, on their management strategies[5].

Collections facilities and all their related activities might actively contribute to accelerate actions towards the SDG 11 (Target 11.4—Strengthen efforts to protect and safeguard the world's cultural and natural heritage) and

[1]Department of Physics, Sapienza Università Di Roma, P.Le A. Moro 5, 00185 Rome, Italy. [2]Institute of Heritage Science, National Research Council, Via Salaria Km 29, 300, 00015 Montelibretti, Italy. [3]Department of the Built Environment, Applied Mechanics, Eindhoven University of Technology, P.O. Box 513, 5600 MB Eindhoven, The Netherlands. [4]Laboratory of Wood Biodegradation and Protection, Latvian State Institute of Wood Chemistry, Riga 1006, Latvia. [5]Royal Danish Academy, Philip De Langes Allé 10, 3.15, 1435 Conservation, Denmark. [6]Department of Mechanical and Industrial Engineering, Norwegian University of Science and Technology, Richard Birkelands Vei 2B, 7491 Trondheim, Norway. ✉email: f.frasca@uniroma1.it

the energy efficiency through the implementation of building renovation and circular economy[6]. Nevertheless, a survey conducted by the Network of European Museum Organisations (NEMO) in 2022 has revealed that more than half of the 578 surveyed EU museums has not climate-friendly or neutral infrastructures[7]. It follows the need to establish heritage commons to support collections facilities in a sustainable decision-making process for the preventive conservation tailored to geographical and environmental contexts. This issue has been also discussed in the latest Business Plan edited by the Technical Committee 346 (TC 346 – Conservation of Cultural Heritage) of the European Committee for Standardization (CEN)[8] and acknowledged in the standards: EN 16141:2012[9], EN 16883:2017[10] and EN 16893:2018[11]. These standards are oriented towards interventions for planning for any new or refurbished collection facilities accounting for their potential energy use and maintenance costs over the whole building life. Additionally, the collections facilities' sufficiency of use is another aspect that needs to be addressed to deal with the growing urgency of a sustainable climate action compatible with heritage conservation[5].

The conventional practice to keep a tight microclimate control to limit damage to collections, together with the use of facilities for visits[12] and users travelling to the location[11], results in high energy demand and greenhouse gas emissions[13]. For collections preserved in inefficient collections facilities (i.e., not climate-friendly or neutral infrastructures), this practice further increases the energy demand, thus being incompatible with the targets of the Green Deal[14]. In this context, interventions for the energy efficiency of these facilities via short- and long-term measures (e.g., coupling passive technologies with renewable energy sources and natural-based solutions) can be a solution according to the current European directives[15,16]. However, their implementation is challenging for heritage at both building- and district-scale if they are protected by law[17]. Additionally, most of the research contributions have dealt with single case studies, providing building-scale solutions[18–21] rather than local- and global-scale indications for the future management programming[22,23]. The lower attention paid to energy-efficiency measures at cultural district, city and regional stocks has also been highlighted by the review conducted by Lidelöw et al.[24]: solutions are mainly aimed at modifying building envelopes and/or other elements[25,26] or at implementing renewable energy sources[13] and heating, ventilation, and cooling systems[27,28], but only at the building scale. Additionally, the effects on the acclimatisation of artworks to their historical climate conditions[29] and the adaptation of such measures to future outdoor climate conditions are rarely discussed[30]. To cite but a few, the rise in air temperature associated with global warming may be responsible for the increase of summer cooling in southern latitudes[30–32], making the use of the so-called "conservation heating" unfeasible for the indoor dehumidification in northern latitudes[33,34]. An alternative approach to responsibly consume energy in collections facilities goes through the reanalysis of the intervention measures and the possibility to rediscuss the operational management practices for the microclimate control according to the specific requirements of people and collections. For example, organic and hygroscopic collections preserved in historic buildings might suffer from mechanical degradation if they are moved to facilities differing from the historical microclimate to which they have acclimatised[29,35,36]. Kramer et al.[37,38] and Kompatscher et al.[39] have demonstrated that relaxing the microclimate thresholds in museums and archives from strict to wider thresholds is beneficial for energy savings without compromising the collection safeguard. Silva et al.[14] have demonstrated that relaxing the temperature control during closing hours can be beneficial to energy savings, but further research should be performed to relative humidity control. Indeed, the current scientific understanding of how collection materials respond to microclimate fluctuations is based on degradation models, which could be employed to identify alternative microclimate thresholds. Although these results are encouraging, no research has focused so far on discussing the possibility to consider 'not-standardised' microclimate thresholds in the facility management. This approach can be complementary to the thresholds issued by norms to mitigate the energy demand of collections facilities while tackling the impact of future outdoor climate conditions[4].

The research aims to discuss the energy implications in collections facilities to satisfy the thresholds for the microclimate control according to values suggested by the standard EN 16893:2018 and three degradation models. To this purpose, weather-based indices (i.e., degree-days and gram-days) were computed to estimate the energy consumption potential trend of collections facilities in three EU cities in different climate zones. Then, the influence of the outdoor climate scenarios on these indices was explored to understand future challenges in the microclimate control activities for different collections and possible implications towards pursuing SDGs. This has allowed to create a database that can be used to estimate the energy demand at urban level. The discussion of the results considers the role of thermal comfort for visitors and personnel, the preservation of collections, and the changing climate scenarios.

## Materials and methods

Since one of the key contributors to climate change is the growing demand for energy, this research explores the potential energy implications in climate control for collections facilities (i.e., the collection-oriented microclimate control) in four cases of temperature (T) and relative humidity (RH) thresholds in different outdoor climate scenarios throughout the twenty-first century:

1. T-RH thresholds from EN 16893:2018 where thermal comfort of people in wintertime is neglected favouring a collection-oriented climatization;
2. T-RH thresholds from EN 16893:2018 where thermal comfort of people in wintertime is considered;
3. T-RH thresholds from EN 16893:2018 according to the vulnerability of selected materials where thermal comfort of people in wintertime is neglected favouring an individual collection with an oriented climatization;
4. T-RH thresholds from tailored degradation models of selected materials where thermal comfort of people in wintertime is neglected favouring an individual collection with an oriented climatization.

The evaluation is based on weather-based indices for estimating energy demand in three European cities located in Cfb, Csa and Dfb climate zones (Indices for microclimate control under different outdoor climate scenarios). Then, two comparisons are performed: case 1 *versus* case 2 to study the role of thermal comfort in wintertime, and case 3 *versus* case 4 to study different climate control opportunities for individual collection facilities. This makes it possible to identify the choices towards a more sustainable management of collections facilities, also in view of the achievement of the different SDGs.

## Thermo-hygrometric thresholds for risk of damage

The EN 16893:2018, titled *"Conservation of Cultural Heritage—Specifications for location, construction and modification of buildings or rooms intended for the storage or use of heritage collections"*, aims at suggesting the most suitable strategies for managing collections facilities[11]. It addresses the criteria necessary to establish appropriate spaces for permanent exhibitions and provides four informative annexes devoted to the relative risk of damage and deterioration due to T and RH conditions. The standard recommends an initial assessment of the needs and vulnerability of the collections to define proper acceptability ranges to limit biological, chemical, and mechanical deterioration that could differently affect climate-sensitive materials (specifically reported in the informative annexes B and C). Annex B classifies materials based on their sensitivity to T: low (e.g., ceramic, glass), moderate (e.g., paper), and high (e.g., plastic, film). Additionally, Annex B provides the optimal range for human thermal comfort. Annex C involves mechanical stability, chemical sensitivity for materials sensitive to hydrolysis, and mould risk related to RH. Both the annexes include qualitative considerations on the energy demand associated with maintaining a particular T and RH range, allowing the set points to vary in specific ranges in different seasons. A note specifies that local climate will affect the energy considerations, thus leaving the decision up to each single facility.

Table 1 reports the first three cases of T and RH thresholds extracted from the Annexes B and C. As the energy demand for (de)humidifying is strictly related to the water vapour content in the air, the mixing ratio of moist air (MR) was computed as a function of the T and RH thresholds according to the equation reported in EN 16242:2012[40].

Three degradation models developed and assessed in the framework of the European project CollectionCare (Grant n. 814624, 2019–2022), were used in this study to assess the climate-induced risks of canvas paintings[41], wooden objects[42] and cellulose-based objects[43,44] and the related energy demands in spaces preserving heritage collections. All these models are dynamic, as they provide the evolution of specific parameters describing the materials to climate conditions over time. A detailed description of the three degradation models is provided in the Supplementary Information. T-RH thresholds extracted from the following degradation models are summarised in Table 2. It is worth noticing that the minimum T thresholds is set by default at 5 °C to reduce the occurrences of temperature responsible for the glass–rubber transition.

## Indices for microclimate control under different outdoor climate scenarios

Since both T and RH play a key role in cultural heritage preservation, energy demands in museums should be estimated while considering both T and RH setpoints of microclimate control systems (Table 1 and Table 2). For this reason, we have proposed an approach that is not limited to the energy refurbishment of collections facilities, but also includes the re-discussion of T-RH thresholds suggested by CEN standard combined with the outputs from degradation models. Our aim is to identify solutions for a sustainable facilities management taking into account both collections vulnerabilities and future climate scenarios, thus positively contributing towards achieving the SDGs.

The energy demand (ED) of a building required to control microclimate conditions is influenced by the difference between the outdoor climate variable and the corresponding expected indoor value. The larger the difference between outdoor climate conditions and the desired microclimate threshold, the higher is the energy needed for heating/cooling and/or (de)humidifying the collections facility. In this study, the index used for estimating thermal energy consumption ("degree-days") is extended and applied to the mixing ratio of moist air (MR), being a conservative property. In this case we have called "gram-days" (GD). "Degree-days" represent the counts of °C that the T must increase or decrease to reach a specific threshold T value. Conversely, "gram-days" represent the counts of grams per kilogram (g·kg$^{-1}$) that the MR must increase or decrease to reach the threshold MR value. Using this approach, four indices can be computed: heating degree-days (HDD), cooling degree-days

| | | T (°C) | RH (%) | MR (g·kg$^{-1}$) | | Collections facilities | Note |
|---|---|---|---|---|---|---|---|
| Case 1 | | 8–23 | 30–55 | 2.0 | 3.6 | mix collection | Thermal comfort of people in wintertime is neglected |
| | | | | 5.2 | 9.6 | | |
| Case 2 | | 16–23 | 30–55 | 3.4 | 6.2 | mix collection | Thermal comfort of people in wintertime is considered |
| | | | | 5.2 | 9.6 | | |
| Case 3 | Canvas paintings | 5–30 | 45–65 | 11.9 | 17.4 | individual collections, showcases, storages | Individual collection with oriented climate control |
| | Wood | 5–20 | 30–55 | 4.3 | 8.0 | | |
| | Paper$^{(1)}$ | 5–10 | 30–50 | 2.3 | 3.8 | | |

**Table 1.** T and RH thresholds (or setpoints) used for the estimation of energy demand in spaces exhibiting climate-vulnerable objects under three cases according to EN 16893:2018[11]. (1) Moderate sensitivity for T and low sensitivity to hydrolysis for RH (e.g., rag paper).

| | Materials | Degradation type | Degradation models (safe thresholds accounting the lowest risk) | Collections facilities |
|---|---|---|---|---|
| Case 4 | Canvas paintings | Mechanical | Highly sensitive materials $^{(1)}$<br>$\Delta RH_{max} = -10\%$ with respect to annual RH average<br>Low sensitive materials $^{(2)}$<br>$\Delta RH_{max} = -40\%$ with respect to annual RH average<br>Maximum Allowable RH = 65% | single collections, showcases, storages |
| | Wood | Biological | No visually detectable mould (M3)<br>RH < 80% up to T = 30 °C | |
| | Paper | Chemical | Expected lifetime > 500 years<br>paired T and RH variations<br>for acid damaged paper (pH = 5 and DP = 600) | |

**Table 2.** Temperature (T) and relative humidity (RH) relative safe thresholds according to EN 16893[11] and lowest risk provided by the selected degradation models tailored for canvas paintings, wood, and paper collections. (1) Paintings with very brittle paint layers (elastic modulus exceeding 200 MPa and 0.3% strain at break in a 30 s strain test) and dimensions exceeding 635 × 762 mm2 or hygroscopic conservation treatment. (2) Aged oil paintings.

(CDD), dehumidification gram-days (DGD), and humidification gram-days (HGD). Specifically, the computation of HDD and CDD is conducted independently on the season based on the equations reported by the UK Met Office[45]. To calculate DGD and HGD, daily outdoor average MR values were compared with a threshold MR computed for each combination of indoor T and RH thresholds. Note that DGD and HGD are computed considering the final indoor RH after the cooling or heating process: if the final indoor RH was within the RH thresholds, DGD and HGD are equal to zero; otherwise, DGD and HGD differ from zero. T-RH thresholds from Table 1 and Table 2 are taking into account. The use of climate variables makes it possible to potentially estimate the impact of outdoor climate scenarios on the energy demand[31].

The evolution of the four indices is analysed in three European cities located along similar meridional direction: site A, Copenhagen (Denmark): Lat. = 56.1° N and Long. = 12.5° E; site B, Rome (Italy): Lat = 41.9° N and Long = 12.5° E; site C, Trondheim (Norway): Lat. = 62.7°N and Long. = 11.3° E. These three sites were chosen as representative of three climate zones in Europe according to the Köppen-Geiger classification[46]: Cfb (site A, temperate oceanic climate), Csa (site B, hot summer Mediterranean climate), and Dfb (site C, humid continental mild summer, wet all year).

Daily data of air T and MR related to the three cities were extracted from the Copernicus Climate Data Store. We used the outcomes from the Sixth Assessment Report (AR6) issued by the Intergovernmental Panel on Climate Change (IPCC), which reports five Shared Socio-economic Pathways (SSP) associated with different future emission scenarios [47]. Each SSP provides a potential scenario that would be caused by different socio-economic conditions, land-use changes, and other human-caused climate drivers that influence greenhouse gas emissions (GHGs), thus also affecting the change in the net radiative flux. The Sixth phase of the Coupled Model Intercomparison Project (CMIP6) dataset used in this analysis was generated by *Centro Euro-Mediterraneo sui Cambiamenti Climatici* (CMCC)[48], providing data for recent past climate (RP, 1981–2010) and the intermediate scenario SSP2-4.5 and extreme scenario SSP5-8.5 for the near future (NF, 2021–2050) and far future (FF, 2071–2100). SSP2-4.5, called "middle of the road", represents a development pattern like the current society development, in which radiative forcing is stabilised at approximately 4.5 $W \cdot m^{-2}$ after 2100. Conversely, SSP5-8.5, called "fossil-fuelled development", represents higher GHGs emissions for which radiative forcing reaches 8.5 $W \cdot m^{-2}$ by 2100.

Then, the energy demands for thermal control ($ED_{therm}$), the energy demands for humidity control ($ED_{hum}$) and the total energy demands ($ED_{tot}$) in $kWh \cdot m^{-3} \cdot year^{-1}$ were computed through Eqs. (1), (2) and (3), respectively:

$$ED_{therm} = \frac{A/V \cdot h \cdot U_{value} \cdot DD}{1000} \tag{1}$$

$$ED_{hum} = ACH \cdot h \cdot k \cdot L_{evap} \cdot \rho \cdot GD \tag{2}$$

$$ED_{tot} = ED_{therm} + ED_{hum} \tag{3}$$

where $A$ is the total surface area of the building $\left[m^2\right]$; $V$ is the total volume of the building space $\left[m^3\right]$; A/V is the surface-area-to-volume ratio $\left[m^{-1}\right]$, i.e., the larger the A/V, the more surface area per unit volume, through which material can exchange heat; $U_{value}$ is the thermal transmittance of the building envelope $\left[W \cdot m^{-2} K^{-1}\right]$; $ACH$ is the air exchange rate $\left[h^{-1}\right]$; $h$ is the number of hour in a day (24 h); $\rho$ is air density $\left[kg \cdot m^{-3}\right]$; $L_{evap}$ is the latent heat of evaporation $\left[J \cdot kg^{-1}\right]$; $k$ is the conversion unit ($2.78\ 10^{-7}\ s^{-1}$). The main advantage of this approach is that it is possible to change only the building features to estimate the potential energy demand in specific case studies.

## Results

### Estimation of f past and future energy demands: case 1 *versus* case 2

The evolution of the four indices (HDD, CDD, DGD, HGD) over a whole calendar year in the three European sites can provide an estimation of the magnitude of energy demands needed for accomplishing with the microclimate ranges suggested by the EN 16893 to limit relative risks of degradation for two cases of climate control.

Figure 1 shows the time evolution of degree-days (DD i.e., HDD and CDD) and gram-days (GD i.e., DGD and HGD) per day during the recent past (RP) period in case 1 (Fig. 1a–c) and case 2 (Fig. 1d–f). HDD values (orange lines) were highest between January and February and almost doubled from case 1 to case 2 (from 6 °C to 15 °C for Cfb and from 13 °C to 21 °C for Dfb), whereas the maximum HDD tripled from 2 °C to 9 °C in the Csa site. CDD (blue lines) were larger than zero only in the Csa zone and reached the maximum value of 5 °C at the end of July. DGD values (yellow lines) were always below 4 g·kg$^{-1}$ in all zones. In case 1, DGD values were higher than 0.5 g·kg$^{-1}$ throughout the year, except for the Dfb zone where it was null in wintertime. In case 2, DGD values were higher than 0.5 g·kg$^{-1}$ in summertime with a different duration: the longest for Csa (from April to November) and the shortest for Dfb (from June to September). HGD values (purple lines) were negligible in all zones, except for Dfb in wintertime in case 2, where the heating required to reach indoor minimum T threshold caused a drop of RH below the threshold of RH = 30%.

For the sake of brevity, the time evolution of degree-days and gram-days for the two future scenarios are not reported, but they are briefly described as follows. In the far future of the extreme scenario SSP5-8.5, in case 2 it was observed that heating demands will decrease in frequency and duration, whereas the cooling and dehumidifying demands will increase with respect to the RP period and last for up to two months.

Figure 2 and Table 3 present the annual values of degree-days (HDD and CDD) and gram-days (DGD and HGD) from the recent past (RP) to the near future (NF) and far future (FF) periods in the intermediate SSP2-4.5 and extreme SSP5-8.5 scenarios. In both cases, HDD values tend to significantly decrease from RP to FF in all climate zones for both SSP scenarios. Conversely, CDD values tend to increase (Cfb from 2 °C to 96 °C in a year and Csa from 270 °C to 1000 °C in a year), except for the Dfb climate zone, where cooling will be negligible in all periods. Cooling to accomplish the T$_{max}$ threshold of EN 16893 will become a novel aspect to consider, especially in the Csa climate zone. In all climate zones, DGD values are higher in case 1 climate control than in case 2. Specifically, in the Cfb and Dfb climate zones, DGD is similar between case 1 and case 2, with a small difference between RP and the two NF scenarios: DGD$_{Cfb,1}$ = 447 ± 22 g·kg$^{-1}$, DGD$_{Cfb,2}$ = 158 ± 15 g·kg$^{-1}$, DGD$_{Dfb,1}$ = 384 ± 23 g·kg$^{-1}$ and DGD$_{Dfb,2}$ = 90 ± 20 g·kg$^{-1}$. In the FF scenarios, DGD is always higher than 250 g·kg$^{-1}$ with a maximum value of 639 g·kg$^{-1}$ according to SSP5-8.5. For the Csa climate zone, DGD increase from 600 g·kg$^{-1}$ in RP to 967 g·kg$^{-1}$ in FF for SSP5-8.5 in case 1, and from 295 g·kg$^{-1}$ in RP up to 815 g·kg$^{-1}$ in FF for SSP5-8.5 in case 2. Finally, HGD are always zero except for the Dfb climate zone in RP and NF scenarios in case 2.

Considering that all the reported values in Table 3 are proportional to the energy demands of buildings, it can be inferred that, compared to case 1, case 2 (tighter control) leads to a higher HDD to keep adequate indoor thermal comfort in wintertime for people (who require a narrow temperature range but are less sensitive to RH variation) and to a lower DGD to keep RH within the allowable thresholds for conservation. HDD increased up to 500 times with respect to their initial value (e.g., in SSP5-8.5 FF in Csa), while DGD lowered up to the 80% of the initial value (e.g., in SSP5-8.5 NF in Dfb). Figure 3 shows the time evolution of the degree-days (DD, left column) and the gram-days (GD, right column) in case 1 (first row) and case 2 (second row) from RP to FF.

In case 1 (Fig. 3a,b), DD in RP were higher in Dfb (DD = 1933 °C) than those in Cfb (DD = 716 °C) and Csa (DD = 370 °C). GD in RP were higher in Csa (GD = 600 g·kg$^{-1}$) than those in Cfb (GD = 443 g·kg$^{-1}$) and Dfb

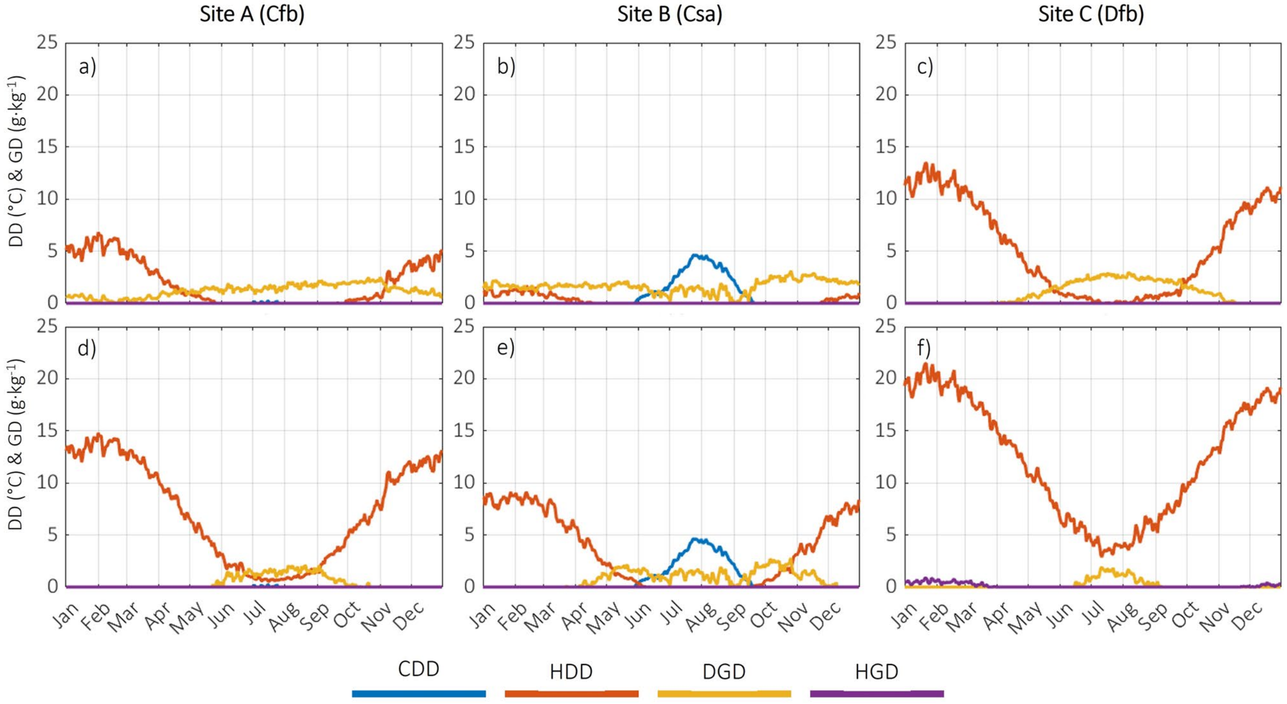

**Figure 1.** Time evolution of degree-days (DD in °C) and gram-days (GD in g·kg$^{-1}$) in three sites corresponding to three different climate zones in the recent past (RP, 1981–2010) in case 1 (a-c) and 2 (d–f).

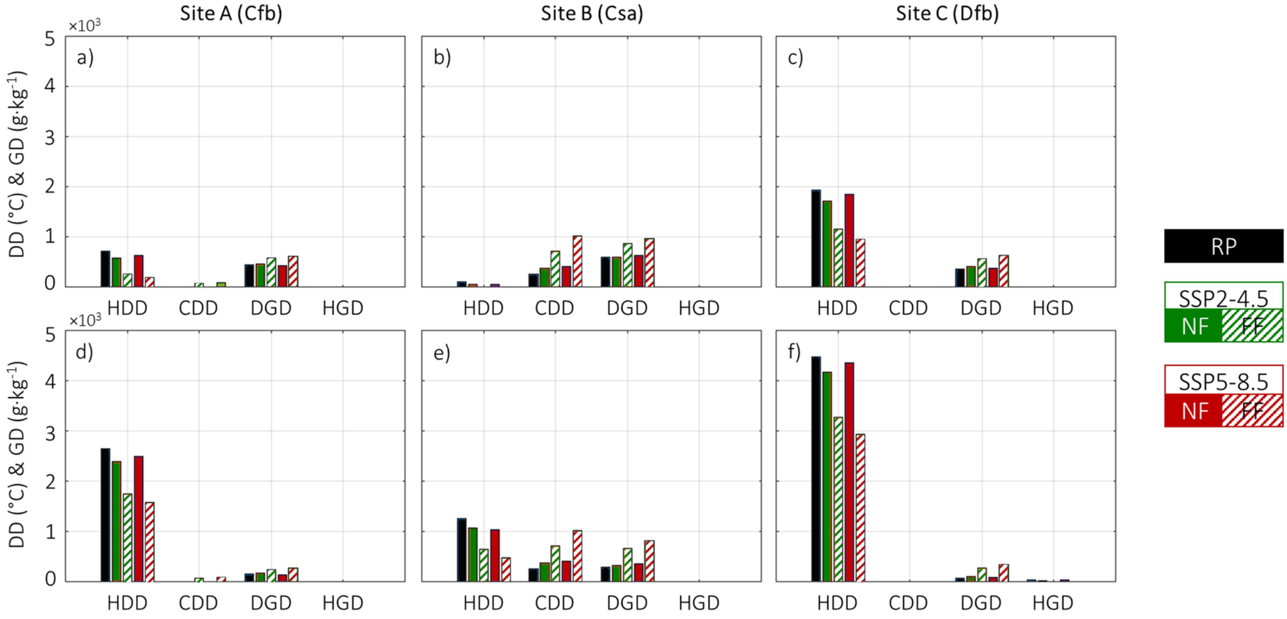

**Figure 2.** Bar plots of degree-days (HDD and CDD in °C) and gram-days (DGD and HGD in g·kg$^{-1}$) in three sites corresponding to three different climate zones from recent past (RP, 1981–2010) towards near future (NF, 2021–2050) and far future (FF, 2071–2100) based on SSP2– 4.5 and SSP5– 8.5 scenarios in case 1 (**a**–**c**) and 2 (**d**–**f**).

| | **Case 1** | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **Site A (Cfb)** | | | | **Site B (Csa)** | | | | **Site C (Dfb)** | | | |
| | **HDD** | **CDD** | **DGD** | **HGD** | **HDD** | **CDD** | **DGD** | **HGD** | **HDD** | **CDD** | **DGD** | **HGD** |
| **unit** | **°C** | | **g·kg$^{-1}$** | | **°C** | | **g·kg$^{-1}$** | | **°C** | | **g·kg$^{-1}$** | |
| Case 1 | | | | | | | | | | | | |
| RP | 714 | 2 | 443 | 0 | 102 | 268 | 600 | 0 | 1933 | 0 | 361 | 0 |
| SSP2-4.5 NF | 579 | 11 | 470 | 0 | 67 | 385 | 608 | 0 | 1719 | 0 | 407 | 0 |
| SSP2-4.5 FF | 268 | 74 | 587 | 0 | 7 | 726 | 875 | 0 | 1156 | 0 | 572 | 0 |
| SSP5-8.5 NF | 637 | 5 | 426 | 0 | 61 | 409 | 637 | 0 | 1846 | 0 | 384 | 0 |
| SSP5-8.5 FF | 188 | 96 | 610 | 0 | 1 | 1014 | 967 | 0 | 950 | 0 | 639 | 0 |
| Case 2 | | | | | | | | | | | | |
| RP | 2642 | 2 | 158 | 0 | 1251 | 268 | 295 | 0 | 4463 | 0 | 72 | 42 |
| SSP2-4.5 NF | 2394 | 11 | 172 | 0 | 1068 | 385 | 329 | 0 | 4167 | 0 | 111 | 27 |
| SSP2-4.5 FF | 1756 | 74 | 252 | 0 | 643 | 726 | 668 | 0 | 3265 | 0 | 284 | 1 |
| SSP5-8.5 NF | 2487 | 5 | 143 | 0 | 1043 | 409 | 356 | 0 | 4342 | 0 | 86 | 35 |
| SSP5-8.5 FF | 1576 | 96 | 280 | 0 | 481 | 1014 | 815 | 0 | 2938 | 0 | 346 | 0 |

**Table 3.** Summary of degree-days (HDD and CDD in °C) and gram-days (DGD and HGD in g·kg$^{-1}$) in three sites corresponding to three climate zones (Cfb, Csa, and Dfb) from recent past (RP, 1981–2010) towards near future (NF, 2021–2050) and far future (FF, 2071–2100) based on SSP2– 4.5 and SSP5– 8.5 in cases 1 and 2 climate control.

(GD = 361 g·kg$^{-1}$). In NF and FF, DD tended to triple in Csa (from 370 °C to 1015 °C) and to decrease in Dfb (-50%) and Cfb (-60%); while GD is expected to increase in all climate zones, with a steeper positive change in SSP5-8.5 in Csa (+61%) and Dfb (+77%).

In case 2 (Fig. 3c,d), DD in RP were higher in Dfb (DD = 4463 °C) than those in Cfb (DD = 2644 °C) and Csa (DD = 1519 °C), with a future reduction in FF in Cfb (-37%) and Dfb (-34%) and a negligible change in Csa (-2%). GD in RP were higher in Csa (GD = 295 g·kg$^{-1}$) than those in Cfb (GD = 158 g·kg$^{-1}$) and Dfb (GD = 114 g·kg$^{-1}$), with a steeper increase in Csa and Dfb.

Starting from a basic knowledge of the building envelope features (e.g., ratio between surface area and building volume (A/V), thermal transmittance of building envelope ($U_{value}$), and air change rate (ACH)), it is possible to approximately estimate the energy demands (ED) of the spaces housing collections located in these specific sites. As an example, to estimate the possible ED over a calendar year to control the microclimate within the

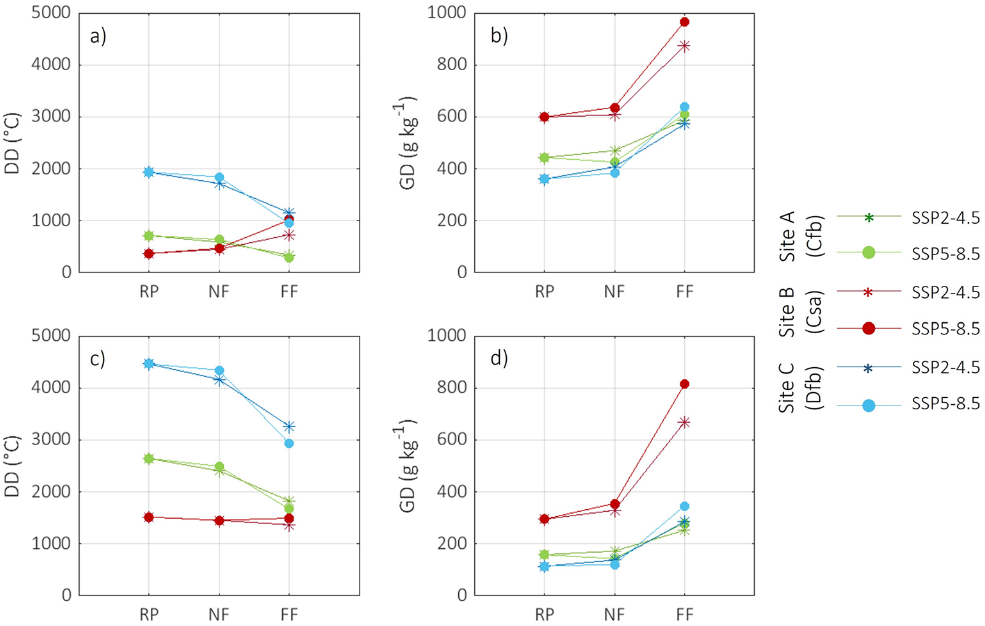

**Figure 3.** Time evolution of degree-days (DD, panels a and c) and gram-days (GD, panels b and d) in three sites corresponding to three different climate zones (Cfb, Csa, and Dfb) from recent past (RP, 1981–2010) towards near future (NF, 2021–2050) and far future (FF, 2071–2100) based on SSP2-4.5 and SSP5-8.5 scenarios in case 1 (**a**, **b**) and 2 (**c**, **d**) climate control.

given T-RH window in cases 1 and 2, we performed calculations setting the following parameters: $A/V = 1 \cdot m^{-1}$; $U_{value} = 1.0\ W \cdot m^{-2} \cdot K^{-1}$; $ACH = 1\ h^{-1}$. Note that users can modify these parameters to estimate the total ED of different spaces housing collections starting from the DD and GD values reported in Table 3. In Fig. 4, it is evident that the total ED tends to double in Csa zone in case 1 (from 21 to 44 $kWh \cdot m^{-3}$) and to increase less than a third in case 2 from RP to FF in SSP5-8.5 scenario (from 42 to 52 $kWh \cdot m^{-3}$). In Cfb and Dfb zones, the total ED tends to decrease of 30% from RP to FF (SSP5-8.5) in both the cases, specifically:

- Cfb: the total ED decreases from 26 $kWh \cdot m^{-3}$ in RP to 19 $kWh \cdot m^{-3}$ in FF in case 1 and in case 2 from 67 $kWh \cdot m^{-3}$ in RP to 46 $kWh \cdot m^{-3}$ in FF in case 2;

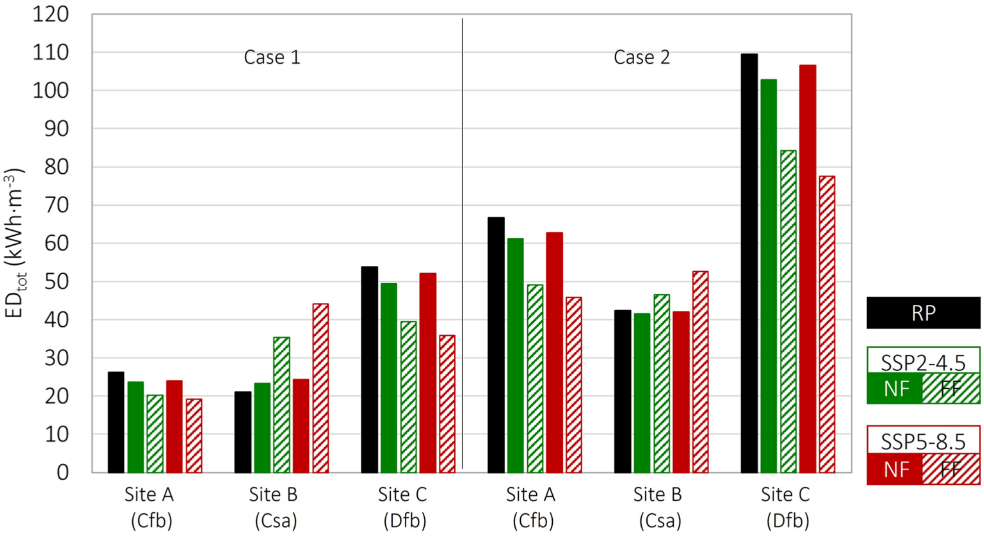

**Figure 4.** Annual energy demands in $kWh \cdot m^{-3}$ estimated in buildings located in three sites corresponding to three different climate zones from recent past (RP, 1981–2010, black bars) towards near future (NF, 2021–2050, solid bars) and far future (FF, 2071–2100, dashed bars) based on SSP2-4.5 (green bars) and SSP5-8.5 scenarios (red bars) in cases 1 and 2. Building features: $A/V = 1 \cdot m^{-1}$; $U_{value} = 1.0\ W \cdot m^{-2} \cdot K^{-1}$; $ACH = 1\ h^{-1}$.

- Dfb: the total ED decreases from 54 kWh·m$^{-3}$ in RP to 36 kWh·m$^{-3}$ in FF in case 1 and in case 2 from 109 kWh·m$^{-3}$ in RP to 78 kWh·m$^{-3}$ in FF.

From the comparison between case 1 and case 2, it is possible to further discuss the expected total ED for different climate control strategies. Indeed, it was highlighted that, to shift from a strategy that did not consider comfort (case 1) to one that considered comfort (case 2), in RP site C (Dfb) and A (Cfb) would have spent about + 30 and + 55 kWh·m$^{-3}$, respectively; on the contrary, to pass from case 1 to case 2, in FF the same sites will be spending approximately 25% less in terms of total ED. As already mentioned, site B (Csa) is the only site for which the total ED in FF is higher than in RP for both cases, with an expected increase of total ED of about + 50% in case 1 and 24% in case 2. The above results suggest that considering thermal comfort of the occupants is expected to become more feasible in climate classes such as Cfb and Dfb, while in view of global warming this change of strategy (case 2) will likely become less sustainable in climates with hot summers such as Csa, where the reduction of HDD will not compensate the increase of CDD.

## Estimation of past and future energy demands: case 3 *versus* case 4

As degradation models are developed to support the identification of T-RH thresholds to limit the relative risks of damage, a comparison with respect to T-RH thresholds suggested by EN 16893 allows to evaluate if the use of degradation models outputs might affect the energy demands required for heritage collections preservation.

Figure 5 present a summary of T and RH thresholds with no relative risk of damage, as suggested by EN 16893 (green areas), and the lowest risk threshold provided by the three degradation models (i.e., T-RH values before any climate-induced deterioration might occur, depicted as white areas) for canvas paintings (a), wooden objects (b) and cellulose-based objects (c).

Figure 5a shows that the T-RH safe thresholds (white area) as identified by the mechanical degradation model for highly sensitive materials (ΔRH = 10% and assuming a maximum allowable RH = 65%) are in line with those recommended by EN 16893. However, it is worth noting that EN 16893 might underestimate the actual mechanical stability in canvas paintings, as it explicitly refers to non-composite and non-constrained hygroscopic objects. The change in RH potentially causing cracks can substantially vary among paintings. Nevertheless, it is generally advised to keep the maximum fluctuation in RH below 40% for low sensitive objects and 10% for highly sensitive objects. When the RH fluctuations remain below the maximum ΔRH recommended threshold, it can be assumed that there is no immediate risk of cracks. Figure 5b shows that consistently maintaining RH values above 80% could put wooden art collections at risk of mould development within approximately 200 days, according to the mould growth isochrone defined through the VTT model. To minimise the risk of spore germination, it is advisable to always keep RH below 75% [49]. Moreover, according to EN 16893 it is recommended to avoid RH values to exceed 55% to limit the risk of mould germination at 20 °C (Table 3). Understanding the risk level provided by the model allows the user of the model to benefit from the possibility to make gradual changes to climate conditions and avoid rapid changes in moisture content causing internal stresses in wood. Figure 5c highlights that the ranges without risk of damage suggested by EN 16893 for cellulose hydrolysis are narrower than those identified by the degradation model for low-quality acidic paper (pH = 5 and DP = 600) over a projected lifetime of 500 years. This indicates that the standard is very conservative and might be no longer sustainable in coping with the present challenges of global warming effect and energy consumption reduction. To limit the energy demand, a feasible strategy could be to use heavyweight buildings for archives and repositories, which have the potential to keep almost constant conditions without relying on energy-demanding systems[50–52].

According to the procedure described in "Indices for microclimate control under different outdoor climate scenarios", we computed the total ED taking the T-RH thresholds reported in Table 2. Table 4 and Table 5

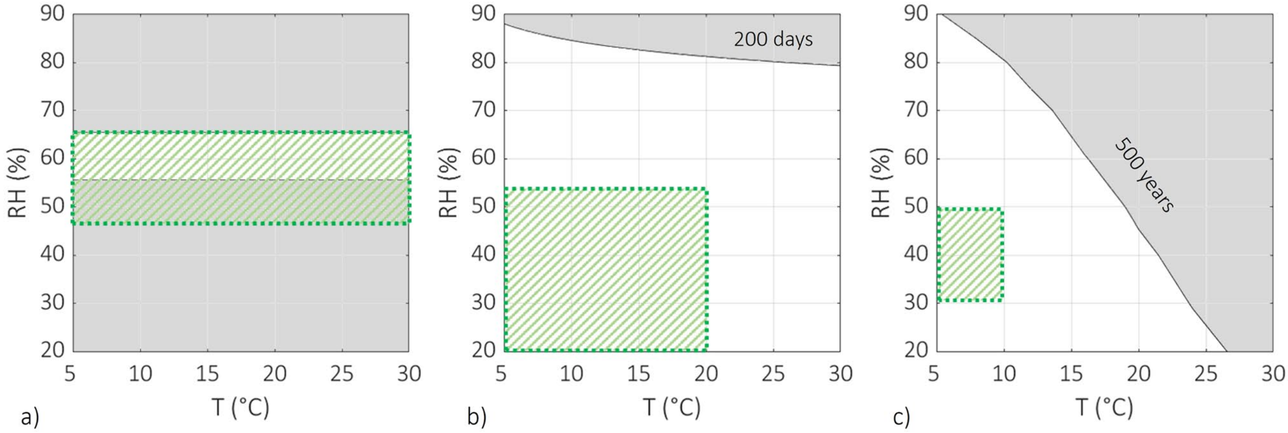

**Figure 5.** Relative risk of degradation diagrams. RH *versus* T diagrams with the T and RH area without relative risk of damage, where the green area is related to EN 16893:2018 and the white area is estimated by the degradation models: (**a**) canvas paintings (considering an annual average RH = 65% of highly sensitive materials), (**b**) wooden objects and (**c**) cellulose-based objects (considering low-quality acidic paper with pH = 5 and DP = 600). The grey area indicates the T-RH relative risk of damage.

| | | Wood | | | | | | | | | | | | Total Energy Demand [kWh·m$^{-3}$·year$^{-1}$] | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Site A (Cfb) | | | | Site B (Csa) | | | | Site C (Dfb) | | | | Site A (Cfb) | Site B (Csa) | Site C (Dfb) |
| | | HDD | CDD | DGD | HGD | HDD | CDD | DGD | HGD | HDD | CDD | DGD | HGD | | | |
| EN 16893:2018 (Case 3) | RP | 261 | 37 | 546 | 0 | 9 | 525 | 758 | 0 | 1221 | 0 | 447 | 0 | 18.3 | 28.3 | 38.4 |
| | SSP2-4.5 NF | 187 | 65 | 559 | 0 | 3 | 700 | 787 | 0 | 1056 | 0 | 504 | 0 | 17.4 | 32.9 | 35.6 |
| | SSP2-4.5 FF | 42 | 211 | 688 | 0 | 0 | 1129 | 1095 | 0 | 625 | 6 | 681 | 0 | 20.1 | 49.4 | 29.0 |
| | SSP5-8.5 NF | 224 | 53 | 519 | 0 | 1 | 728 | 817 | 0 | 1163 | 0 | 471 | 0 | 17.2 | 34.2 | 37.5 |
| | SSP5-8.5 FF | 21 | 272 | 723 | 0 | 0 | 1473 | 1213 | 0 | 451 | 19 | 752 | 0 | 21.8 | 60.1 | 26.6 |
| | | Canvas paintings | | | | | | | | | | | | Total Energy Demand [kWh·m$^{-3}$·year$^{-1}$] | | |
| | | Site A (Cfb) | | | | Site B (Csa) | | | | Site C (Dfb) | | | | Site A (Cfb) | Site B(Csa) | Site C (Dfb) |
| | | HDD | CDD | DGD | HGD | HDD | CDD | DGD | HGD | HDD | CDD | DGD | HGD | | | |
| | RP | 261 | 0 | 258 | 0 | 9 | 0 | 271 | 0 | 1221 | 0 | 266 | 0 | 11.5 | 5.7 | 34.7 |
| | SSP2-4.5 NF | 187 | 0 | 271 | 0 | 3 | 0 | 229 | 1 | 1056 | 0 | 300 | 0 | 10.0 | 4.8 | 31.5 |
| | SSP2-4.5 FF | 42 | 0 | 327 | 0 | 0 | 0 | 273 | 10 | 625 | 0 | 415 | 0 | 7.7 | 5.8 | 23.5 |
| | SSP5-8.5 NF | 224 | 0 | 235 | 0 | 1 | 0 | 249 | 2 | 1163 | 0 | 281 | 0 | 10.2 | 5.1 | 33.7 |
| | SSP5-8.5 FF | 21 | 0 | 305 | 0 | 0 | 0 | 246 | 37 | 451 | 0 | 470 | 0 | 6.7 | 5.8 | 20.4 |
| | | Paper | | | | | | | | | | | | Total Energy Demand [kWh·m$^{-3}$·year$^{-1}$] | | |
| | | Site A (Cfb) | | | | Site B (Csa) | | | | Site C (Dfb) | | | | Site A (Cfb) | Site B (Csa) | Site C (Dfb) |
| | | HDD | CDD | DGD | HGD | HDD | CDD | DGD | HGD | HDD | CDD | DGD | HGD | | | |
| | RP | 0 | 839 | 963 | 0 | 0 | 2249 | 1518 | 0 | 0 | 224 | 771 | 0 | 39.8 | 85.0 | 21.1 |
| | SSP2-4.5 NF | 0 | 1000 | 1029 | 0 | 0 | 2601 | 1610 | 0 | 0 | 301 | 835 | 0 | 45.0 | 95.3 | 24.3 |
| | SSP2-4.5 FF | 0 | 1542 | 1318 | 0 | 0 | 3429 | 2076 | 0 | 0 | 605 | 1065 | 0 | 63.9 | 124.6 | 36.3 |
| | SSP5-8.5 NF | 0 | 942 | 971 | 0 | 0 | 2646 | 1647 | 0 | 0 | 243 | 796 | 0 | 42.4 | 97.1 | 22.1 |
| | SSP5-8.5 FF | 0 | 1719 | 1402 | 0 | 0 | 3988 | 2283 | 0 | 0 | 746 | 1167 | 0 | 69.9 | 142.3 | 41.7 |

**Table 4.** Database of the degree-days (HDD and CDD in °C) and gram-days (DGD and HGD in g·kg-1) in three sites corresponding to three climate zones (Cfb, Csa, and Dfb) from recent past (RP, 1981–2010) towards near future (NF, 2021–2050) and far future (FF, 2071–2100) based on SSP2-4.5 and SSP5-8.5 for wood, canvas paintings and paper according to EN 16893[11]. In addition, the total energy demand is provided (Building features: A/V = 1·m$^{-1}$; U$_{value}$ = 1.0 W·m$^{-2}$·K$^{-1}$; ACH = 1 h$^{-1}$.).

summarise the key indices used in this study and their evolution in the near and far future. The preservation of paper collections from cellulose hydrolysis poses the greatest challenge compared to other materials, as it requires the highest energy demands and generates the most $CO_2$ emissions. Both indices are expected to rise from RP to FF in the three cities, with a higher impact on climate zone Csa. A comparison between the thresholds outlined in EN 16893 and the degradation model reveals that following the former consumes significantly more energy than the latter. The preservation of canvas paintings from mechanical degradation does not show significant differences between the thresholds outlined in EN 16893 and the degradation model. Both indices are expected to decrease from RP to FF in the three cities, with a lower impact on climate zone Csa, as no heating and cooling demand are required. Finally, the preservation of wooden objects from the occurrence of mould growth has the higher energy demand if T-RH thresholds from EN 16893 are followed. In both Cfb and Csa climate zones, the energy demand will tend to increase from RP to FF, the opposite in the Dfb climate zone. The energy demand is significantly reduced when T-RH thresholds from the degradation model are followed.

## Discussion

To understand challenges and perspectives of different operational management in collections facilities while achieving SDGs, the outcomes of "Results" are discussed taking into account the roles of (a) visitors and personnel thermal comfort, (b) the collection-oriented microclimate control, and (c) the changing climate. Table 6 provides the list of the Sustainable Development Goals (SDGs) most relevant for this topic[53] and the specific SDGs targets whose achievement can be influenced by different operational management of the microclimate control in collections facilities.

Achieving thermal comfort in wintertime (case 2) doubles the energy demand needed to keep T-RH thresholds for mixed collections preservation (case 1) in all climate zones. Even though case 1 is more favourable for accelerating the building's energy efficiency (SDG 9) and enhancing the preservation of collections (SDG 11), a side effect with respect to case 2 can occur in facilities located in Cfb and Dfb zones, where outdoor daily temperatures are on average below 8 °C for more than half of the year. Opting for case 1 (as well as for cases 3 and 4) could be responsible for a lower attractiveness of museums to visitors (negatively impacting the touristic flows) and worse working conditions for personnel (negatively impacting the accomplishment of SDG 8). Additionally, in the Dfb zone, winter heating should be coupled with a humidifying system to minimise too dry

| Degradation models (Case 4) | | Wood | | | | | | | | | | | | Total Energy Demand [kWh·m$^{-3}$·year$^{-1}$] | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Site A (Cfb) | | | | Site B (Csa) | | | | Site C (Dfb) | | | | Site A (Cfb) | Site B (Csa) | Site C (Dfb) |
| | | HDD | CDD | DGD | HGD | HDD | CDD | DGD | HGD | HDD | CDD | DGD | HGD | | | |
| | RP | 261 | 0 | 37 | 0 | 9 | 0 | 28 | 0 | 1221 | 0 | 54 | 0 | 7.0 | 0.8 | 30.4 |
| | SSP2-4.5 NF | 187 | 0 | 48 | 0 | 3 | 0 | 20 | 0 | 1056 | 0 | 61 | 0 | 5.5 | 0.5 | 26.6 |
| | SSP2-4.5 FF | 42 | 0 | 85 | 0 | 0 | 0 | 27 | 0 | 625 | 0 | 87 | 0 | 2.7 | 0.6 | 16.8 |
| | SSP5-8.5 NF | 224 | 0 | 37 | 0 | 1 | 0 | 25 | 0 | 1163 | 0 | 59 | 0 | 6.1 | 0.5 | 29.1 |
| | SSP5-8.5 FF | 21 | 0 | 83 | 0 | 0 | 0 | 22 | 0 | 451 | 0 | 93 | 0 | 2.2 | 0.4 | 12.7 |
| | | Canvas paintings | | | | | | | | | | | | Total Energy Demand [kWh·m$^{-3}$·year$^{-1}$] | | |
| | | Site A (Cfb) | | | | Site B (Csa) | | | | Site C (Dfb) | | | | Site A (Cfb) | Site B (Csa) | Site C (Dfb) |
| | | HDD | CDD | DGD | HGD | HDD | CDD | DGD | HGD | HDD | CDD | DGD | HGD | | | |
| | RP | 261 | 0 | 258 | 0 | 9 | 0 | 271 | 58 | 1221 | 0 | 266 | 8 | 11.5 | 6.9 | 34.9 |
| | SSP2-4.5 NF | 187 | 0 | 271 | 0 | 3 | 0 | 229 | 87 | 1056 | 0 | 300 | 4 | 10.0 | 6.5 | 31.5 |
| | SSP2-4.5 FF | 42 | 0 | 327 | 0 | 0 | 0 | 273 | 183 | 625 | 0 | 415 | 0 | 7.7 | 9.3 | 23.5 |
| | SSP5-8.5 NF | 224 | 0 | 235 | 0 | 1 | 0 | 249 | 104 | 1163 | 0 | 281 | 6 | 10.2 | 7.2 | 33.8 |
| | SSP5-8.5 FF | 21 | 0 | 305 | 0 | 0 | 0 | 246 | 290 | 451 | 0 | 470 | 0 | 6.7 | 10.9 | 20.4 |
| | | Paper | | | | | | | | | | | | Total Energy Demand [kWh·m$^{-3}$·year$^{-1}$] | | |
| | | Site A (Cfb) | | | | Site B (Csa) | | | | Site C (Dfb) | | | | Site A (Cfb) | Site B (Csa) | Site C (Dfb) |
| | | HDD | CDD | DGD | HGD | HDD | CDD | DGD | HGD | HDD | CDD | DGD | HGD | | | |
| | RP | 261 | 8 | 379 | 0 | 9 | 338 | 1120 | 0 | 1221 | 0 | 177 | 0 | 14.2 | 31.2 | 32.9 |
| | SSP2-4.5 NF | 187 | 24 | 462 | 0 | 3 | 479 | 1243 | 0 | 1056 | 0 | 228 | 0 | 14.5 | 36.9 | 30.0 |
| | SSP2-4.5 FF | 42 | 104 | 836 | 0 | 0 | 848 | 1759 | 0 | 625 | 0 | 443 | 0 | 20.6 | 56.3 | 24.0 |
| | SSP5-8.5 NF | 224 | 16 | 396 | 0 | 1 | 506 | 1281 | 0 | 1163 | 0 | 198 | 0 | 13.9 | 38.3 | 32.0 |
| | SSP5-8.5 FF | 21 | 140 | 950 | 0 | 0 | 1155 | 1992 | 0 | 451 | 2 | 543 | 0 | 23.2 | 68.4 | 21.9 |

**Table 5.** Database of the degree-days (HDD and CDD in °C) and gram-days (DGD and HGD in g·kg-1) in three sites corresponding to three climate zones (Cfb, Csa, and Dfb) from recent past (RP, 1981–2010) towards near future (NF, 2021–2050) and far future (FF, 2071–2100) based on SSP2-4.5 and SSP5-8.5 for wood, canvas paintings and paper according to the degradation models described in "Thermo-hygrometric thresholds for risk of damage". In addition, the total energy demand is provided (Building features: A/V = 1·m$^{-1}$; U$_{value}$ = 1.0 W·m$^{-2}$·K$^{-1}$; ACH = 1 h$^{-1}$.).

conditions, contributing to decelerating the achievement of more sustainable patterns in energy consumption (SDGs 9 and 12) and hampering resilience capacity (SDG 13) in the facility management. Some studies have already investigated how to dynamically set indoor T thresholds for thermal comfort with respect to outdoor climate conditions[54] and how to combine them with T thresholds suitable for collections preservation[55,56]. They have demonstrated that the energy demand and relative costs of this option largely depends on the outdoor climate and, to a lesser extent, on the energy performance of the building. Moreover, a behavioural change of visitors and personnel based on an increased awareness of sustainability issues of facilities management and of conservation requirements of the collections might be key to foster energy savings[57].

A collection-oriented climate control is preparatory in achieving SDG 11, as all the efforts are devoted to the collection's preservation. The T-RH thresholds suggested by degradation models (case 4) need less energy to be hold if compared to those suggested by EN 16893 (case 3). The energy demand widely varies from collection to collection based on the specific vulnerability of each material. Since each facility can thus manage the most appropriate thresholds according to the collections it preserves, this allows to further improve the preservation of collections (SDG 11) and the responsible consumption of energy (SDG 12). The preservation of paper objects is the most energy demanding practice and it could not be environmentally and economically sustainable at the same time, especially in the Csa zone. It follows that in libraries and archives, which are the most susceptible facilities, keeping the T-RH thresholds can negatively impact the achievement of resilient (SDG 9) and adaptive (SDG 13) buildings being responsible for larger inequalities in facilities within and among countries (SDG 10).

The analysis of the energy implications in the near and far future climate scenarios has demonstrated that the energy demand for heating in wintertime will tend to significantly decrease, thus decreasing the demand for humidification (especially in northern latitudes). In turn, winter heating might also be responsible for an increase of the energy demand for the dehumidification in all climate zones. It follows that in the future it will be easier to accomplish thermal comfort of visitors and personnel in wintertime (i.e., better working place in accordance with SDG 8), thus reducing the risk of energy poverty and, hence the inequalities among facilities within and across countries (SDG 10). On the opposite, this positive effect does not counterbalance the drastic increased energy demand in the Csa zone for summer cooling and dehumidification, enhancing the risk of energy poverty in facilities located in similar climate zone. However, when standardised thresholds (case 3) are

| | | | SDGs[(*)] | | | | | |
|---|---|---|---|---|---|---|---|---|
| | **Reference for T-RH thresholds** | **Microclimate control** | **8** | **9** | **10** | **11** | **12** | **13** |
| Case 1 | EN 16893 | Thermal comfort is neglected in wintertime prioritising mixed collections preservation | ↓ | ↑ | ↔ | ↑ | ↓ | ↓ |
| Case 2 | | Thermal comfort is considered in wintertime together with mixed collections preservation | ↑ | ↓ | ↔ | ↔ | ↓ | ↓ |
| Case 3 | | Individual collection-oriented climate control | ↓ | ↓ | ↓ | ↑ | ↓ | ↓ |
| Case 4 | Degradation models | | ↓ | ↑ | ↑ | ↑ | ↑ | ↑ |

**Table 6.** Synthesis of the role of different management strategies for the microclimate control in collections facilities in accelerating (↑), unchanging (↔) and decelerating (↓) the achievement of the SDGs. (*) The list of the SDG and targets used in this discussion: SDG 8 – Decent work and economic growth. Target 8.3—Promote development-oriented policies that support productive activities, decent job creation, entrepreneurship, creativity and innovation, and encourage the formalization and growth of micro-, small- and medium-sized enterprises, including through access to financial services. SDG 9 – industry, innovation and infrastructure. Target 9.4—By 2030, upgrade infrastructure and retrofit industries to make them sustainable, with increased resource-use efficiency and greater adoption of clean and environmentally sound technologies and industrial processes, with all countries taking action in accordance with their respective capabilities. SDG 10 – Reduce inequality. Target 10.b—Encourage official development assistance and financial flows, including foreign direct investment, to States where the need is greatest, in particular least developed countries, African countries, small island developing States and landlocked developing countries, in accordance with their national plans and programmes. SDG 11 – Sustainable cities and communities. Target 11.4—Strengthen efforts to protect and safeguard the world's cultural and natural heritage. SDG 12 – Responsible consumption and production. Target 12.7—Promote public procurement practices that are sustainable, in accordance with national policies and priorities. Target 12.a—Support developing countries to strengthen their scientific and technological capacity to move towards more sustainable patterns of consumption and production. Target 12.b—Develop and implement tools to monitor sustainable development impacts for sustainable tourism that creates jobs and promotes local culture and products. SDG 13 – Climate action. Target 13.1—Strengthen resilience and adaptive capacity to climate-related hazards and natural disasters in all countries.

considered, global warming will contribute to exacerbate the environmental, economic and energy challenges in the facilities preserving paper collections. Such information on the energy implications of changing climate is fundamental in the early-stage design of adaptation interventions since it is possible to define indications at climate-zone level. Indeed, the future challenges for collections facilities involve making buildings more resilient to increasingly warmer outdoor conditions. The adaptive capacity of facilities will be more sustainable if the management for collections preservation is based on the use of the T-RH thresholds suggested by degradation models rather than on invasive energy refurbishment to keep standardised thresholds. Climate challenges vary across Europe according to the different impacts in individual areas, even within the same country. The main risk is that some museums or archives may be unable to address these challenges (i.e., inefficient historical buildings and/or located in low-resilient climate zones[58], urban heat island and urban canyoning effects[59–61], thus decelerating SDG 13), with an adverse side-effect on the energy poverty of facilities and on the preservation of collections. To reduce such risks, it may be worth considering a relocation of the collections in less challenging climate zones (e.g., those that are not expected to drastically change in the future) and higher scientific and technological capacity to move towards more sustainable patterns of consumption and production (SDG 12). On the other hand, such a solution could have dire consequences at the local level, potentially leading to job and cultural identity losses. To overcome such barriers, the implementation of collaborative actions based on a responsive, inclusive, participatory, and representative decision-making at all levels together with the investment promotion regimes for least developed countries can promote accelerating SDGs at regional level with positive impact on the single facility[62]. In Europe, this action can be guided by the CEN TC 346 regarding the definition of protocols and procedures to adopt in the preventive conservation of cultural heritage. In our opinion, the results of this paper could be leveraged in the upcoming revision of the EN 16893 standard as a preliminary step in this process. Indeed, the positive implications of case 4 open the opportunities to include further annexes devoted to the application of weather-based technical indices to support stakeholders in the early-stage decision-making to concurrently achieve sustainability and preservation goals.

## Conclusions

This research provided a method for estimating energy demand in collection facilities since the early stages of the decision-making process, supporting the establishment of new European heritage commons, which is one of the primary challenges that heritage managers will face in the coming years. Our results demonstrated that adjusting the microclimate thresholds used in the operational management of collections facilities can be a valid alternative to energy refurbishment, especially when the facilities cannot sustain its elevated costs. The main advantage of our method is that it leverages solutions that do not require new costly infrastructures but can take advantage of the cooperation and alliance among similar facilities in the same climate zone, thus supporting the preservation of cultural objects. Therefore, it lays the ground for conservation policies based on sustainable management practices for the future programming at climate-zone level rather than at a building level. The results represent a valid support to understand how to achieve the SDG target 11.4 and the possible implications of different operational management strategies on the others (SDGs 8, 9, 10, 12 and 13). Additionally, the results can serve as basis for planning effective adaptation measures to the expected global warming, thus fine-tuning the microclimate control to safeguard heritage collections and thermal comfort while enhancing energy saving.

The discussion focussed on the future climate scenarios in three EU climate zones (Cfb, Csa, and Dfb) and on the role of collections facilities in achieving Sustainable Development Goals and climate-neutrality of the European Green Deal, paying attention to the implications of both the human thermal comfort and the collection-oriented climate control. The weather-based indices used are completely independent of the building performance and allow to estimate the potential energy demand of collection facilities according to different temperature and relative humidity thresholds resulting from the use of degradation models in the place of the ranges suggested in EN 16893. Additionally, they make it possible to estimate the potential energy demand in several collections facilities located at the same climate zone by simply changing the coefficients of the building features. Since the UNESCO Institute for Statistics oversees defining internationally comparable indices to monitor SDG target 11.4, these outcomes can effectively support this process. Additionally, the application of these weather-based indices can be included in the revision of the EN 16893, as an informative annex to estimate trends in the potential energy demand of a collection facility through a user-friendly method with a low computation effort. In this way, it would be possible to implement collaborative actions among collections facilities for a more integrated approach at regional level with a positive impact on facility level.

To conclude, the methodology and database provided in this article can be used also by non-experts to approximately estimate the energy demand of collections facilities in accordance with microclimate conditions limiting the relative risk of degradation, advantageously extending this application from a city scale to a regional scale.

## Data availability

The datasets generated during and/or analysed during the current study are available from the corresponding author on request.

Received: 14 June 2024; Accepted: 5 August 2024

## References

1. EN 15898:2019. Conservation of cultural property - Main general terms and definitions.
2. Potts, A. (Lead A. *European Cultural Heritage Green Paper*. (2021).
3. Laine, A., Davies, J., Buchanan, K., Warren, K. & Turtinen, J. *Heritage Research Matters, Joint Programming Initiative on Cultural Heritageand Global Change (JPI CH)*. (Swedish National Heritage Board (Riksantikvarieämbetet), 2019).
4. Brimblecombe, P. & Richards, J. Applied climatology for heritage. *Theor. Appl. Climatol.* https://doi.org/10.1007/s00704-024-05059-6 (2024).
5. European Commission, Directorate-General for Education, Youth, Sport and Culture. *Strengthening Cultural Heritage Resilience for Climate Change – Where the European Green Deal Meets Cultural Heritage*. https://data.europa.eu/doi/10.2766/44688 (Publications Office of the European Union, 2022).
6. Foster, G. Circular economy strategies for adaptive reuse of cultural heritage buildings to reduce environmental impacts. *Resour. Conserv. Recycl.* **152**, 104507 (2020).
7. Wilde, E. *Museums in the Climate Crisis. Survey Results and Recommendations for the Sustainable Transition of Europe*. (2022).
8. CEN Technical Committee 346. *BUSINESS PLAN CEN/TC 346 Conservation of Cultural Heritage. EXECUTIVE SUMMARY.. European Committee for Standardization* (2022).
9. EN 16141. Conservation of cultural heritage - Guidelines for management of environmental conditions - Open storage facilities: definitions and characteristics of collection centres dedicated to the preservation and management of cultural heritage. Preprint at (2012).
10. EN 16883. Conservation of Cultural Heritage-Guidelines for Improving the Energy Performance of Historic Buildings. Preprint at (2017).
11. EN 16893. Conservation of Cultural Heritage - Specifications for location, construction and modification of buildings or rooms intended for the storage or use of heritage collections. Preprint at (2018).
12. Farreny, R. *et al.* The metabolism of cultural services. Energy and water flows in museums. *Energy Build.* **47**, 98–106 (2012).
13. Cadelano, G. *et al.* Improving the energy efficiency, limiting costs and reducing CO2 emissions of a museum using geothermal energy and energy management policies. *Energies (Basel)* **12**, 3192 (2019).
14. Silva, H. E. & Henriques, F. M. A. Energy Efficiency in Historic Museums: The Interplay between Thermal Rehabilitation, Climate Control Strategies and Regional Climates. *Appl. Sci.* **13**, 12732 (2023).
15. Directive (EU) 2024/1275 of the European Parliament and of the Council of 24 April 2024 on the energy performance of buildings. (2024).
16. Directive (EU) 2023/1791 of the European Parliament and of the Council of 13 September 2023 on energy efficiency and amending Regulation (EU) 2023/955 (recast). (2023).
17. Lucchi, E. Renewable energies and architectural heritage: advanced solutions and future perspectives. *Buildings* **13**, 631 (2023).
18. Kompatscher, K., Seuren, S., Kramer, R., Van Schijndel, J. & Schellen, H. Energy efficient HVAC control in historical buildings: A case study for the Amsterdam Museum. *Energy Procedia* https://doi.org/10.1016/j.egypro.2017.09.703 (2017).
19. Frasca, F., Cornaro, C. & Siani, A. M. A method based on environmental monitoring and building dynamic simulation to assess indoor climate control strategies in the preventive conservation within historical buildings. *Sci. Technol. Built. Environ.* **25**, 1253–1268 (2019).
20. Schito, E. & Testi, D. Integrated maps of risk assessment and minimization of multiple risks for artworks in museum environments based on microclimate control. *Build Environ.* **123**, 585–600 (2017).
21. Schito, E., Conti, P., Urbanucci, L. & Testi, D. Multi-objective optimization of HVAC control in museum environment for artwork preservation, visitors' thermal comfort and energy efficiency. *Build Environ.* **180**, 107018 (2020).
22. van Schijndel, A. W. M., Schellen, H. L., Martens, M. & Huijbregts, Z. Simulating and mapping future energy demands for European museums. *Energy Procedia* https://doi.org/10.1016/j.egypro.2015.11.367 (2015).
23. van Schijndel, A. W. M. J. & Schellen, H. L. H. Mapping future energy demands for European museums. *J. Cult. Herit.* **31**, 189–201 (2018).

24. Lidelöw, S., Örn, T., Luciani, A. & Rizzo, A. Energy-efficiency measures for heritage buildings: A literature review. *Sustain. Cities Soc.* https://doi.org/10.1016/j.scs.2018.09.029 (2019).
25. Zannis, G. *et al.* Energy efficiency in retrofitted and new museum buildings in Europe. *Int. J. Sustain. Energy* **25**, 199–213 (2006).
26. Annibaldi, V., Cucchiella, F., De Berardinis, P., Gastaldi, M. & Rotilio, M. An integrated sustainable and profitable approach of energy efficiency in heritage buildings. *J. Clean Prod.* **251**, 119516 (2020).
27. Ferdyn-Grygierek, J. Indoor environment quality in the museum building and its effect on heating and cooling demand. *Energy Build.* **85**, 32–44 (2014).
28. Ferdyn-Grygierek, J. & Grygierek, K. Proposed strategies for improving poor hygrothermal conditions in museum exhibition rooms and their impact on energy demand. *Energies (Basel)* **12**, 620 (2019).
29. Bertolin, C., Camuffo, D. & Bighignoli, I. Past reconstruction and future forecast of domains of indoor relative humidity fluctuations calculated according to EN 15757:2010. *Energy Build.* **102**, 197–206 (2015).
30. Hong, S. H. *et al.* Climate change mitigation strategies for mechanically controlled repositories: The case of the national archives. *Kew. Atmos. Environ.* **49**, 163–170 (2012).
31. Spinoni, J. *et al.* Changes of heating and cooling degree-days in Europe from 1981 to 2100. *Int. J. Climatol.* **38**, e191–e208 (2018).
32. Frasca, F. *et al.* A quantitative comparison on the use of thermal insulation materials in three European countries through the TEnSE approach: Challenges and opportunities. *Build. Environ.* https://doi.org/10.1016/j.buildenv.2023.110973 (2023).
33. Blades, N., Lithgow, K., Staniforth, S. & Hayes, B. Conservation Heating 24 Years On. *Stud. Conser.* **63**, 15–21 (2018).
34. Thomson, R. Heating or Dehumidification? Maintaining Appropriate Relative Humidity Levels in Historic Buildings Containing Museum Collections. *Stud. Conser.* **65**, 321–326 (2020).
35. EN 15757. Conservation of Cultural Property - Specifications for temperature and relative humidity to limit climate-induced mechanical damage in organic hygroscopic materials. Preprint at (2010).
36. Camuffo, D., Bertolin, C., Bonazzi, A., Campana, F. & Merlo, C. Past, present and future effects of climate change on a wooden inlay bookcase cabinet: A new methodology inspired by the novel European Standard EN 15757:2010. *J. Cult. Herit.* **15**, 26–35 (2014).
37. Kramer, R., Schellen, H. & Van Schijndel, J. Energy impact of ASHRAE's museum climate classes: A simulation study on four museums with different quality of envelopes. *Energy Procedia* https://doi.org/10.1016/j.egypro.2015.11.147 (2015).
38. Kramer, R. P., Schellen, H. L. & van Schijndel, A. W. M. Impact of ASHRAE's museum climate classes on energy consumption and indoor climate fluctuations: Full-scale measurements in museum Hermitage Amsterdam. *Energy Build.* **130**, 286–294 (2016).
39. Kompatscher, K., Kramer, R. P., Ankersmit, B. & Schellen, H. L. Intermittent conditioning of library archives: Microclimate analysis and energy impact. *Build. Environ.* **147**, 50–66 (2019).
40. EN 16242. Conservation of cultural heritage - Procedures and instruments for measuring humidity in the air and moisture exchanges between air and cultural property. Preprint at (2012).
41. Lee, D.S.-H. *et al.* Numerical modelling of mechanical degradation of canvas paintings under desiccation. *Herit. Sci.* **10**, 130 (2022).
42. Kuka, E., Cirule, D., Andersone, I., Andersons, B. & Fridrihsone, V. Conditions Influencing Mould Growth for Effective Prevention of Wood Deterioration Indoors. *Appl. Sci.* https://doi.org/10.3390/app12030975 (2022).
43. Parsa Sadr, A., Bosco, E. & Suiker, A. S. J. Multi-scale model for time-dependent degradation of historic paper artefacts. *Int. J. Solids Struct.* https://doi.org/10.1016/j.ijsolstr.2022.111609 (2022).
44. Parsa Sadr, A., Maraghechi, S., Suiker, A. S. J. & Bosco, E. Chemo-mechanical ageing of paper: effect of acidity, moisture and micro-structural features. *Cellulose* https://doi.org/10.1007/s10570-024-06005-5 (2024).
45. CIBSE. Degree-days: theory and application. Technical Manual 41. Preprint at (2006).
46. Beck, H. E. *et al.* Present and future köppen-geiger climate classification maps at 1-km resolution. *Sci. Data* https://doi.org/10.1038/sdata.2018.214 (2018).
47. Pörtner, H. O. *et al.* Technical Summary. In *Climate Chang: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* (eds Pörtner, H. O. *et al.*) (Cambridge University Press, 2023).
48. Lovato, T. *et al.* CMIP6 Simulations With the CMCC Earth System Model (CMCC-ESM2). *J. Adv. Model. Earth Syst.* https://doi.org/10.1029/2021MS002814 (2022).
49. Johansson, P., Ekstrand-Tobin, A., Svensson, T. & Bok, G. Laboratory study to determine the critical moisture level for mould growth on building materials. *Int. Biodeterior. Biodegradation* **73**, 23–32 (2012).
50. Ryhl-Svendsen, M., Larsen, P. K. & Jensen, L. A. Ultra-low energy buildings for storage in museums and archives. In 10th International Conference on Healthy Buildings, (2012).
51. Padfield, T., Ryhl-Svendsen, M., Larsen, P. K. & Aasbjerg Jensen, L. A Review of the Physics and the Building Science which Underpins Methods of Low Energy Storage of Museum and Archive Collections*. *Stud. Conser.* **63**, 209–215 (2018).
52. Verticchio, E., Frasca, F., Bertolin, C. & Siani, A. M. Climate-induced risk for the preservation of paper collections: Comparative study among three historic libraries in Italy. *Build. Environ.* **206**, 108394 (2021).
53. ICOMOS. *ICOMOS Action Plan: Cultural Heritage and Localizing the UN Sustainable Development Goals (SDGs)*. https://www.icomos.org/images/DOCUMENTS/Secretariat/2017/ICOMOS_Action_Plan_Cult_Heritage_and_Localizing_SDGs_20170721.pdf (2017).
54. Kramer, R., Schellen, L. & Schellen, H. Adaptive temperature limits for air-conditioned museums in temperate climates. *Build. Res. Information* **46**, 686–697 (2018).
55. Kramer, R., van Schijndel, J. & Schellen, H. Dynamic setpoint control for museum indoor climate conditioning integrating collection and comfort requirements: Development and energy impact for Europe. *Build. Environ.* **118**, 14–31 (2017).
56. Kramer, R., Van Schijndel, J. & Schellen, H. Dynamic setpoint calculation including collection and comfort requirements: Energy impact for museums in Southern Europe. *Energy Proc.* **133**, 195–206 (2017).
57. Kotsopoulos, D. *et al.* Designing a Serious Game to Motivate Energy Savings in a Museum: Opportunities & Challenges. In *Games and Learning Alliance: 8th International Conference, GALA 2019, Athens, Greece, November 27–29, 2019, Proceedings* (ed. Kotsopoulos, D.) (Springer International Publishing, 2019).
58. Verticchio, E. *et al.* Assessing the Impact of Climate Change on the Biodeterioration Risk in Historical Buildings of the Mediterranean Area: The State Archives of Palermo. *Atmosphere (Basel)* https://doi.org/10.3390/atmos14071169 (2023).
59. Lopez-Cabeza, V. P., Alzate-Gaviria, S., Diz-Mellado, E., Rivera-Gomez, C. & Galan-Marin, C. Albedo influence on the microclimate and thermal comfort of courtyards under Mediterranean hot summer climate conditions. *Sustain Cities Soc.* https://doi.org/10.1016/j.scs.2022.103872 (2022).
60. Salata, F. *et al.* Estimating building cooling energy demand through the Cooling Degree Hours in a changing climate: A modeling study. *Sustain Cities Soc.* https://doi.org/10.1016/j.scs.2021.103518 (2022).
61. Frasca, F., Siani, A. M. & Bertolin, C. Energy demand for indoor climate control in museums: challenges and perspectives in time of a changing climate. *Procedia Struct. Integrity* **55**, 32–38 (2024).
62. Europa Nostra. *Europa Nostra Strategic Plan: Horizon 2025*. https://issuu.com/europanostra/docs/2022-en-strategic-plan-horizon-2025 (2022).

## Acknowledgements

F. Frasca acknowledges the grant PON "Ricerca e Innovazione" 2014-2020 IV.6 "Dottorati e contratti di ricerca su tematiche green" (ex D.M. 1062/2021). E. Bosco is grateful for the support by the Netherlands Organisation for Scientific Research (NWO), Project 19655 "An integrated numerical-experimental approach to predict aging and degradation of oil paintings (NUANCES)", within the personal grant funding scheme "NWO VIDI Award".

## Author contributions

F.F., C.B. and A.M.S.: Conceptualization, Methodology. F.F.: Data curation, Formal analysis, Writing- Original draft preparation, Supervision. E.V., E.B., E.K., D.S.H., C.K.A., C.B. and A.M.S.: Writing-Reviewing and Editing. A.M.S.: Funding acquisition. All authors have read and agreed to the submitted version of the manuscript.

## Funding

This research was partly supported by CollectionCare project, a European Union's Horizon 2020 research and innovation programme [grant agreement No 814624]; "Progetti di Ricerca Grandi" Sapienza University of Rome [grant number RG 123188AFDE2E0D].

## Competing interests

The authors declare no competing interests.

## Additional information

**Supplementary Information** The online version contains supplementary material available at https://doi.org/10.1038/s41598-024-69395-3.

**Correspondence** and requests for materials should be addressed to F.F.

**Reprints and permissions information** is available at www.nature.com/reprints.