Low-energy storage facilities

- concept and sustainability

MUSEERNES GRØNNE AKADEMI

Low-energy storage facilities

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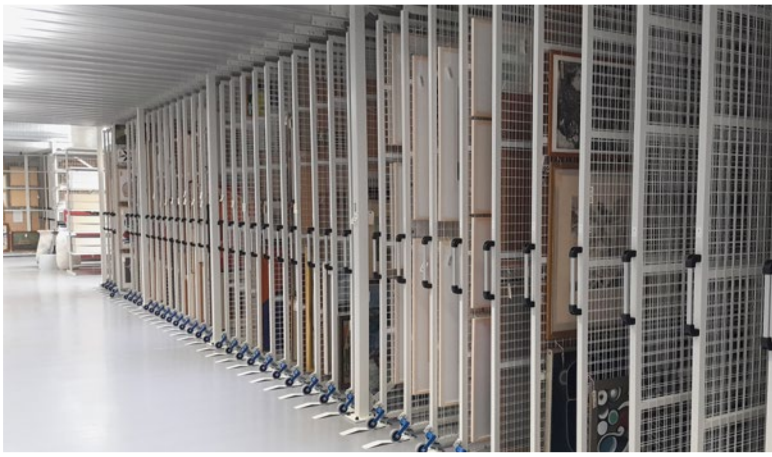

Preface

The core task of museums is to preserve art, cultural and natural heritage, for present and future generations alike. This places strict requirements on the environmental conditions in museum storage facilities, where stability and quality are essential to ensure the long-term preservation of collections. Museums, like the rest of society, are in the midst of a green transition that requires reductions in energy use, CO_2 emissions, and overall resource consumption. Low-energy consumption storage buildings are one answer to this dual challenge. The concept utilizes the physical properties of the building and its outdoor environment to create stable conservation conditions, often without heating and with minimal technical control.

The origin of the low-energy concept for museum storage facilities can be seen in several early Danish storage facilities built during the 1980s-90s. Inspiration also comes from the stable environment conditions that could be observed in certain historic castles and church buildings, see, for example, Ræder Knudsen & Lundby (2017), and Ryhl-Svendsen & Smedemark (2025).

Several modern low-energy storage facilities have been built on this basis over the past 25 years; both in Denmark and abroad. The ambition was to achieve high preservation quality while having only low energy requirements and resource consumption, both in operation and construction resources. Experience shows that this was not always possible, however. We therefore need a clear compilation of expertise and practical experience that can be used to guide future projects.

This report describes the requirements that must be met to establish low-energy storage buildings to ensure the long-term preservation of cultural heritage, while minimising environmental impact. It brings together more than two decades of Danish experience with low-energy storage facilities and is based on documented examples where both conservation quality and energy consumption have been measured and analysed. It is intended to be a practical tool for contractors, consultants, museum professionals and authorities working on the planning, design and operation of low-energy storage facilities for movable cultural heritage.

The report is based on Danish conditions, including references to Danish rules and regulations, but offers principles for building construction that can be applied broadly. Low-energy storage facilities provide a scalable, cost-effective alternative to traditional indoor environment control systems. Extensive computer modelling and experience from real buildings has demonstrated that omission of ground slab insulation and increase of building insulation in temperate climates (and beyond) allows the storage internal environment to be stable and safe for the collections without the need for additional heating or cooling energy in most instances. In this report, we define a low-energy storage facility based on the following parameters: a facility that ensures high preservation quality (expressed as a Time-Weighted Preservation Index above 100) while maintaining a relative energy consumption for environment control of less than 3 kWh per cubic meter of storage space annually.

The concept has the potential to change conservation practices in temperate climates across continental boundaries. At the same time, the report addresses potential challenges that may arise when using alternative building materials or choosing not to use conventional ventilation and heating, while emphasising what works in actual practice.

By sharing this knowledge, we hope to inspire and support decision-makers all over the world towards making informed, more sustainable choices; thus, helping to make the management of our shared cultural heritage more future-proof.

Morten Ryhl-Svendsen, Lise Ræder Knudsen, Pil Rasmussen and Jesper Stub Johnsen.
December 2025


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Reading guide

This report is intended to be a practical tool for contractors, consultants, museum professionals and authorities working on the planning, design and operation of low-energy storage facilities for movable cultural heritage.

The report is structured to serve as an introduction, as documentation and as a specification of requirements. Each section can be read independently. We recommend that you first familiarise yourself with Part 1 with a view to understanding the rationale behind the requirements in Part 2.

Part 1: Functional description

Reviews the basic principles for the technical construction of low-energy storage facilities, including structure, air conditioning principles and the importance of the indoor environment for preservation quality. This section introduces key concepts such as Time-Weighted Preservation Index (TWPI) and environmental control zones (standard, dry, ultra-dry, and cold environment).

Part 1 is recommended for all readers as an introduction to the concept of the low-energy storage facility.

Part 2: Specific functional requirements

Describes technical and building requirements that must be satisfied when establishing a low- energy storage facility. Part 2 presents detailed requirements for the building envelope, structure, ventilation installations, measurements and energy consumption. It serves as specifications and checklist for new builds or renovation work and is mainly aimed at building design consultants and contractors.

Appendix and table

The end of the report presents a technical description of the Time-Weighted Preservation Index (TWPI) calculation and a table overview of selected Danish low-energy storage facilities and their performance according to several parameters.

The indoor environment in the unheated low-energy storage facilities is cool all year round and ensures high preservation quality.

Examples of Danish low-energy storage facilities

The map shows the location of eight low-energy storage facilities in Denmark. These facilities represent different building types and environmental control principles but have in common that they all operate with low energy consumption and high preservation quality. While the selected buildings is not an exhaustive list of all Danish storage facilities, the listed examples were all selected because of their inclusion in research projects and surveys for which detailed data is available.

The technical specifications for each storage facility, including temperature and humidity levels, air change rate, TWPI and energy consumption, are summarised in Table 1, at the end of the report. This table can be used as reference material when assessing design choices and operational performance.


The Historical Collections / North Jutlands Museums
Vestbjerg
Museum Østjylland
Randers
The National Museum of Denmark / The Royal Danish Library
Vinge
Vejle Conservation Centre / Shared Museum Storage Facility
Vejle
Museum Vestsjælland
Ugerløse
Museum of Copenhagen / Arts & History
Høje Taastrup
Museum Vest
Ribe
Museum Sønderjylland
Rødekro

Part 1

Functional description

1

Low-energy storage facilities

Museum storage facilities must be able to accommodate movable physical cultural heritage in an indoor environment with high preservation quality (in terms of climate, air quality and security). When using low-energy storage facilities, the goal is to achieve this at the lowest possible cost, in terms of investment, energy consumption and running costs.

The low-energy concept is based around the building's structure as the central controlling element, with only a minimum of mechanical control. To achieve this in a temperate, northern European climate, the following principles are applied:

- A large degree of thermal mass to smooth out short-term temperature variations. The ground under the storage facility (uninsulated floor) is used as thermal buffer storage. Put simply, this turns the floor into a large cooling surface during the summer and a large heating surface in the winter.
- High insulation of external walls and the roof to even out daily temperature fluctuations and reduce heat exchange with the surroundings, which in Denmark varies from approximately -1 °C to +18 °C annually (monthly averages).
- An unheated building. When combined with the above, this will provide an indoor environment that follows the annual outdoor temperature cycle, but with greatly reduced amplitude.
- An air-tight building envelope with a very low air change rate. This minimises the influence of fluctuations in moisture content outside (too dry or too humid), A low air exchange allows passive stabilisation of indoor relative humidity through the hygroscopic buffering provided by the building materials and the objects within the collection, supported by occasional mechanical dehumidification as and when needed. The air-tight building also shields against outdoor air pollution.

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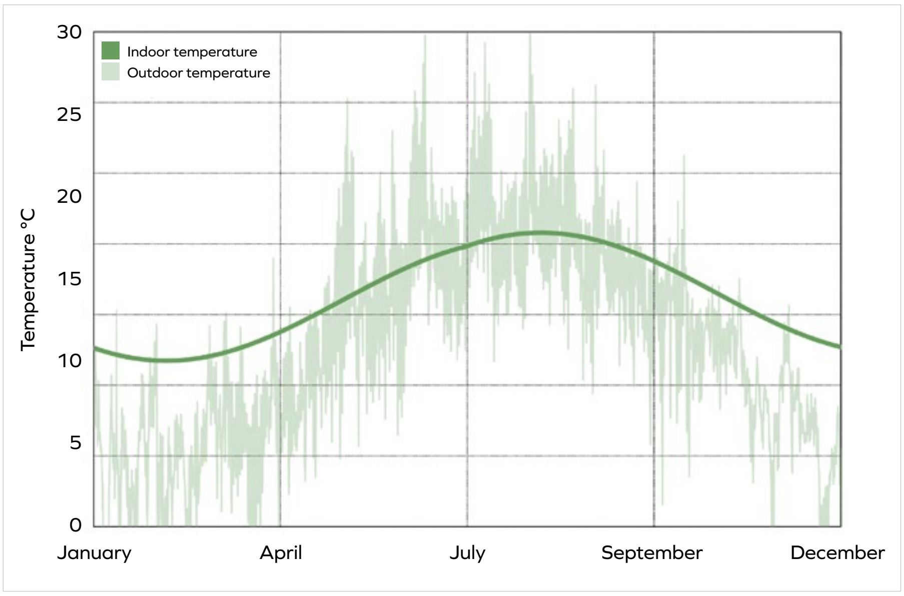
The air-tight, well-insulated building and the heat storage capacity of the floor ensures stable temperatures indoors (bold curve), which will only be impacted slowly by seasonal changes (outdoor temperature thin curve). Principle model based on data from the Ribe Storage Facility.



There are several specific functional requirements for low-energy storage facilities that supplement or deviate from traditional storage facility construction requirements, including specifications for building materials and construction.

Well-functioning examples of this concept can be found in several existing museum storage facilities in Denmark, the majority of which achieve an annual indoor environment with a temperature cycle interval within 7 and 17 °C and relative humidity (RH) between 45-55% for an energy consumption of less than 3 kWh/m^3 of storage volume (Table 1).

It must be emphasised, however, that no two museum storages are alike. As shown in Table 1, there can be significant variations in size, environmental control concept and setpoints for indoor environment control, all of which are reflected in how each building performs with regard to indoor environment and energy consumption. In other words, the so-called "Danish model" does not cover a single specific design. Rather, it represents a building design based on variations of the principles listed above.

All legislation, standards and regulations that apply to ordinary museum storage facilities also apply to low-energy storage facilities. Functional requirements that are applicable for storage facilities in general (such as protection against water ingress, break-ins, impact from air pollution, fire, vibrations, etc.) will not be reiterated in this description of functional requirements for low-energy storage facilities.

It is also assumed that there are no permanent workplaces in the actual storage areas, and therefore no workplace (occupational) health and safety requirements about temperature, daylight, air quality, etc. For specifications for museum storage facilities in general, reference is made to, for example, EN 16893:2018.

There are several specific functional requirements for low-energy storage facilities that supplement or deviate from what is required when building traditional storage facilities. If a low-energy storage facility is required, these specific functional requirements must be achieved in design and construction. It is important that these are clearly specified when tendering the construction project. These requirements can either supplement or deviate from those that apply to traditional storage facility construction and are described in further detail in the chapter "Part 2: Specific functional requirements".

The following sections outline how low-energy storage facilities operate in practice and establish the framework for the specific requirements necessary to ensure a stable storage environment that are based on low-energy principles.

2

The storage building

2.1 Building design and internal environment control principles

Existing low energy storage facilities in Denmark are typically constructed as a shell building using concrete elements for walls and roofs, with a concrete slab cast on site on a capillary-break shingle layer base with varying layer thicknesses (normally 150 mm). The capillary-break layer must have high thermal conductivity, so it does not act as an insulating layer beneath the floor.

While the ground floor slab has no thermal insulation, the walls and roof are airtight and well-insulated, typically using mineral wool thicknesses of 250-300 mm (see Section 5 in "Specific functional requirements"). External walls can be constructed as sandwich elements, or possibly as lightweight concrete elements with external insulation and metal cladding. Roofs can be built using pre-stressed hollow core decking or as TTS elements with trapezoidal panels. A few other variations in building construction are seen in Danish storage facilities, such as the use of brickwork.

The primary environmental control consists of internal, recirculating ventilation systems with mechanical dehumidification, but without humidification. Dessicant dehumidifiers are often used instead of condensation dehumidification. Ideally, storage temperature can be controlled entirely passively in that the environment in the unheated storage hall follows outdoor seasonal change with a time lag, depending on the heat capacity of the ground soil volume (see diagram on page 13). However, some existing storage facility buildings have an option for slight heating during the winter if temperature falls below an allowed threshold value. Cooling is not needed in the storage facilities, except for collections that may require specialized environmental conditions (see Section 3.4).

When assessing energy consumption for internal environmental control, it may be appropriate to use the energy consumption per cubic metre of storage facility volume as a metric, as this takes variations between storage buildings' ceiling clearance height into account. This also allows for a direct comparison of consumption at the various storage facilities, regardless of their differences in size. The unit for relative energy consumption is thus kWh/m^3 per year.

Low-energy storage facilities are typically built as large halls, preferably with an internal clearance height of 6-8 m (see examples in Table 1). Compact shelves are often used for space optimisation. In addition to one or more storage facility areas, storage facility buildings can include a number of ancillary spaces, including indoor truck bay, handling and conservation workshops, as well as staff facilities. This report does not cover ancillary spaces.

→

One of the key parameters is the optimal utilisation of space within the storage facilities, both vertically and through the use of movable compact-shelving systems.

2.2 Environmental impact

The environmental impact of several low-energy storage facilities was mapped in two recently completed projects from 2024.

Project A: A study of six newer existing storage facilities, in which the building-related CO_2 emissions generated during construction, operation, maintenance and disposal after use were calculated according to a life cycle analysis (LCA) (Ryhl-Svendsen, Jensen & Larsen, 2025).

Project B: A study of an existing storage facility from 2012 at the Vejle Conservation Centre (described in Table 1, Column 2). This study was the model for five of the buildings included in Project A (Ræder Knudsen *et al*, 2025). The study investigated whether the good performance of the current building storage quality and construction costs could be achieved in future buildings using more sustainable building materials.

Both studies performed LCA calculations based on the guidelines in the Danish BR18 Building Regulations (Danish Social and Housing Agency, 2018), with a service life of 50 years. (The actual service life of most modern storage facility buildings is expected to be significantly longer; however, 50 years is the guideline benchmark).

Study A found that the CO_2 emissions for all buildings were between 6-10 kg CO_2/m^2 per year, which in all cases was below the maximum 12 kg CO_2/m^2 per year requirements of then-current Building Regulations. Four of the buildings also had emissions that were below requirements for the low-emission class of 8 kg CO_2/m^2 per year [1]. For all storage facilities that were studied, the largest contribution by far came from concrete (40-65%), followed by insulation materials (15-25%). Sheet metal used in roofs or façades amounted to 15-20%. The analysis was specifically carried out on the storage facility component of the buildings and did not include ancillary functions (staff sections, etc.).

For study B, three alternative concepts were set up to investigate the use of building materials corresponding to increasingly ambitious CO_2-reduction targets. The concept designs were expected to provide physical and environmental protection to collections, against fire, theft, water damage, mould, vermin and unsuitable levels of temperature, humidity and light. In addition to LCA, LCC (life cycle cost) calculations were made for the three concepts.

This provided an indication of the relative costs of a more sustainable build when compared to the existing traditional construction concept, which is primarily based on concrete, mineral wool and sheet metal.

[1]: Figures according to valid BR18 requirements for 2024. Note that the CO_2 threshold limit for buildings' climate impact continues to fall, as seen in the latest amendment to BR18, dated 1 July 2025 (https://www.retsinformation.dk/eli/lta/2025/271).

The shared storage facility in Vejle was expanded in 2012 with a section of storage halls, which provide indoor environmental conditions with a very high Time-Weighted Preservation Index for a very low energy consumption, and represents a leading example of the "Danish model" (see Table 1, Vejle Hall F).

2.3 Alternative construction materials

For study A, it was found that floors, foundations, external walls and partition walls, as well as the roof construction accounted in total for about 90% of the total CO_2 emissions. By way of contrast, the CO_2 emissions from environmental control energy consumption (operational CO_2) are lower than the emissions from the building's construction and materials (embodied CO_2) by a factor of at least 10, if dehumidification was the only environmental control used. It was therefore obvious to investigate whether the use of especially concrete can be minimised, and whether the use of alternative building materials can reduce environmental impact. One of the storage buildings from the study was simulated in alternative versions, the optimal version being with glulam load bearing structure, a wood-clad façade and paper wool insulation. This resulted in approximately halved CO_2emissions over a 50-year period, compared to the actual building in concrete and steel. There are significant environmental gains from constructing a light, wood-based building envelope instead of a heavy construction in concrete.

In study B, similar simulations were carried out with comparable results. The analysis, however, also pointed out problems with the alternative versions when it came to addressing the various risk factors mentioned above. Study B also found that only limited benefits could be achieved from the use of certain alternative materials, such as unfired clay bricks for internal walls or rammed earth walls.

It must be acknowledged that there are still no implemented examples of storage facility buildings constructed from sustainable materials in Denmark, which may partly be due to challenges associated with the testing, approval and certification of non-traditional construction materials. We would encourage that this is explored further.

The two projects were supported by the Danish National Agency for Palaces and Culture, Fund for Sustainable Museums (2024). Project B was also supported by the Augustinus Foundation.

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Concrete accounts for about half of the total environmental footprint of a storage facility building. When elements of the building can be constructed using alternative materials, the building's sustainability can be significantly increased.

3
Indoor environment

3.1 Environmental control zones

There can be numerous different environmental control zones in a low-energy storage facility, depending on the requirements of the collection materials currently stored within. The main part of the storage area is typically comprised of so-called "Standard storage environment" where the relative humidity set point is about 50% RH and no active cooling is required. For a typical museum collection, the standard environment can constitute over 90% of the total storage area.

Depending on the collection, there may also be a need for additional, separate special environmental conditions zones. Often, these would be: "Dry" (30-40% RH), "Ultra- dry" (<10% RH), or "Cold" (<10 °C). There may be other environmental zones for material groups with special requirements, but those mentioned above are the most common.

Typical requirements for the different types of indoor environmental conditions are described below. It must be emphasised that the preservation requirements of the stored objects are what determine the requirements. There may therefore be scenarios where the specific collection's requirements deviate from typical specifications. For hygroscopic objects (objects that can absorb or release water vapour), EN 15757:2010 provides guidance on how environmental requirements can be specified. Recommendations for environment in storage facilities can also be found in the collected *"Anbefalinger til museernes forebyggende bevaringsindsats"* (Rasmussen et al, 2021), (in Danish, a collection of preventive conservation guidelines). The indoor environmental requirements that are necessary for the collection in question must in each individual case be determined in consultation with conservation staff.

The most common environmental zones are briefly described below. In "Part 2: Specific functional requirements" further elaboration is provided with more detailed specifications about establishing a standard storage environment. For storage facilities with a dry, ultra- dry or cold environment, only few functional requirements will deviate from the standard storage environmental conditions, such as increased dehumidification capacity or cooling systems. There may be a number of workspaces and handling areas outside the storage facility area which require their own indoor environment. The specifications for such zones may follow requirements other than preservation, e.g. human comfort. This subject will not be addressed in this report.

3.2 General standard conditions

A standard environment will satisfy requirements of the majority of typical museum collections. This environment zone's boundary limits typically lie within a humidity range of 40-60% RH and a temperature below 20 °C. Experience shows that in a Danish climate most low-energy storage facilities can passively maintain a temperature that fluctuates on an annual basis within a range of approximately 7-17 °C, with daily fluctuations less than +/- 2 °C.

The upper relative humidity threshold is controlled by mechanical dehumidification. The control setpoint is typically set at around 50% RH, with best practice showing that air humidity can often be kept constant, within +/- 5% fluctuation. Precise humidity threshold limits are set according to the needs of the current collection. Preservation quality, as expressed in the Time Weighted Preservation Index (TWPI), must be higher than index 100 (see Preservation Parameters, Section 4).

Energy consumption for a general storage facility must be below 3 kWh/m^3 per year. Best practice shows, however, that, under optimal conditions, a standard environment can be maintained for less than 1 kWh/m^3 per year.

3.3 Dry/Ultra-dry environment

Dry environmental conditions are typically used for the storage of contemporary metal objects. Ultra-dry conditions are used especially for the conservation of archaeological metal, as well as objects that contain salts and the like. Relative humidity (RH) in dry environmental conditions is typically between 30-40% RH but can be lower than this. Relative air humidity lower than 10% is categorised as "ultra-dry". Temperature conditions normally correspond to those for general storage environment.

For energy reasons, air humidity adjustment should be performed using mechanical dehumidification processes, not heating. The lower the setpoint for relative humidity is, the higher the energy consumption for dehumidification will be. Best practice for dry environmental conditions shows that it is possible to maintain 30% RH using 10 kWh/m^3 per year.

Preservation quality expressed as TWPI makes no sense for the aforementioned categories of materials listed in this section. The primary preservation requirement is the absence of moisture (low RH), which prevents corrosion or salt efflorescence.

3.4 Cold environment

A cold indoor environment is used for chemically unstable objects, such as modern objects made of plastic (toys, household items, textiles etc.), acidic paper (newspapers etc.), film and audio media, photographic negatives and similar artifacts.

Appropriate temperature is determined in each case based on expert conservator's assessments but will always be 10 °C or lower. The relative humidity value should typically be 30-40% RH. This will result in a TWPI that exceeds index 200. An index of 400 would be a sensible benchmark for the long-term storage of unstable objects.

Temperature adjustment would have to be performed using mechanical cooling. The lower the temperature, the higher the energy consumption. Best practice for a cold environment shows that 10 °C can be maintained with an annual consumption of 30 kWh/m^3.


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Preservation parameters

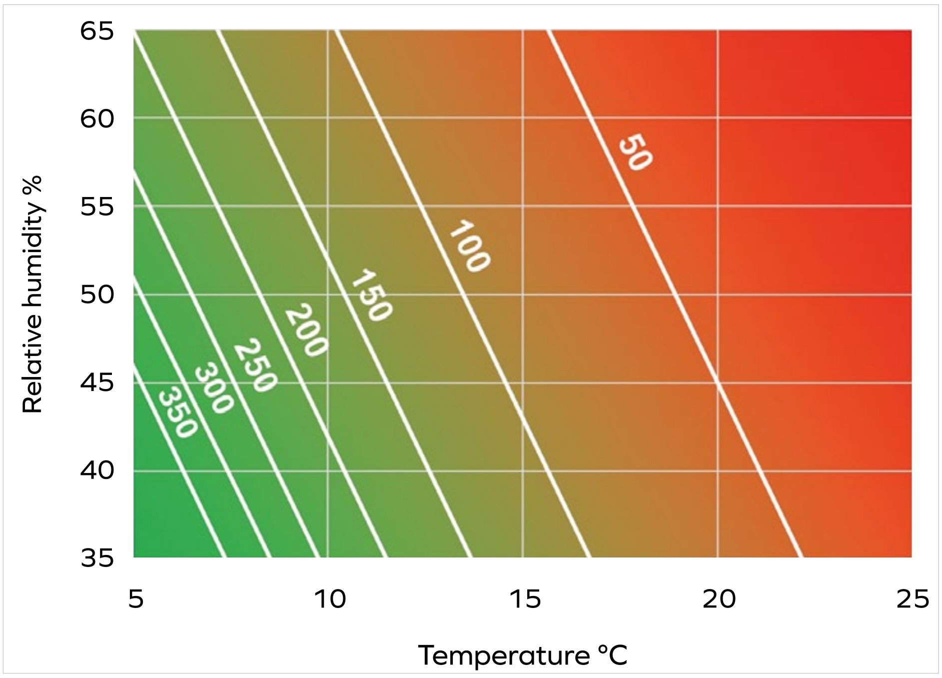
4.1 Time-Weighted Preservation Index

When classifying indoor environments in low-energy storage facilities, the Time-Weighted Preservation Index (TWPI) is used to indicate the quality of preservation achieved by a particular indoor environment (Nishimura, 2007; Richardson, 2023). TWPI indicates an index number that expresses the average chemical degradation rate of organic materials under the influence of the temperature and humidity of the indoor environmental conditions in question. The higher the TWPI, the slower the rate of degradation (and the better the quality of preservation). If, for example, the indoor environment is changed so that TWPI increases from 50 to 100, the durability (or "lifespan") of organic materials will be doubled.

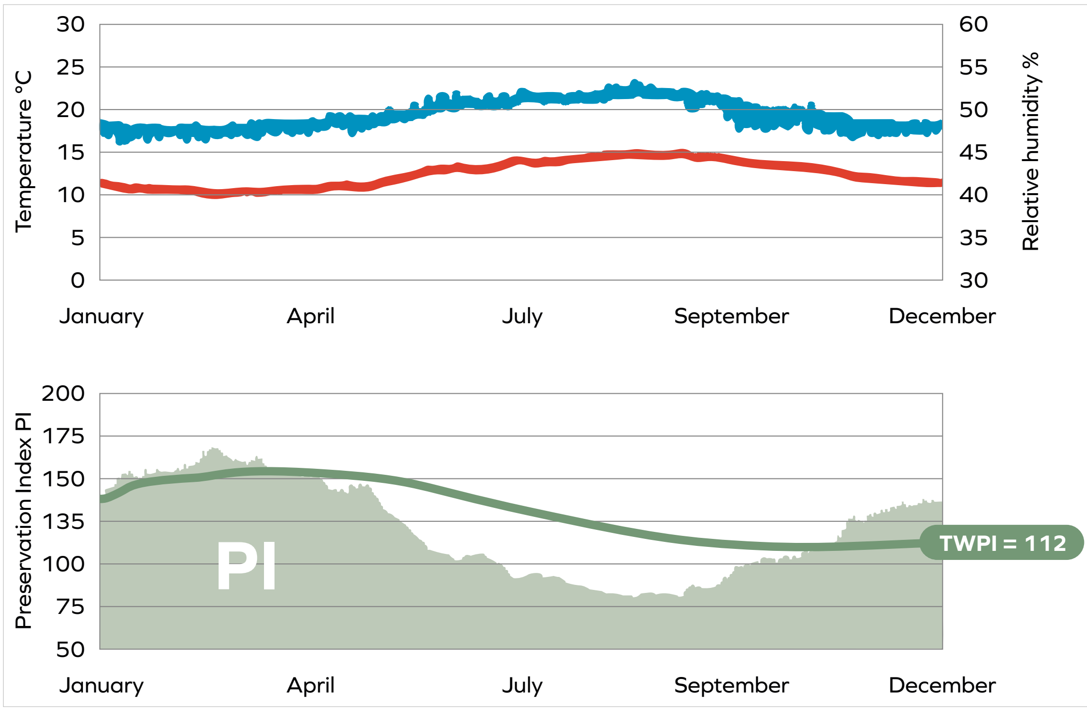
Temperature and humidity in museum storage facilities can vary over the seasons because of outdoor temperature changes and possible influence from the building's air conditioning system. A storage facility where temperature and humidity remain constant over a longer period of time is therefore rare. A TWPI value takes into account the influence of temperature and relative humidity including fluctuations, weighted over a period of a whole year. This gives an overall preservation quality value, which takes the influence of all seasons into account. See the Appendix for a description of TWPI calculation.

The environmental quality in terms of TWPI levels is generally assessed as follows (Nishimura, 2007):

- TWPI < 45: Poor environment, rapid degradation
- TWPI 45-75: OK environment, medium durability
- TWPI 75-100: Good environment, good durability
- TWPI > 100: Excellent environment, long durability



Preservation Index (PI) as a function of the indoor environment: temperature and relative humidity. White contours indicate how PI increases in line with lower temperature and relative humidity and decreases with higher temperature and relative humidity.



Temperature (red) and relative humidity (blue) in a storage facility and the corresponding preservation index PI (light green) at any given time. PI decreases as temperature and/or relative humidity increases, and vice versa.

The dark green curve shows how the time-weighted preservation index (TWPI) accumulates over time. After exactly one year, a full TWPI is obtained; in this case with an index of 112.

Data from the Vejle Storage Facility.
See the Appendix for more information about TWPI.

4.2 Other preservation factors

TWPI is only valid for the chemical degradation of organic materials. For object categories that fall outside this grouping and their associated degradation mechanisms, the following risk factors are important (Nishimura, 2007):

Risk of corrosion: The lower the relative humidity, the better. For metal objects of recent origin, preferably 40% RH or lower. For archaeological metal and objects contaminated with salts <10% RH.

Risk of mould: The lower the relative humidity, the better. Temperature also influences mould growth conditions, however, in the typical environment ranges found in museum storage facilities the relative humidity will be the driving factor. An indoor environment with RH below 65% has traditionally been considered safe from mould infestation. Recent discoveries of xerophilic moulds (which require very little moisture) in museum storage facilities suggest, however, that these fungi can thrive at lower humidity, down to levels just below 60% RH (Bastholm et al., 2024). The risk of mould outbreak remains minimal for typical standard conditions with a dehumidification setpoint at about 50% RH as described above (Section 3.2).

Risk of moisture-induced mechanical damage: Air humidity will affect the water content (equilibrium moisture content) of some organic materials in a way that can lead to mechanical damage when the humidity varies.

This can be manifested as cracks due to drying, or deformation due to dimensional changes in the material at high relative humidity. Among the many types of objects that can be vulnerable to this are paintings on canvas and wood, furniture, and tooth and bone material. See, for example, EN 15757:2010.

Part 2

Specific functional requirements

5
Building envelope

5.1 Purpose

The building envelope of a low-energy storage facility serves to insulate the indoor environment against short-term and large external temperature fluctuations. Danish average outdoor monthly temperatures fluctuate annually from approximately -1 °C to +18 °C. Ideally, these figures should be halved and smoothed out internally using building envelope airtightness and insulation capacity (see General standard conditions, Section 3.2). A high degree of airtightness will also minimise energy consumption for dehumidification of infiltrating air.

The following describes the special functional requirements for the building envelope surrounding a standard storage environment. The functional requirements for other internal environment zones (dry, ultra-dry or cold environment) will be slightly different to those of a standard environment, primarily with regard to insulation capacity.

5.2 Energy framework

Danish BR18 Building Regulations paragraph 260 stipulates the following requirement ("Energy framework for buildings other than residential buildings") that the total energy requirement of a building may not exceed 41.0 kWh/m^2 per year plus 1,000 kWh per year divided by the heated floor area. Furthermore, buildings other than residential can be assigned a low-energy classification when total energy supply requirements for heating, cooling, hot water and lighting per m^2 of heated floor area do not exceed 33.0 kWh/m^2 per year (BR18 paragraph 475).

Because the actual storage area of a low-energy storage facility is not defined as a heated building, these figures can only be used as a basis for comparison. Regardless of this, low-energy storage facilities are able to satisfy the previously mentioned requirements, as proven in several realized completed projects (see Table 1).

5.3 Validation of energy consumption and temperature stability

The choice of building envelope and structures must be validated by dynamic internal environment simulations using suitable software, such as BSim, IDA ICE, or similar. A recognized, two or three-dimensional heat calculation program (such as HEAT2, HEAT3 or COMSOL) which can analyse the heat transfer from the museum storage facility to the ground beneath must be used before the dynamic internal environment simulations can be performed.

The floor area must be divided into a minimum of five floor surface sections, according to their distance from the museum storage facility outer wall. This makes it possible to determine the thickness of the underlying heat retaining soil layer for each individual floor surface section. Once determined, these thicknesses must be transferred to the dynamic internal environment simulation software, the floor being similarly divided into a minimum of five floor surface sections. Because the soil mass has a very high heat retention capacity, ten years of weather data must be simulated using the indoor environment simulation software before the required stability is achieved.

The simulations must document that the internal environment (temperature, relative humidity and TWPI) and energy consumption described by the project owner are compliant with the low-energy storage facility.

Weather data needs to be used to validate the specified internal environment and derived preservation quality (TWPI) in accordance with Danish BR18 Building Regulations together with climatic data for extreme weather and including future weather data projections The latter is required due to the function of the building and the expected long service life.

The construction project must also ensure that the conditions in the ground below and up to a distance of 8 meters away are not subject to temperature impact of nearby buildings and facilities.

For simulation purposes, it is recommended that the method outlined here is applied and that a calculation for a 10-year period is performed using the selected weather data until the required stability is achieved:

- Validation of the building's internal environment with the selected building envelope, structure and HVAC installations with dynamic simulations. If applicable, conditions must be included from local land survey records or the storage facility's own land register if they could impact the temperature of the ground below up to a distance of 8 meters around the low-energy storage facility. The simulation is performed using weather data that can be found on Aalborg University's website in connection with BSIM software: https://www.build.aau.dk/til-byggebranchen/software/bsim/klimadata or built into the respective program:

    - Generally applicable standard weather data for Denmark (DRY 2013 for the calendar year 2010) in accordance with Danish BR18 building regulations.
    - Weather data sets for extreme situations ("hot", "cold", "sunny" and "cloudy") are not suitable for standalone simulations, as these data sets do not cover the full 10-year period required if stability is to be achieved. Should an assessment of the sensitivity of the internal environment to such scenarios be required, this can be done, for example, by first simulating eight years using DRY2013 data, followed by two years using weather data for extreme situations.
    - Weather data for simulating future internal environment in 2050 and 2090.

Results from the simulation must be:

- Compiled in table form for each weather data set and compared with the indoor environment (TWPI) and energy consumption as provided by the project owner.
- Included in a final report with an evaluation of the simulations to show that the building, when in its final use state, complies with internal environment specifications, preservation quality (TWPI) and energy consumption with regard to:

    - Weather data DRY 2013 for calendar year 2010 (in accordance with building regulations)
    - Weather data for extreme situations ("hot", "cold", "sunny" and "cloudy")
    - Weather data for future climatic conditions in 2050 and in 2090

5.4 Airtightness of the building envelope

The following describes requirements for building envelope airtightness and the associated documentation.

5.4.1 Air change rate

The total airtightness of the building envelope must result in an average air change rate of less than 0.02 air changes per hour (ACH) for the entire storage room. Where multiple environmental zones are established, the average air change rate for each environmental zone must also be less than 0.02 ACH.

The airtightness of the building envelope is determined for each environmental zone by measuring the average air exchange rate for a period of at least one month, such as by application of the perfluorocarbon/PFT tracer gas method, cf. SBi instruction 227 (Bergsøe, 1992).

The result is documented in a report stating the measured values in relation to the requirement for an average air change rate of less than 0.02 ACH.

5.4.2 Radon

The following describes requirements for radon protection and radon level documentation.

Radon protection

The low air exchange rate in a low-energy storage facility represents a risk of radon accumulation inside the buildings, as any radon that enters will largely remain undiluted. The building must therefore be constructed with radon protection to prevent radon content in the indoor environment exceeding 100 Bq/m^3. The radon protection system must be regularly checked during construction.

Radon protection requirement remains in unoccupied buildings (no staff facilities and no permanent workplaces in the storage section) (cf. BR18 Danish Building Regulations and Denmark's Executive Order on Ionising Radiation and Radiation Protection (BEK no. 84 of 02/02/2018)). One of the reasons for this is that there may be staff areas elsewhere in the building and that air from the storage area can infiltrate these areas.

Measurement of radon levels

There are requirements for:

- Measurement in the low-energy storage facility to determine the estimated annual average radon content value within the indoor environment, cf. SBi instruction 270 (Rasmussen, 2018), after the building is occupied. Measurements are taken with no form of active radon extraction, even if the building has been provided with such systems.
- Documentation report stating the measured values in relation to the requirement for a maximum indoor air radon content of 100 Bq/m^3.

6

Building envelope element requirements (roof, outer walls, etc.)

6.1 Roof structure requirements

Roof of a low-energy storage building needs to be heavily insulated. The U-value for the roof of existing low-energy storage facilities is typically 0.09-0.12 W/(m^2K).

The selected U-value for the roof structure, including linear heat loss in the external wall, must be validated by a simulation, as stated in Section 5.3.

Insulation and airtightness are subject to the following requirements:

- Insulation capacity: U-value below 0.12 W/(m^2K).
- Skylights may not be installed, not even as smoke vents. The latter must be negotiated with fire safety authorities.
- Perforations through the roof structure are not permitted. This is partly to ensure compliance with building envelope air-tightness requirements (Section 5.4).
- Junctions with other building elements, airtightness, components or connections must be made with a long-term durable two-stage seal that is as easy to install and maintain. Flexible joints as the only form of seal are not permitted.
- "Green" roofing must not be installed due to building moisture protection requirements.

6.1.1 Specific to solar cells

While it may seem like an obvious choice to include solar cells to supply the storage facility with energy, it is not advisable to install these on the roof, due to the stringent moisture protection requirements of the storage spaces within the facility. Risks include penetration of the roof membrane and the difficulty of accessing the roof for maintenance tasks. It is recommended that solar cells are installed on the ground next to the building instead. If placement on the roof is a necessity, the solution may be to establish an accessible and an inspectable roof void between the roof and the storage facility, possibly designed as a gable-ended roof structure with external air ventilation.

The fire hazard risk posed by solar panels and batteries should also be carefully considered when choosing where to position them.

6.2 Outer wall requirements

Low-energy storage facility external walls need to be heavily insulated. The U-value for the external walls of existing low-energy storage facilities is typically 0.12-0.13 W/(m^2K).

The selected U-value for the external walls, including linear heat loss through the roof and foundations/ground slab must be validated by a simulation, as stated in Section 5.3.

External walls and roofs are constructed to be air-tight and well-insulated, with a minimum of doors, windows and openings, with insulation typically in the order of 250-300 mm.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There are requirements for:

- Insulation: U-value below 0.13 W/(m^2K).

The building envelope is subject to the following airtightness requirements:

- External walls must be constructed according to the "two-stage sealing" principle to ensure compliance with building envelope air- tightness requirements, see Section 5.4.
- No windows may be installed.
- Fire compartment must be selected to be sufficiently small (e.g. less than 1,000 m^2) that no smoke vents are required. The exact dimensions must be negotiated with fire safety authorities.
- The external walls must be built with as few perforations as possible, partly to ensure compliance with building envelope air-tightness requirements, see Section 5.4.
- Junctions with other building elements, components or jointing must be made with a long-term durable two-stage seal that is easy to install and maintain. Flexible joints as the only form of seal are not permitted.

6.3 Requirements for partition walls to other environmental control zones

Depending on room layout and the chosen floor plan, there will be internal partition walls to areas with different internal environment requirements, such as comfort zones, or other storage facility environment zones.

Interfacing walls between the general storage areas and other facilities must be designed to support the passive principle for maintaining required temperature conditions inside the storage room. This includes requirements for insulation and airtightness performance, which necessitate minimising service routes and penetrations.

The selected U-value for the partition wall's structure, including linear heat loss through the roof and foundation/ground level slab must be validated by a simulation, as stated in Section 5.3.

There are requirements for:

- Thermal performance of the insulation adjacent to comfort zones: As a rule of thumb, it is the same as for external walls (Section 6.2), but can be reduced, as partition wall is not adjacent to external temperature. Lower thermal performance of insulation may be sufficient and cost-efficient.
- Thermal performance of the insulation against ultra-dry, dry, or cold environment zones must be specified such that energy consumption and temperature stability in both storage facility zones can be validated as described in Section 5.3.
- Building envelope airtightness: The same as for external wall structures (Section 6.2).

6.4 Access requirements

The insulating function of the building envelope against the outdoor environment must be compromised as little as possible; there must be no windows or skylights. Doors and any other essential perforations (such as smoke vents) must be kept to a minimum and installed with insulation.

Access routes into the low-energy storage facility must be kept to a minimum. Only one access route is typically needed. The access route must be established to minimise air change rate and energy loss, both when closed and during use.

The access route must be established as an airlock. Additional to its function as part of the building envelope, the outer door also has other functions in relation to safety and fire. The inner door (high- speed, sectional and upward-opening) must ensure that the air change rate is minimal.

There are requirements that:

- The access route is established from adjacent premises, not with direct access from an open-air environment.
- The access route is executed as an airlock. The indoor environment inside the lock chamber is not controlled separately.

Applicable to the gate into the airlock:

- This access gate must be selected to fulfil the necessary functions required for access routes in storage facilities in general, including fire and safety, etc.

Gate from the airlock into the low-energy storage facility:

- This access gate must be a high-speed sectional door (or roll up gate).
- This access gate is supplied and installed to be airtight to ensure compliance with building envelope air-tightness requirements, see Section 5.4.
- Sealed joints around the gate must be using a two-stage seal system.

6.5 Requirements for emergency exits

The number of emergency exits must be kept to a minimum. This requirement must be confirmed in consultation with the fire safety authorities.

Following requirements need to be met:

- Doors to emergency exits must be well insulated, with a total U-value of less than 1.0 W/(m²K).
- Emergency exit doors must be supplied and installed to be airtight to comply with building envelope airtightness requirements, see Section 5.4.
- Sealed joints must be installed using a two-stage seal system.

6.6 Ground level structural requirements

A low-energy storage facility uses an unusual form of ground slab arrangement: it does not have insulation because the floor and the underlying ground are used as a passive heat store (see Section 1). A low-energy storage facility therefore does not generally satisfy Building Regulations' minimum building envelope insulation thermal capacity requirements (U-value less than 0.2 W/(m²K) (BR18, paragraph 257). A low-energy storage facility is, however, an unheated building so BR18 building regulation energy framework requirements can be satisfied when the energy performance for the entire building is considered. This should be pointed out during the regulatory approval process.

6.6.1 Ground level slab - thermal characteristics

A low-energy storage facility's ground level slab is left uninsulated so as to utilise the temperature-stabilising potential of the soil underneath the building. Materials that conduct heat well (e.g. concrete) are also used. The U-value for the ground level slab of existing low-energy storage facilities is typically 3.8-4.4 W/(m²K). For the capillary-breaking layer, gravel with high thermal conductivity (e.g. lambda = 2 W/mK) is used to prevent it from working as a slab insulator.

Ground slab during construction with a capillary-barrier of shingles covered by plastic sheeting. The concrete floor is cast on top of this, including preparation for the installation of compact shelving rails.

This also means that the ground underneath and within a certain perimeter around the building must not be used simultaneously for storing energy, for heating or cooling purposes. This area of ground must also not be affected in any other way that might interfere with its natural temperature conditions. An 8-metre perimeter radius is established to be an effective distance.

The selected U-value for the ground slab structure must be validated by a simulation, including linear loss at the external wall and any conditions in the ground under and around the low-energy storage facility, as outlined in Section 5.3. In this context, any insulating properties of the capillary-barrier must be taken into account. The use of gravel or crushed rocks as capillary barriers is recommended.

Because low-energy storage facilities have extremely low air change rate, radon protection must be installed during construction of the ground level slab Radon measurements must be performed to document that the protection has been properly implemented, as mentioned in Section 5.4.2.

The following requirements apply:

- Thermal properties: U-value must exceed 3.7 W/(m^{2}K). Thermal capacity of the full depth of the capillary barrier must be included in a dry state, i.e. without reductions, cf. DS 418:2011.
- Components that affect the ground temperature, such as geothermal heating/cooling systems, must not be installed below and/or within 8 m from the storage facility's building envelope and building elements. Adjacent buildings with different internal environmental conditions than the low-energy storage facility must be constructed with highly insulated ground level slab with U-value less than 0.15 W/(m^{2}K).

The building envelope is subject to the following airtightness requirements:

- The ground level slab must be installed to be airtight to ensure compliance with building envelope air-tightness requirements, see Section 5.4.
- The ground level slab must be installed with as few perforations as possible, partly to ensure compliance with building envelope air-tightness requirements, see Section 5.4.
- Joints between building or structural elements, including grouted connections, must be constructed using long-term durable solutions such as membranes, expansion profiles, or other operation- and maintenance-free joint types. Flexible (elastic) joints used as the sole form of sealing are not permitted.

6.6.2 Specific to radon protection

The following requirements apply:

- The ground level slab must be installed such that indoor radon levels within the building do not exceed 100 Bq/m^3, see also Section 5.4.2.
- In order to satisfy the functional requirements outlined in this report, durable sealing systems must be used as a priority. This can be combined with pressure equalisation beneath the ground-level slab or with a passive radon extraction system. It should be noted that the indoor air quality requirements for radon concentration must be met without the need to connect an active radon extraction system, as such systems are energy-intensive, operationally demanding, and require frequent maintenance.

The following items must be given special consideration beyond general building practices with regard to radon protection. This list is not exhaustive, but addresses typical challenges:

- When using concrete decking as airtight layers, concrete quality, shrinkage reinforcement, finishing, placement and execution of expansion joints must be executed in accordance with applicable regulations and coordinated so that a concrete slab with no through cracks is achieved.
- Joints between building or structural elements, and around service routes, must be constructed using long-term durable solutions such as membranes, expansion profiles, or other operation- and maintenance-free joint types. Flexible (elastic) joints used as the sole form of sealing are not permitted
- Any pressure equalisation beneath the ground slab, or provision for radon extraction, must not be routed through the building envelope of the low-energy storage facility.

6.6.3 Specific to floor-mounted fixtures

- It can be advantageous to use open fixtures (shelving, cabinets etc.) bases that allow air to circulate above the floor and in connection with the rest of the indoor environment.

6.7 Requirements for internal surfaces

General:

- The storage facility should be constructed as a "low-polluting building", cf. Danish Indoor Climate Labelling (Dansk Indeklima Mærkning/DIM): https://indeklimamaerket.dk. Documentation for this should be available.

Specific to wall surfaces:

Low-energy-consumption storage facilities should use white or light-coloured wall surfaces to reduce the energy demand for lighting. They should also be highly vapour-permeable to allow indoor humidity stabilisation provided by the wall materials themselves. Surface coatings with all the following characteristics are therefore used:

- Colour: white
- Highly vapour-permeable
- Inorganic/mineral type
- Approved for use in indoor environment
- Examples of usable paint types include pure silicate paint (without plastic binder) or cement- based wall paint.

Specific to floor surfaces:

- Floor surfaces must be light in colour and easy to clean; i.e. a surface treatment is typically required on the concrete slab.
- The surface must be strong enough to withstand wear from heavy traffic with pallet trucks and forklifts.

6.8 Other general functional requirements

Please note that other functional requirements (such as those relating to fire, safety/security and working environment) may pose challenges to the low-energy storage facility concept. These factors should therefore be incorporated at the earliest planning stage when planning a conversion, extension or new building.

- **Fire:** Building fire safety requirements are set out in Danish BR18 Building Regulations. In Denmark, fire inspections are performed by municipal emergency services. There may therefore be varying requirements when it comes to satisfying fire safety requirements, depending on the local emergency services and the building's specific layout. Alternatives to requirements for measures such as sprinkler systems and smoke vents should be discussed with the local fire authorities (see also Sections 6.1, 6.2 and 6.5).

- **Security:** Guidelines for choosing a security level can be found, for example, in the "Forsikring og Pension" security guide at: https://www.sikringsguiden.dk/. It is important to ensure that the building materials selected to meet security requirements do not conflict with those specified for the construction of low-energy storage facilities. This also applies to storage of objects or works that are covered by Danish National Indemnity (NI). NI is a state insurance scheme where the state can assume the insurance risk for Danish and foreign loans of museum objects: https://kum.dk/ministeriet/organisation-og-institutioner/bestyrelser-raad-naevn-og-udvalg/kulturministeriets-sikringsudvalg.

- **Working environment:** Factors such as the low air change rate and lack of daylight found in low-energy storage facilities make them incompatible with the placing of permanent workplaces within the storage facility itself. This must be taken into account when organising working hours, especially when moving into a newly built storage facility.

7

Installation Requirements

7.1 Ventilation

The following describes only the requirements for general storage conditions, and the Heating Ventilation and Air Conditioning (HVAC) installations that provide it. Storage facilities with dry, ultra-dry or cold environments have functional requirements that differ from those for standard storage such as increased dehumidification capacity, increased internal ventilation rate, or cooling systems.

7.1.1 Ventilation principle

Mixing ventilation must be used, whereby the dehumidified air is blown in through ceiling ducts and mixed with the air inside the room.

The very limited need for mechanical ventilation in low-energy storage facilities means that ventilation units are small and space-saving. The primary elements are a dehumidifier and a fan.

7.1.2 Air volume-sizing

- The ventilation system must supply a volume of air that will ensure sufficient air movement to achieve an even distribution of the conditioned air, achieving stable humidity and temperature throughout the room.
- An internal air change rate (ACH) (i.e. a recirculation rate) of 0.25 times per hour is considered sufficient to achieve this.

7.1.3 Ventilation system

Principle:

- The Air Handling Unit (AHU) must be recirculation only, without the supply of fresh air.

Filters:

- A minimum F7 filter with an initial pressure loss of 30 Pa and a final pressure loss of 130 Pa must be used. If greater air filtration efficiency is required, an F9 filter with an initial pressure loss of 50 Pa and a final pressure loss of 200 Pa can be used instead.
- It can be advantageous to use carbon filters in specific situations involving collections that emit significant pollutants, such as large newspaper archives or acetate-based plastic materials. Bag filters combining carbon impregnation with particle filtration may be employed, typically with an initial pressure drop of around 150 Pa and a final pressure drop of approximately 250 Pa. When using carbon cylinders designed solely for gas adsorption—since particle filtration takes place separately in other (bag) filters—there is virtually no increase in pressure drop over the service life of the carbon filter.
- The requirement for filtration of harmful substances must be determined through an assessment by conservation specialists, based on the type and extent of relevant objects within the storage facility.
- Filters are changed when pressure loss exceeds the maximum specified final pressure loss.
- Carbon filters are changed when their filtration capacity is exhausted. This can be monitored, for example, using VOC or corrosion sensors (Section 7.2.5).


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Heating and cooling elements:

- Active temperature regulation should not be necessary because temperature regulation is achieved passively using insulation that is correctly dimensioned for the building envelope.

Fans and motors:

- Centrifugal fans (fans with backward curved blades (B-wheels) must be used.
- IE3 or IE4 motors must be used. Permanent magnet motors (PM motors) are preferred.

Supply and return air fittings:

- Short-circuiting of air in the storage area must be avoided (supply air going directly to the return outlet).

Dehumidification system:

- An energy-efficient absorption dehumidifier with heat recovery from the desiccant reactivation process must be used. The warm and moist exhaust air from the reactivation process must be channeled through a crossflow heat exchanger before being discharged into the open air. This will significantly reduce energy consumption for regeneration heat.

Location of HVAC Plant:

- HVAC plant is located in engineering/technical rooms inside the building, separate from the actual storage area. Drainage must be installed in the engineering/technical room to drain water from the dehumidifier.

Building Management System (BMS):

- The ventilation system is controlled so as to maintain the required relative humidity in the storage room. The dehumidifier self-adjusts according to humidity sensors placed at evenly distributed intervals throughout the storage room and at different heights (typically three levels), as well as in the exhaust duct. The setpoint is set to not exceed the required maximum RH.
- No humidification system is used, as lower limits for RH are maintained passively by the building and its temperature.

7.2 Internal Environment

The following describes the measurement (monitoring) points and their location, sensor types and their accuracy, as well as requirements for calibration, data collection and data storage.

7.2.1 Measurement points

Below is listed the description and optimal locations for measurement points required to maintain the internal design conditions.

→
Top/middle: Electricity meters on the individual system components to document the storage facility's energy consumption. Energy consumption should be logged separately (sub-metered) for each individual system component, including dehumidifier, fan and BMS, heating surface (where applicable), etc.

Bottom: Environmental sensors must be positioned at evenly distributed intervals throughout the storage facility and at different heights.

7.2.2 Sensors in the air injection duct (temperature and humidity)

Sensors for measuring the temperature and relative humidity of the injected air are placed in the air supply duct after the climate control unit.

Acceptable deviation:

- Temperature sensor [°C]: +/-1 °C
- Relative humidity sensor [%]: +/-3% RH

7.2.3 Sensors in the air supply duct (temperature and humidity)

Sensors for measuring the temperature and relative humidity of the injected air are placed in the air supply duct after the AHU.

Acceptable deviation:

- Temperature sensor [°C]: +/-1 °C
- Relative humidity sensor [%]: +/-3% RH

7.2.4 Sensors in rooms and halls (temperature and humidity)

Relative humidity and temperature sensors must be positioned at evenly distributed intervals throughout the storage facility and at different heights. They can either be placed in the middle of the storage room or at each end of the storage room. The difference between the measured temperatures at the different heights must not exceed 2 °C.

Acceptable deviation:

- Temperature sensor [°C]: +/-1 °C
- Relative humidity sensor [%]: +/-3% RH

7.2.5 Air pollution

Air quality sensors are a possible additional option. These are primarily used in connection with carbon filtration, or when particularly polluting materials or activities are present in the immediate area.

Particle monitor:
The particle sensors are placed in the return duct before the AHU. Either infra-red or laser sensors are used.

Acceptable deviation:

- Ultra-fine particles: [Smaller than 1.5 μm] +/- 10%
- Larger particles: [From 1.5 to 10 μm] +/- 5%

VOC (volatile organic compounds) sensor:
The VOC sensors are placed in the return duct before the AHU. Electrochemical sensors are used.

Acceptable deviation:

- VOC: [concentration] +/- 20%

Corrosion sensors:
An alternative to VOC sensors is corrosion monitors that indicate the "aggressiveness" of the air in relation to metal-coated electronic sensors, by measuring the rate at which they corrode. These types of sensors are typically silver and copper based.

7.2.6 Calibration of equipment

All sensors must be calibrated once a year, with traceable, accredited equipment. Sensors must be mounted for easy access when performing the calibration procedure.

7.2.7 Data, access and ownership

This section focuses on operating data that remains available to the storage facility, regardless of the operator.

The BMS system should have a module for recording all data from regulated or controlled parameters, adjustment regulation and control signals, operating status/alarms, and energy consumption. Electricity consumption data for the entire storage facility must be collected, as well as separate electricity consumption data for ventilation systems, dehumidifiers, lighting systems, and other operating systems (submetering).

Points below are from the guidance on building automation in the Danish BR18 Building Regulations:

- All data from regulated or controlled parameters, adjustment/regulation and control signals, operating status and alarms must be collected with a minimum frequency of once every five minutes and stored for at least 60 weeks. Room and outdoor temperatures only need to be logged with a minimum frequency of once every 15 minutes.
- In addition, operating personnel will be able to set up aggregated ad hoc logging of parameters, signals, operating status and alarms of their own choice, with frequency resolution options (5 sec. – 6 hours) and time periods that they can determine themselves.
- Metered data is collected at intervals of a maximum of one hour and stored for at least 10 years. Metered data is displayed in diagrams and in tables as hourly values and summed for 24 hours, week, month and year. The tables are designed so that data can be transferred for further use in other IT systems.

↑
Mobile energy meter mounted directly on the dehumidifier.

7.3 Functionality testing and operational control

This section describes which functional tests and operational controls must be performed.

7.3.1 Functionality testing

The following functional tests must be performed:

- Air volume/flow measurements
- Inspection of SEC factors (specific electricity consumption). There are no SEC factor requirements in the Danish BR18 Building Regulations for recirculation systems, but a maximum of 600 W/ m^3/s would be a reasonable requirement.
- Checking AHU control and regulation (temperature and humidity control)
- Checking dehumidification systems. Inspection of the dehumidifier's capacity to deliver the required air volume (from the ventilation system) with the required humidity at the lowest possible electricity consumption. There are no recommendations for energy consumption for dehumidification systems in BR18 Building Regulations. However, the total annual energy consumption for the dehumidification system and ventilation system for a low-energy storage facility must not exceed 3 kWh/m^3 of storage volume per year. Best practice shows that consumption of less than 1 kWh/m^3/year can be achieved.

The requirements and guidance for the functionality testing of ventilation systems specified in Danish BR18 Building Regulations serve as the point of departure.

Reference is also made to Chapter 9 of DS 447:2021 (Ventilation in buildings).

7.3.2 Operation and maintenance

The purpose of energy-efficient operation is to ensure that the systems deliver the services for which they are designed or sized, with the lowest achievable energy consumption and service and maintenance costs.

The technical systems include ventilation and dehumidification systems. These systems determine the indoor thermal and air quality conditions.

Reference is made to Chapter 9 of DS 447:2021 (Ventilation in buildings). Service/maintenance work should be performed by maintenance companies that have appropriate certification.

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Appendix

Calculation of Time-Weighted Preservation Index

Preservation Index (PI) is a metric derived from indoor temperature and relative humidity that describes the chemical degradation rate of organic materials, primarily through hydrolysis. The higher the index number, the slower the degradation (i.e. the longer the object's "life").

The concept is based on the temperature dependence of chemical reaction rates, as described by the Arrhenius equation, and reflects the degradation behaviour of typical cultural heritage materials studied under accelerated ageing condition (e.g., paper and plastics).

The PI concept was developed by the Image Permanence Institute at the Rochester Institute of Technology (Nishimura, 2007; Richardson et al., 2023). In association with this research, the Image Permanence Institute has published an online Preservation Index (PI) calculator for fixed temperatures and relative humidity: http://www.dpcalc.org

To calculate the Preservation Index in a dynamically varying indoor environment over a longer period, a time-weighted analysis of all the consecutive individual measurements is performed. This results in a "Time- Weighted Preservation Index" (TWPI). Evaluating a storage facility's TWPI and comparing the TWPIs for different indoor environments requires the use of indoor climate data for exactly one or more full years to ensure that the winter and summer periods are given equal weighting in the calculation.

The Image Permanence Institute provides an integrated web platform with software for TWPI calculation, analysis and data storage (on a subscription basis): http://eclimatenotebook.com. The software additionally calculates the risk of metal corrosion, mould growth and mechanical damage to organic materials.

The algorithm behind the Image Permanence Institute's tool is not openly available. An open-source version of the same type of calculation is, however, available on the website https://conservationphysics.org (Padfield, 2004). This gives within close margins the same TWPI calculation as the Image Permanence Institute software.

The calculation method is quoted from here:

- For a combined temperature T (°C) and relative humidity RH (%), the value RATE is calculated according to the formula: $RATE = RH \times 5.9 \times 10^{12} \times \exp(-90300/(8.314 \times (T + 273)))$
- Preservation index PI = 1/RATE
- For a time period with varying measurements, first calculate RATE for each set of temperature and RH values
- Then calculate the average of all RATE values
- TWPI = 1/ (average of RATE)

Check: T = 20 °C and RH = 50% should give TWPI = index 43

A more detailed description of the open TWPI calculation can be found in Padfield (2004).

Table 1: Danish low-energy storage facilities and their specifications (for Standard storage environment)

Source: Ryhl-Svendsen et al, 2012; Ryhl-Svendsen, Jensen & Larsen, 2025; Ryhl-Svendsen & Smedemark, 2025.

Storage facility	Shared Storage Vejle, Hall A (Vejle Conservation Centre)	Shared Storage Vejle, Hall F (Vejle Conservation Centre)	Ribe Storage Facility (Museum Vest)	Randers Storage Facility (Museum Østjylland)
Construction year	2003	2012	2005	2007
Area, general storage zone	1060	700	1000	1640
Ceiling clearance height (m)	6.3	6.2	6.2	7.0
Temperature control, principle	Passive	Passive	Passive	Passive
Setpoint temperature (°C)	Unregulated	Unregulated	Unregulated	Unregulated
Temperature, annual span, measured (°C)	7-17	7-19	9-15	8-19
Humidity control, principle	Recirculation, mechanical dehumidification	Recirculation, mechanical dehumidification	Recirculation, mechanical dehumidification	Recirculation, mechanical dehumidification
Setpoint, dehumidification (%RH)	50	50	50	55
Humidity, annual span, measured (%RH)	45-55	45-55	45-55	40-60
Building airtightness, measured air change rate (h^{-1})	0.05	0.01	0.03	0.04
TWPI (index)	115	112	115	90
Energy consumption (kWh/m^3/year)	1.5	0.7	1.5	3.0
Data origin (year)	2007-2010	2018-2025	2007-2010	2008-2010
Separate special environment zones beyond the standard area (where applicable)	Dry, Semi-dry	Dry, Semi-dry	Dry	Dry
Special conditions (where applicable)	(b)	(c)	(d)	

a): Measurement subject to uncertainty.

b): Hall A is one of four connected halls built in the first construction phase (2003) of the Vejle storage facility.

c): Hall F is one of three connected halls built in 2012 as an extension of the Vejle storage facility.

d): Building with gable roof. Bricks were used for the façade and inner wall surface.

e): Ventilation runs with a slight overpressure of air from outside, and carbon filtration.

f): Floor with thermal insulation, heated building.

g): Carbon filter inserted in the recirculation system.

h): The storage facility is shared with the Royal Danish Library but divided into separate areas. The library's storage room is controlled exclusively as a special environment with overpressure.

	Ugerløse Storage (Museum Vestsjælland)	Shared Storage Vestbjerg (Nordjyske Museer / North Jutland Museums)	Høje Taastrup Storage (Museum of Copenhagen)	Conservation Centre Sønderjylland, Rødekro (Museum Sønderjylland)	Shared Storage Vinge (National Museum)
	2010	2011	2018	2021	2022
	1800	3950	5200	1900	7800
	7.6	6.8	8.0	7.9	9.4
	Slight heat, winter	Slight heat, winter	Slight heat, winter; Cooling, summer	Heated, winter	Passive
	>10	>8	11-18	15	Unregulated
	10-20	9-19	11-17	14-19	10-16
	Recirculation, mechanical dehumidification	Recirculation, mechanical dehumidification	Recirculation, mechanical dehumidification	Recirculation, mechanical dehumidification	Recirculation, mechanical dehumidification
	55	55	50	50	55
	50-60	50-55	40-60	40-55	50-55
	0.02	<0.01	0.03	0.02	<0.01
	68	85	78	64	99
	2.4	1.4	(approx. 3) (a)	(approx. 5) (a)	0.6
	2023-2025	2024-2025	2022-2025	2024-2025	2022-2025
	Humidified	Dry, Cold, Frost	Ultra-dry, Cold	Dry, Ultra-dry, Cold, Frost	Semi-dry, Cold
			(e)	(f)	(g,h)

Glossary

The following is a list of definitions for the most important technical terminology used when discussing low- energy storage facilities for movable cultural heritage.

Buffering materials	Materials that passively absorb and release moisture or heat, thereby helping to maintain indoor environment stability. Examples of heat-stabilising materials include heavy materials such as concrete and brick. Many organic objects in museum collections are hygroscopic and by this able to buffer relative humidity, including objects composed of wood and paper.
Building envelope	The building's outer shell (walls, roof, floor) that separates outdoor and indoor environment. The envelope needs to be air-tight and well insulated to protect against weather and environment fluctuations, whilst also minimising energy consumption.
Capillary-barrier	A layer of gravel or broken stones beneath the ground level decking to prevent ground moisture from flowing upwards into the building.
CO_2 emissions (buildings)	Total environmental impact of the building expressed as the amount of CO_2 released during construction and operation (embodied and operational carbon). Concrete is the largest source of such emissions. There is considerable potential to reduce CO_2 emissions by using alternative materials such as wood and other bio-materials.
Dehumidification (mechanical)	Moisture is physically extracted from the air, typically only during periods of high outdoor humidity. Low-energy storage facilities use energy-efficient systems with low energy consumption, such as sorption dehumidifiers that use a desiccant to absorb water vapour. These are effective at low temperatures, which makes them particularly suitable for low-energy storage facilities with no heating.
General Storage Internal (Design) Conditions	General (or standard) storage environmental conditions in storage rooms: approx. 50% relative humidity with temperatures below approx. 17 °C. Covers requirements for the majority of objects in museums.
Ground level slab	The floor structure adjacent to the subsoil. The concrete slab of a low-energy storage facility has no thermal insulation, ensuring that the ground itself can act as a passive temperature buffer.
Internal Environment Zones	Different areas with specially adapted environments, e.g.: – General/standard environment for general museum collections – Dry (30–40% RH) for metals – Ultra-dry (<10% RH) for archaeological metal – Cold (<10 °C) for plastics, photographs and other chemically unstable materials

Low-energy storage facility	A storage building that ensures high conservation quality (TWPI > 100) with low energy consumption, i.e. below 3 kWh/m^3/year. Utilises the building's physical properties as a way to maintain passive environment control using a minimum of technology.
Radon	A radioactive underground gas. Low-energy storage facilities require a high degree of radon protection, as the low air change rate can otherwise lead to the accumulation (and increased concentration) of radon in the storage area.
Relative energy consumption	The energy consumption required to run the facility, measured per cubic metre of storage space. Used for documentation and comparison purposes. Best practice in Denmark is below 1 kWh/m^3/year.
Thermal mass	Expresses the building's ability to counteract rapid temperature changes. This is established in storage buildings by using heavy construction materials, primarily an uninsulated floor that serves as passive heat storage.
TWPI (Time-Weighted Preservation Index)	A relative measure that indicates how well the indoor environment protects organic materials over time. High TWPI = slow chemical decomposition and long durability. The target for long-term preservation is TWPI > 100.
Ventilation (recirculated)	The air is circulated internally without the addition of fresh air. Ventilation is only for dehumidification and internal air distribution purposes, not for comfort.

Colophon

Low-energy storage facilities
- concept and sustainability

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Low-energy storage facilities - concept and sustainability

This report compiles two decades of experience with low-energy storage facilities in Denmark and presents a comprehensive knowledge base for storage facility construction in the future. It focuses on combining high conservation quality with low energy consumption and reduced climate impact.

This publication was prepared by a group of experts with backgrounds in research, conservation and construction technology and belongs to the Green Museum Academy which is part of the Association of Danish Museums. The work took place in close collaboration with the Danish Technological Institute. It is based on documented examples and analyses from existing low-energy storage facilities in Denmark.

The report aims to qualify the decision-making basis for new constructions of and renovation work on storage facilities, as well as to promote the dissemination of low-energy solutions, whereby a building's own physical properties are conducive to conservation efforts, using only a minimum of technical management.

The report is aimed at project owners, consultants, authorities and museum institutions. It can be used both as an introduction to the low-energy concept and as a concrete tool for use in planning design and when specifying requirements.

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