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Eidgenössisches Departement für
Umwelt, Verkehr, Energie und Kommunikation UVEK

**Bundesamt für Energie BFE**

**Final Report, March 27, 2013**

# Sustainable Renovation of Historical Buildings (SuRHiB)

## Nachhaltige Erneuerung historisch wertvoller Bauten

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**Funding organisation:**

Bundesamt für Energie BFE
Forschungsprogramm Energie in Gebäuden
CH-3003 Bern
www.bfe.admin.ch

**Co-financing:**

Competence Centre for Energy and Mobility CCEM, Villigen PSI
Förderagentur für Innovation KTI, Bundesamt für Bildung und Technologie

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# Zusammenfassung

Das CCEM-SuRHiB Projekt wurde 2009 gestartet, um die Renovationsmöglichkeiten für historische Bauten zu verbessern. Im Zentrum standen traditionelle Gebäude die am Ende des 19. oder zu Beginn des 20. Jahrhunderts erstellt wurden. Es war offensichtlich, dass diese Gebäude nicht mit modernen Baumethoden renoviert werden konnten. Es braucht angepasste Technologien, die ihren architektonischen und handwerklichen Ausdruck zu erhalten.

Historische Bauten machen in der Schweiz etwa 20% der Bausubstanz aus. Viele dieser Gebäude sind keine geschützten Gebäude. Und trotzdem sind sie die charakteristischen Elemente der europäischen Innenstädte, die es bestmöglich zu erhalten gilt. Allerdings verursachen diese Gebäude – falls normal beheizt – auch einen verhältnismässig grossen Energieverbrauch. Falls die historischen Gebäude, welche rund 20% der beheizten Gebäude ausmachen, nicht energetisch verbessert würden, würden sie, falls die übrigen Gebäude energetisch saniert sind, langfristig rund 60% des Heizenergiebedarfs verursachen.

Dadurch, dass vor allem die Fassaden dieser Gebäude erhalten werden sollten, wird die thermische Verbesserung der historischen Bauten häufig schwierig und riskant. Nebst der Energiebilanz muss auch die Feuchtebilanz der alten Mauern beachtet werden. Eine sorgfältige Wärme- und Feuchteanalyse ist erforderlich. Die im Projekt durchgeführten Arbeiten haben dieses Problem unter spezieller Berücksichtigung der denkmalpflegerischen Aspekte  und der mögliche Auswirkungen der zukünftigen Klimaveränderungen untersucht.

Das Ziel war es, das hygro-thermische Verhalten historischer Gebäude zu verstehen und Renovationstechnologien zu entwickeln, welche es ermöglichen den Energieverbrauch zu verringern und gleichzeitig die kulturellen Werte zu schützen.
Die Untersuchungen beinhalteten die Analyse herkömmlicher Bauweisen und Baumaterialien und deren mögliche Beanspruchung infolge Klimaänderung. Die zu erwartende Klimaerwärmung und die Zunahme von Schlagregen wurden in die kombinierten Wärme-Feuchtesimulationen einbezogen.

Speziell die thermisch-hygrischen Auswirkungen der Innendämmung wurden untersucht, da diese nicht nur die Wärmeverluste reduzieren sondern auch das Austrocknen der Wände behindern. Gestaute Feuchtigkeit in Wänden könnte wertvolle historische Fassaden in kurzer Zeit beschädigen. Um dies zu vermeiden wurden die Schadensrisiken bewertet und Richtlinien für sichere Innendämmungen entwickelt.

Als wesentlich weniger risikoreiche Technologie  wurde ein Hochleistungsdämmputz entwickelt, welcher besser dämmt als eine herkömmliche Aussendämmung mit Polystyrolschaum, jedoch auf rein mineralischen, dampfdurchlässigen Materialien basiert. Die Entwicklung dieses neuartigen Putzes basiert auf Aerogelgranulat, welches eine Wämeleitfähigkeit von weniger als 30 mW/(m·K) erlaubt. Der Dämmputz kann sowohl aussen wie auch inwendig appliziert werden. Die Entwicklungen wurden zusammen mit einem Industriepartner erfolgreich abgeschlossen. Bereits konnten diverse Demonstrationsgebäude realisiert werden und der Dämmputz ist seit anfangs 2013 auf dem Markt verfügbar.

Nebst der Untersuchung von baulichen Massnahmen wurde auch untersucht, inwieweit die Regelung des Raumklimas geeignet wäre um Schadensrisiken zu minimieren und es wurden die Möglichkeiten zur Integration solarer Energiesysteme im historischen Umfeld evaluiert. Historische Bauten brauchen zwar nicht Null-Energiegebäude zu werden, aber sollten vernünftig Energieeffizient sein, um auch auch in Zukunft nachhaltig betrieben und unterhalten werden zu können.

# Summary

The CCEM-SuRHiB project was started 2009 in order to improve renovation technologies for sustainable renovation of traditional buildings. The focus was on traditional buildings that have been built at the end of the 19th or at the beginning of the 20st century. It was obvious that such buildings require adapted renovation measures that do not harm the original architecture and workmanship of these buildings.

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Historical buildings count for about 20 % of the existing building stock. Many of them are not protected buildings but they are characterizing the centres and history of European cities and are part of our cultural heritage. However, these buildings, if normally heated, cause relatively high energy consumption. Without improving the energy efficiency of historical buildings, this part of our building stock providing 20 % of heated space could become responsible for about 60 % of the thermal energy demand of the total building stock assuming, the other buildings will be retrofitted.

Due to the fact, that the façades of historical buildings should be conserved, the thermal insulation of these buildings becomes difficult and risky. The moisture balance of walls has to be carefully considered besides the energy balance and a careful risk assessment related to heat and moisture transfer has to be done. The work was done based on a survey of monument preservation requirements and climate load assessment.

The aim was to understand the hygro-thermal behaviour of historical buildings and to develop renovation technologies that allow reducing energy consumption and protecting the cultural qualities of such buildings. The investigations included the analysis of traditional construction technologies and materials and the challenges due to climate change. The expected impact of temperature increase and driving rain has been simulated by combined heat and moisture simulations.

Especially the hygro-thermal behaviour of internal insulation has been studied because it will not only reduce thermal losses, it will also hinder the drying process of walls. Accumulated moisture could destroy valuable historic façades within short time. A careful risk assessment and robust guidelines has been developed.

As another, less risky option a highly insulating light weight plaster rendering has been developed that insulates better than polystyrene foam but is based on mineral materials and is open for moisture diffusion. The development of this new building material is based on aerogel particles. It allows a thermal conductivity of less than 30 mW/(m·K) and can be applied inside and outside of a façade wall. The technology development was focussed on a novel type of highly insulation rendering and optimized solutions for internal insulation systems. The technology development has successfully been completed. Several demonstration projects have been insulated with the new type of rendering that is be available on the Swiss market since 2013.

In addition it has been studied how damage risks can be minimized by indoor climate control and guidelines have been developed for the application of solar energy collectors in historical environments. Finally, historic buildings will not become zero energy buildings, but will be reasonably energy efficient to operated and maintained in the future.

# 1. Historical buildings characterisation

In a first step, a survey on the historical building stock has been done by the ETHZ “Institute of Historic Building Research and Conservation”. Construction methods and building materials used for traditional urban multifamily buildings that have been constructed between 1850 and 1919 have been characterised [1].

In order analyse the heterogeneous composition of the Swiss building stock methods like Data Mining and Geographical Information Science have been used to handle the large number of building data. The building stock composition needs to be critically situated in the given historical context. Building survey and archival research focused on reference buildings selected by Historic Building Research interpretation and combined analysis by Data Mining and Knowledge Discovery. Several singular object studies emphasize the heterogeneity of details and constructions.

From the strategic retrofitting aspect, it must be considered that the relevant age-band (1850-1919) represents a very heterogeneous and characteristic stock. It is therefore impossible to develop a reasonable typology or just one overall retrofitting concept. A two-stage analytical procedure resulted in the selection of several reference buildings. The first step included techniques of spatial analysis and statistics (Top-Down-Analysis).

*Figure 1: Spatial probability of housing stocks (built before 1919), cell size (X, Y): 25m, 25m, r=1000m*

The analysis shows that the traditional building stock, which characterizes the centres of our cities, is very heterogeneous and does not allow standardised renovation concepts. A series of representative buildings were analysed (Fig. 2). Construction details of walls, ceilings and windows were documented and described and material samples (e.g. brick, plaster) were collected and characterized. The collected data was used for the hygro-thermal long-term heat and moisture simulations. Each reference building is fully documented and presented in its specific characteristics and neighbourhood [2].

The second step comprises the building survey and research in the archives (Bottom-Up-Analysis). The following reference buildings have been analyzed and documented during renovation or demolition works.

Seefeldstrasse, Zürich Schönleinstrasse, Zürich Feldstrasse, Zürich

Feldstrasse, Zürich Kernstrasse/Marmorgasse, Zürich Habsburgstrasse

*Figure 2: Historical reference buildings in Zürich*

The deliverables are a localized view and a better understanding of the relevant age-band in Switzerland. Material samples (e.g. brick, plaster) and construction details of walls, ceilings and windows, etc. were collected and are forming the basis for thermal and long-term moisture simulations [3].

*Figure 3: The energy relevant construction of a series of historical buildings has been documented and material samples have been analysed*

*Figure 4: Typical wall constructions: natural stone wall (Seefeldstrasse), mixed masonry wall (Feldegstrasse), brick wall (Kernstrasse)*

All documented buildings have single wall constructions. However, material use and masonry type vary considerably. Normally heterogeneous construction material has been used. The change from stone walls to brick walls occurred between 1870 and 1890. Most floors are wood beam constructions. In order to avoid moisture damages, vault constructions have been often built above cellars, kitchens and sanitary rooms.

*Figure 5: The construction of historical building is often complex and heterogeneous: Wooden beams running to a window alcove with a filled discharging brick arch. Grouted anchors of iron*

## 2. Climate load aspects

Historical buildings often suffer from moisture damages due to uncontrolled humidity and rain exposure. Rain water is absorbed by exposed façades. But insulation measures may hinder the drying process of the wall and increase or even create new damage risks. In addition, future climate conditions with an increased rain load could create further damage potential.

Data from various research groups using different climate models (European ENSEMBLES project, ETHZ-IAC and Royal Netherlands Meteorological Institute) have been used to predict the expected climate change that might occur within the next 40 years [4]. Relatively good data was found relating to future temperature increase but forecasts on future precipitation and wind directions are more difficult (Fig. 6, 7). The conclusions of the available climate studies are inconsistent. It is not obvious whether increased temperatures also mean an increased load of driving rain or not.

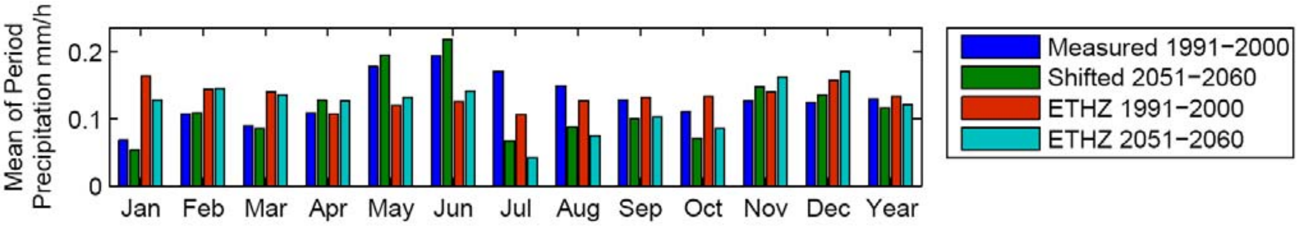


*Figure 6: Precipitation, monthly mean of the 10 years period: Measured data (1991-2000) and generated data (2051-2060. The “Shifted” data represents the most probable scenario, based on ENSEMBLES yearly data and ETHZ monthly distribution.*

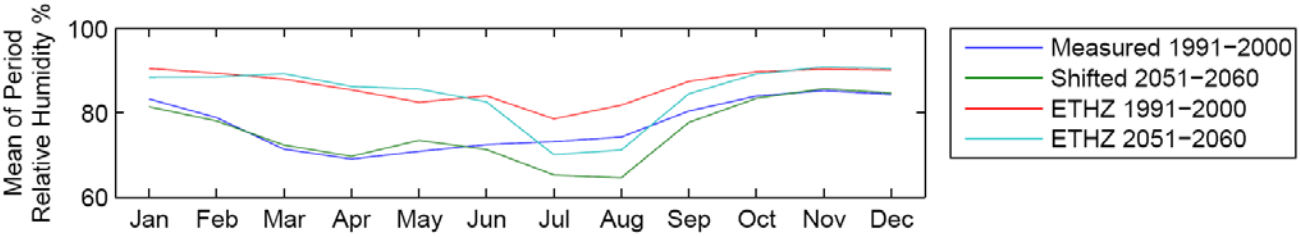


*Figure 7: Relative humidity, monthly mean of the 10 years period: Measured data (1991-2000); generated data (2051-2060); Again the “Shifted” data represents the most probable scenario, based on ENSEMBLES yearly data and ETHZ monthly distribution.*

# 3. Moisture damage risk assessment

The data on future climate and the material properties collected from historic building materials was used for detailed heat and moisture simulations and risk analysis. The evaluation of renovation strategies for historical buildings and the connected damage risk was analyzed with combined Heat, Air and Moisture (HAM) simulations. The software WUFI was mainly used for final results, also thanks to its extended historical material database. In the first step the influences of materials properties of the different layers of the external envelope have been studied with 1D simulations. The simulation of generic wall sections with many layers variations have shown that the type of external render plays an important role for the hygro-thermal behavior of the building envelope. If water is prevented from entering the structure, moisture content remains low as well as damage risk. But if the render absorbs water, moisture is transported through the structure and accumulates over time.

Especially if internal insulation is applied as retrofit solution, the moisture content of internal layers may be increased. It is essential to consider insulation moisture transport properties in order to reduce damage risks. 1-dimensional simulations of the general wall cross highlight increased saturation values in the innermost brick layer if a vapour tight insulation layer such as Vacuum Insulation Panels (VIP) is applied. In contrast, the introduction of a vapour open material like the newly developed aerogel render results in saturation values similar to the original situation (Fig.8).

The simulations using aerogel plaster and vacuum insulation show the following results:

- The use of outside renders, with different capillary absorption coefficients, results in very different moisture accumulation in the wall. This means that the rainwater take-up of the façade is most important and should be studied before any inside insulation retrofit;
- The choice of the internal insulation layer has great influence on the drying-out process to the inside. Vapour open insulating aerogel rendering does hardly change the drying process while the vapour tight VIP (Vacuum Insulation Panels) result in a much worse moisture behaviour of the outer wall;

- The moisture content of a brick wall without insulation or with aerogel rendering is low and causes no moisture damage. With VIP the moisture content increases over the years reaching a very high value which increases the risk for moisture damage in the outside wall (Fig. 8).
- Drying out to the inside may result in higher relative humidity values in layers sensitive to the mould growth such as gypsum board. Vapour open inside insulation should be used in combination with moisture insensitive finishes.

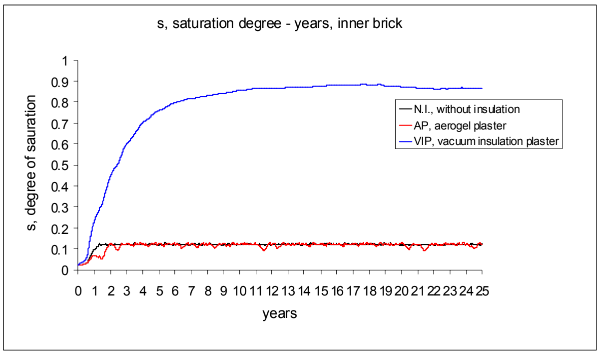


Figure 8: Degree of saturation in the inside brick without insulation, with aerogel render and Vacuum Insulation Panels (VIP).

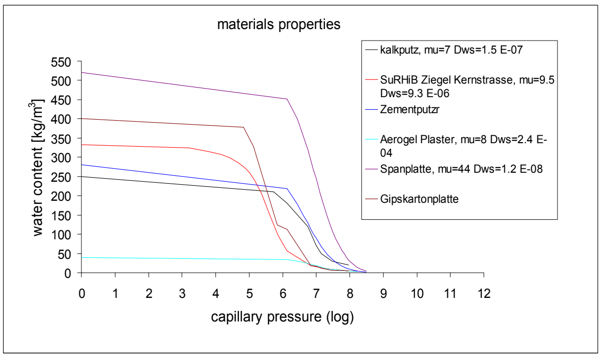


Figure 9: Simulated water content of different construction materials based on capillary pressure

The influence of internal finishes with vapour open and vapour tight paints was studied. The results show that a vapor open paint at the inside improves the drying of the masonry structure especially in the case of a very absorbing external render and if a capillary active insulation material is used, such as Calcium Silicate.

After analysis of the general wall cross section, the intersection between a wood beam and the building envelope was studied. Consequences of perfect and no-perfect contact between materials have been simulated, where no-perfect contact is modelled with an additional air layer between the wood and the masonry. The results show that the presence of the air gap decreases risky conditions in the wood beam head. Fig. 10 shows relative humidity and temperature (RH-T) conditions in the most outside part of the wood beam with an increasing air gap of 5 and 10 mm. The red curve gives the mould growth curve (isopleth), where for values above the curve mould growth occurs. We can note that an air gap of 10 mm (right picture) limits moisture accumulation after 5 years (dark dots) whereas perfect contact (left) and 5 mm air gap (middle) accumulate additional moisture.

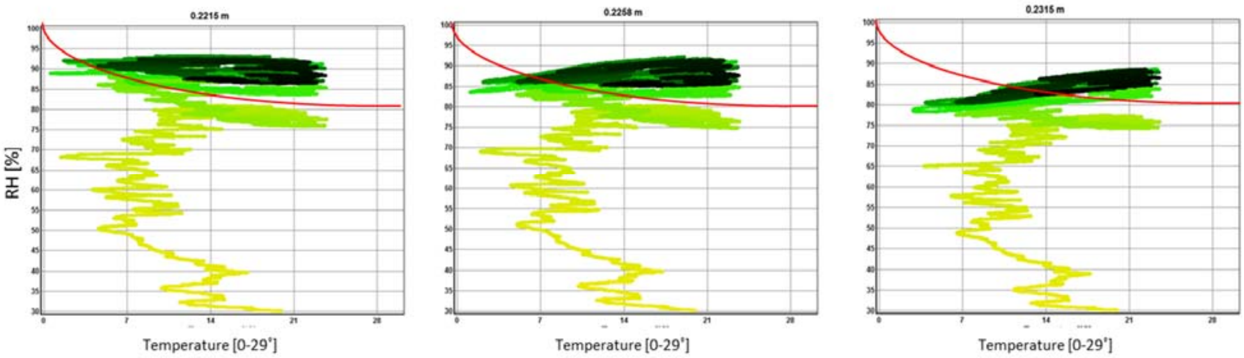


*Figure 10: Moisture accumulation over 5 years in the wood beam head in contact with the external masonry (left), with air gap of 5 mm (middle), and 10 mm (right). The red curve gives the the mould growth curve (isopleth), where for values above the curve mould growth occurs. The yellow curve gives the RH-T values for the first year, the light green curve the RH-T values for the second year and the dark colour curve the RH-T values for the 5th year after applying the aerogel rendering.*

Finally 2-dimensional simulations have been performed in order to study the behavior of the wood beam head. The analysis was done with the model of Viitanen [*Viitanen et al. "Towards modeling of decay risk of wooden materials", Eur. J. Wood Prod. (2010) 68: 303-313*], that evaluates mass loss of the wood structure due to the decay caused by rot fungi. The mass loss of the wood beam was evaluated in brick walls with different outside renders and internal insulations. Again the influence of the outermost rendering layers is highlighted. Water absorbing renders [$A_{cap}$higher than 0.015kg/m²s$^{0.5}$, such as Lime Cement Plaster] and the application of a vapor tight internal insulation like VIP create increased moisture contents and accelerate the wood rotting process. The presence of a vapor open internal insulation such as Aerogel Plaster and an external render with good rain protection decreases this risk substantially. Figure 11 shows the influence of the type of rendering (rain protection quality) on the wood rot of the beam head. It is clear that a good rain protection is essential for preventing moisture damage by wood rot at the beam head.

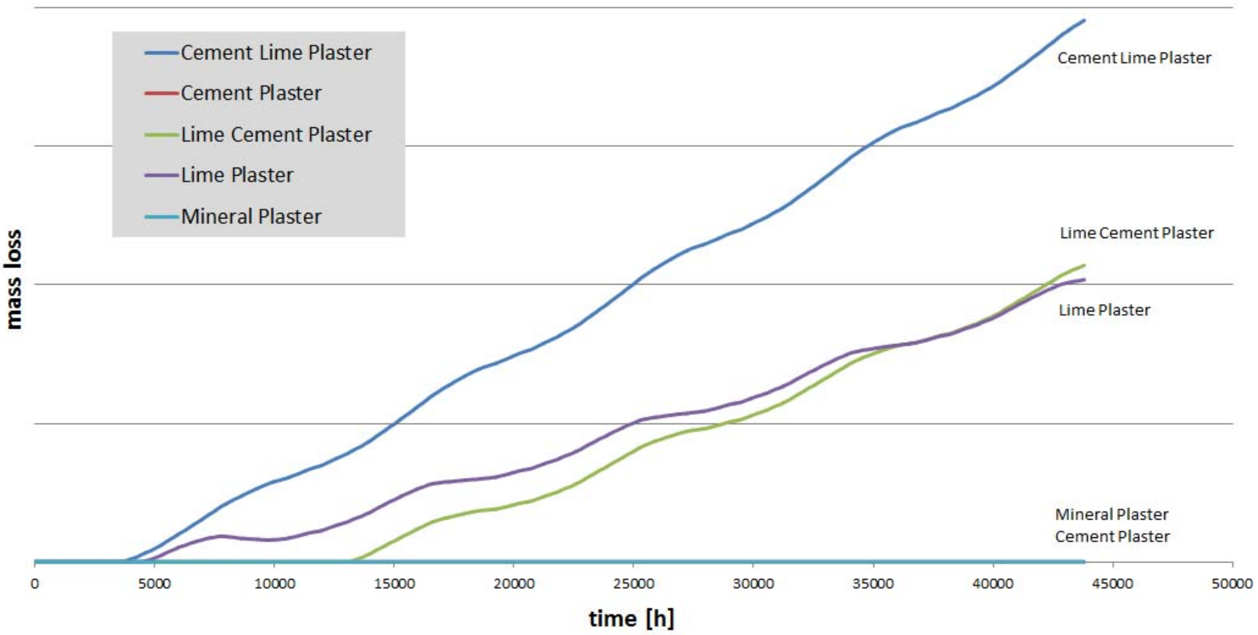


*Figure 11: Mass loss in wood due to wood rot as evaluated with Viitanen model in the wood beam in contact with the inside brick for different external renders. The inside insulation is the internal aerogel render. Start and inclination of the curves show how fast the rotting process will occur.*

In conclusion, we can assert that the choice of an external render with low water absorption is important if internal insulation is applied. If the external render has a low capillary absorption coefficient in the range 0.002-0.008 kg/m²s$^{0.5}$, conditions are safe even with vapor tight insulation materials. If moisture, such as wind driven rain, can be easier absorbed and transported by the external render ($A_{cap}$ in the range of 0.01-0.05 kg/m²s$^{0.5}$), the choice of a vapor open solution for internal insulation, such as aerogel rendering, and internal finishes is recommended in order to avoid structural damages. Vapor open inside insulation systems should however be chosen with care, since they should not lead to moisture damage due to interstitial condensation during winter time. Therefore vapor open inside insulation systems should show sufficient moisture buffering capacity, which has to be evaluated for the specific wall and building by simulation.

# 4. Highly insulating light weight plaster

The main technology developed in the project is a highly insulating rendering system that is based on aerogel granulates. Based on the simulation results a new type of a highly insulating rendering system was developed. The use of aerogel as main ingredient allowed the optimisation of the properties of the render especially for the renovation of historical buildings. The thermal conductivity of the render should be lower than that of traditional insulation materials in order to allow a reduction of the insulation thickness. At the same time, the render should be water repellent but still vapour open in order to allow the drying of wall structures.

The expected properties are: a mineral system with very low thermal conductivity (lower than traditional insulation materials), a high vapour permeability combined with a hydrophobic behaviour. These properties would be ideal for internal and external insulation of historic brick and stone walls.

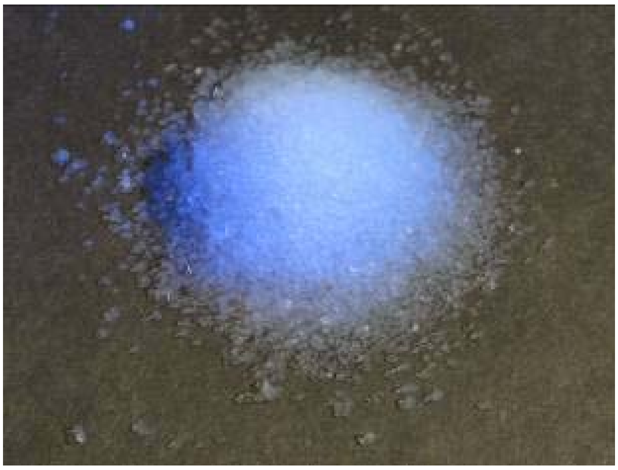


*Figure 12: About 85% nanoporous aerogel granulate is used as additive for the light weight plaster*

*Figure 13: Sample of the highly insulating rendering. The pores are filled with transparent nanoporous Aerogel*

Various recipes have been tested and optimized. The final laboratory samples achieved a thermal resistance of 25 mW/(m·K) what was 5 mW lower than originally expected. The first rendering samples that were produced at Empa achieved a thermal insulation that was three times better than available rendering systems on the market.

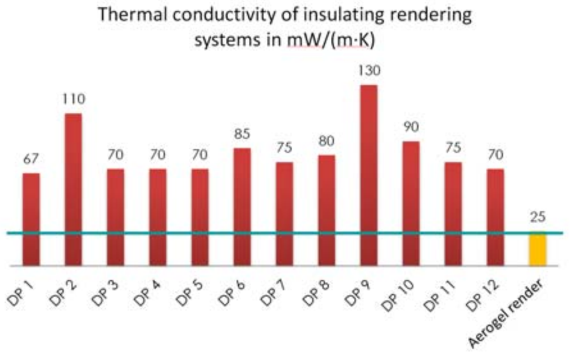


*Figure 14: Thermal conductivity of aerogel render in comparison with 12 insulating renders available on the Swiss construction market.*

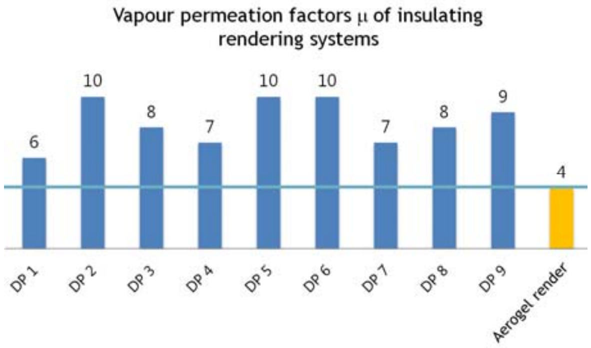


*Figure 15: Vapour permeation factors $\mu$ of aerogel render in comparison with 12 insulating renders available on the Swiss construction market.*

However, large size spray tests done by the industrial development partner showed that highly insulating aerogel particles are fragile and partially destroyed by the high pressure and shear forces in the spraying pumps. The recipe and mixing processes had to be improved in order to allow spraying application of the rendering. At the same time the thermal conductivity, the vapour permeation, the avoidance of cracking and the spraying process was optimized. An optimised mixture was found that can be applied by spraying machines and that guarantees a thermal conductivity of 29 mW/(m·K). The solution found is being patented.

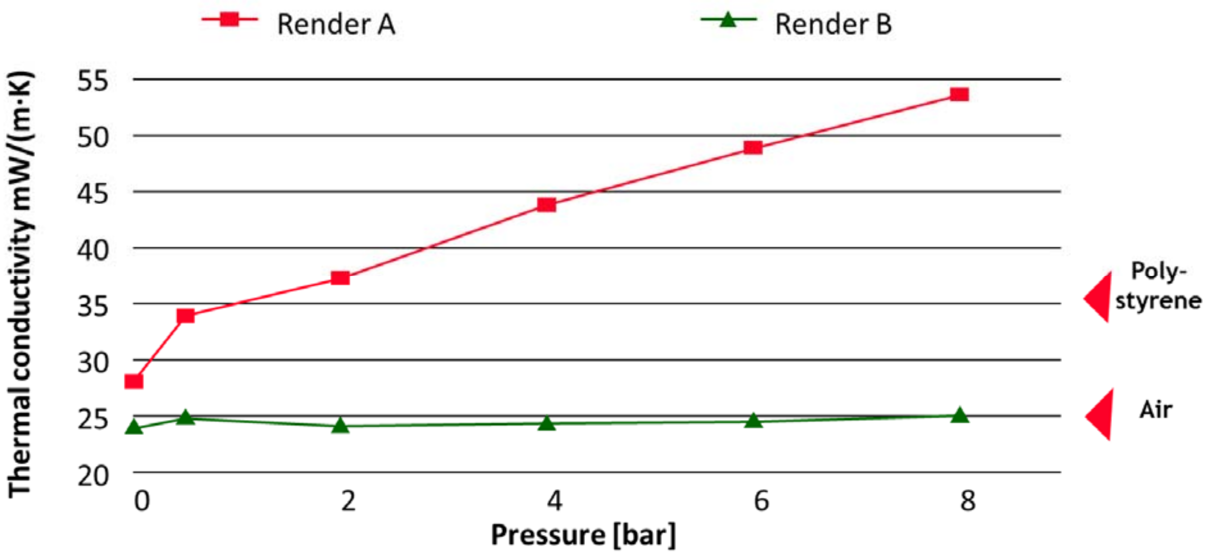


*Figure 16: High pressures of approx. 8 bars can press free water into the aerogel pores. If this happens, the thermal conductivity will increase rapidly (mixture A). The optimised rendering mixture B can avoid this problem.*

A historical timber frame construction has being built at Empa for long term testing of the insulating render under real climatic conditions (Fig. 17). The test building allows testing of various wall constructions (insulating rendering, moisture buffering rendering, combinations and a calcium silicate insulation as reference). The measurements are still on-going. It is planned to record the thermo-hygric data for a time period of 2 - 3 years.

*Figure 17: Retrofitted historical timber frame test wall for long term testing under real climatic conditions*

During 2012 three pilot applications in Winterthur, Sissach, and Dübendorf were successfully realized. All three buildings are historical buildings that required a careful renovation of the façades. Data loggers for temperature and relative humidity were installed and are now continuously monitored by Empa. This new and efficient way to renovate historic buildings was presented during a media conference end of 2012 and its market introduction was announced. The aerogel rendering is distributed from January 2013 under the name “Fixit F 222” on the Swiss market. A European distribution is planned as soon as sufficient long term experience is available.

*Figure 18: Renovation of an old row house in Winterthur: spraying and equalizing of aerogel render (left), aerogel render before application of finishing render*

*Figure 19: Historical building dating from the 14th century that was renovated in Sissach (BL) with aerogel render in close corporation with the monument preservation authorities, before renovation and after renovation with approx. 6 cm aerogel rendering*

# 5. Moisture buffering system

In parallel to the aerogel rendering development, also new types of moisture buffering materials were investigated. The rendering and boards developed in collaboration with an industrial partner are highly water absorbing and capillary active. They avoid moisture accumulation at critical areas in the construction. Free water is rapidly absorbed, distributed and evaporated. The application of these hygroscopic products will improve the indoor climate and reduce the variations in indoor relative humidity, the risk of local condensation and mould growth. The moisture buffering capacity of the developed render and boards is much better than that of other available construction materials.

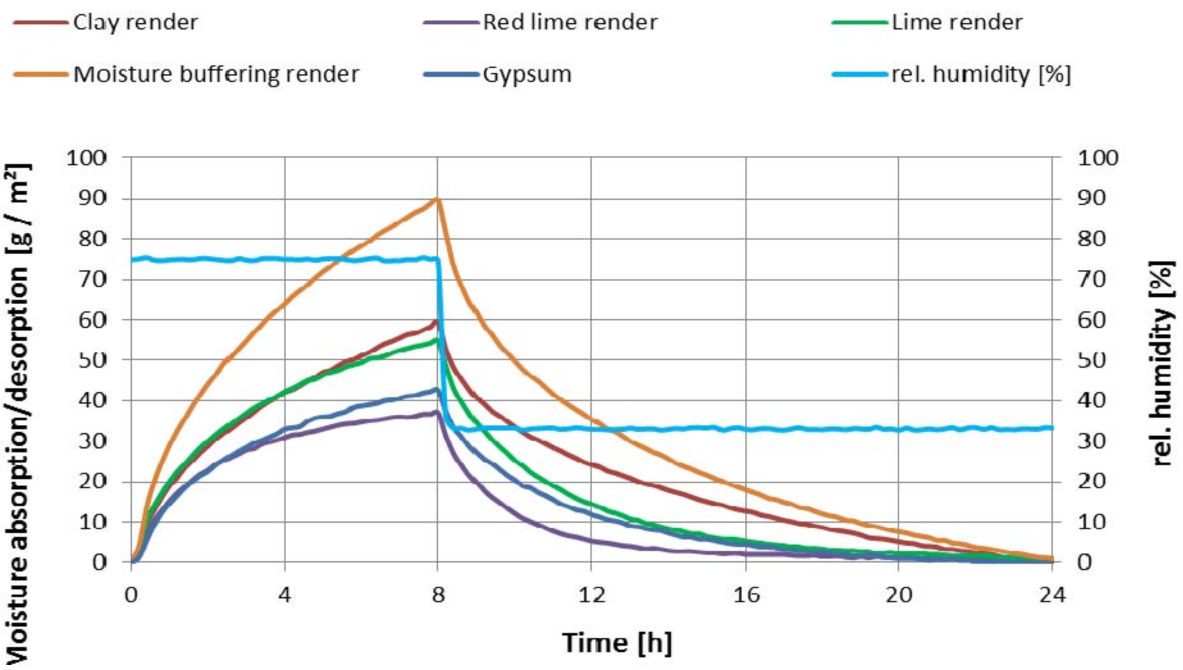


*Figure 20: Moisture absorption and desorption curves of various moisture responsive render types. The newly developed moisture buffering render increases the buffering capacity by about 50% compared with clay render as the second best choice.*

Successful test objects were carried out by the industry partner. The moisture buffering rendering will be distributed on the Swiss and German market from Spring 2013. A license agreement was signed by Empa and the industry partner.

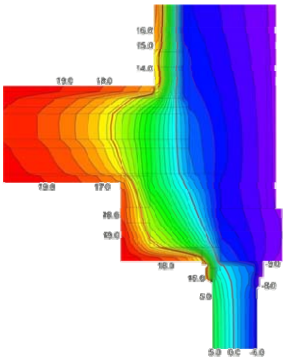
# 6. Internal insulation systems

Historical façades cannot always be insulated from outside. Internal insulation is often the only way for thermal improvement. However, internal insulation systems are more risky and can damage historical structures (see “Moisture damage risk assessment”). The SuRHiB project therefore also investigated new concepts and adapted rules for internal insulation.

The feasibility of internal insulation systems in historical buildings was studied at the Berner Fachhochschule in Biel (BFH-AHB) [5].

In a first step, different insulation systems were systematically investigated in order to identify potentials and risks by their internal implementation. The building construction materials which are typical for the time period from 1850 to 1920 were identified. The values of thermal properties like thermal conductivities were set. These numbers serve as input parameters for the calculation of the thermal bridges and for the simulation of the hygro-thermal behaviour of renovated walls with internal insulation systems.

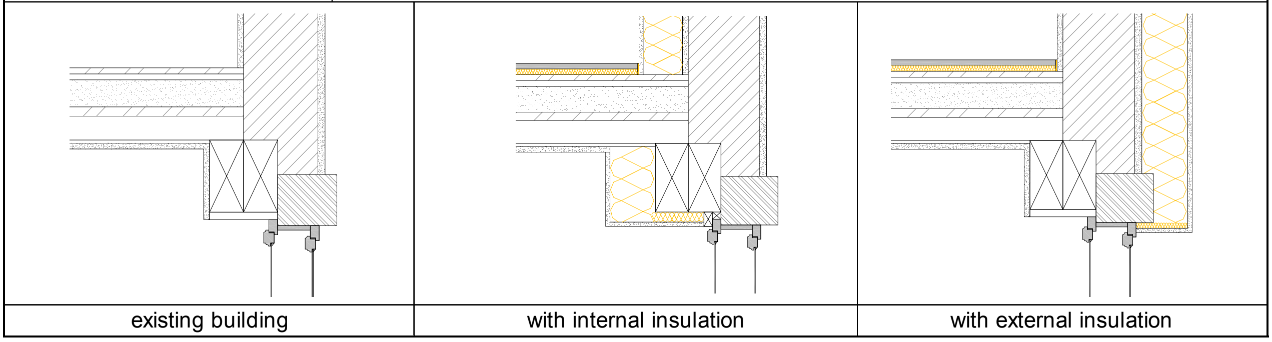
The calculation of the additional thermal losses of thermal bridges ($\Psi$-Values) and their thermal protection in terms of inner surface temperatures ($f_{Rsi}$-values) were done for exterior wall details with 27 variations per construction type. To complete the thermal bridge catalogue, details for windows, balcony connection, plinth, etc. were added. The calculations were done with the software Flixo. Figure 21 shows an example of the thermal bridge at the Architrave of a double window.



**5.3-5-250 architrave of a double window**

| **U-value of wall** | **Ψ-value** | $f_{Rsi}$-value | **comment** |
|---|---|---|---|
| W/m$^2$K | W/mK | [-] | |
| 2.00 | -0.14 | 0.63 | existing building |
| 0.20 | 0.30 | 0.80 | 160 mm external insulation, λ = 0.035 W/mK |
| 0.24 | 0.32 | 0.79 | 140 mm internal insulation, λ = 0.032 W/mK |
| 0.30 | 0.31 | 0.79 | 140 mm internal insulation, λ = 0.045 W/mK |
| 0.38 | 0.30 | 0.79 | 80 mm internal insulation, λ = 0.032 W/mK |
| 0.47 | 0.28 | 0.79 | 80 mm internal insulation, λ = 0.045 W/mK |

Notice: thickness of brick wall 250 mm



existing building | with internal insulation | with external insulation

*Figure 21: Thermal bridge at the architrave of a double window in existing and retrofitted historical buildings. The thermal properties of the thermal bridges were calculated for a brick wall thickness of 25 cm. The calculations are presented for three cases: the existing wall, the retrofitted wall with an internal thermal insulation and the retrofitted wall with an external thermal insulation.*

Wall constructions with internal insulation were simulated with the hygro-thermal calculation software WUFI. The simulation of the hygro-thermal behaviour of the renovated walls for cellulose fibre and wood fibre insulation were done using the WUFI® software. These simulations have been extended for insulation systems with diffusion resistant insulation like cellular glass and for mineral wool.

The influence of the span width of the hygro-thermal properties of historical brick types on the water content of the historical and retrofitted walls has been studied. *Figure 1* shows the comparison of the distribution of the water content of seven different brick types taken from the Masea data base for the last year of the simulation period. As a conclusion of these studies all simulations of the retrofitted walls have been done for the two brick types ZC and HWZ in order to see the interaction between the brick types and the internal insulation systems.

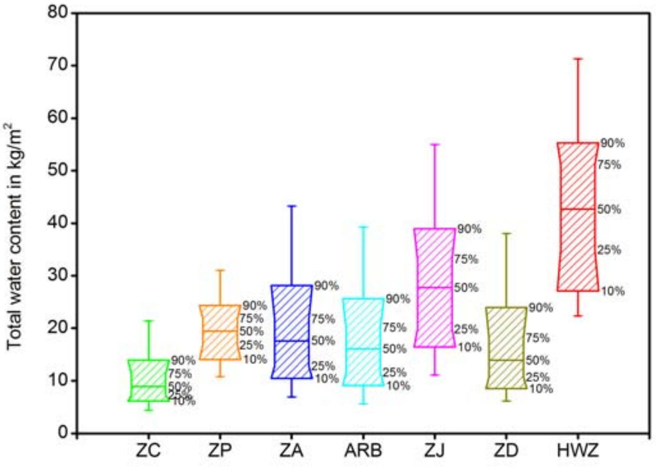


*Figure 12: Calculated distribution of the water content of the existing wall as a function of the brick type from ZC to HWC. The calculations are done for a thickness of the existing wall of 56 cm.*

Damage criteria were compiled for high moisture content in walls, for frost damage of the outer brick wall layer, and for condensation behind new insulation layers. The behaviour of two types of mineral wool (rock wool and glass wool), wood fibre and cellulose fibre was investigated.

In a second step, efficient and reliable solutions were developed that improve the energy performance of the building envelope and the thermal comfort, making sure that the construction won’t be damaged by moisture or by mold growth. These optimized solutions have been implemented in a catalogue, which not only includes the key figures for typical thermal bridges, but also provides a set of renovation measures with construction details. Beside this thermal bridge catalogue, a guideline document describes the influencing factors and boundary conditions to be considered for a successful implementation of an internal insulation.

Various new solutions for internal insulation systems have been developed by industry partners and tested by Empa. The systems include new types of capillary active EPS and PUR foam, multilayer aerogel mats (Fig. 23) and vacuum insulation panels. Three test walls were built, which allow the testing of the internal insulation systems in weathering chambers. The test walls include a linked internal wall section and two wood beam connections. Each wall was first measured at Empa`s weathering chamber without insulation (status before retrofit) and with internal insulation (status after retrofit). These test walls have been exposed to changing climatic conditions like rain, frost, and sunshine. Temperature and relative humidity profiles were measured across the wall.

In addition, the relevant material properties of 45 building materials have been determined. The data obtained from these measurements is used to validate and improve hygro-thermal simulation tools.

*Figure 23: Test wall for accelerated weathering tests at Empa. Two different aerogel insulation layers are applied. Wooden beam heads in the test wall represent the most critical detail for internal insulation.*

*Figure 24: The test walls have been exposed to rain, sun and frost cycles in Empa's weathering chambers and temperature (right, inside view of testing chamber) and relative humidity profiles were measured across the wall.*

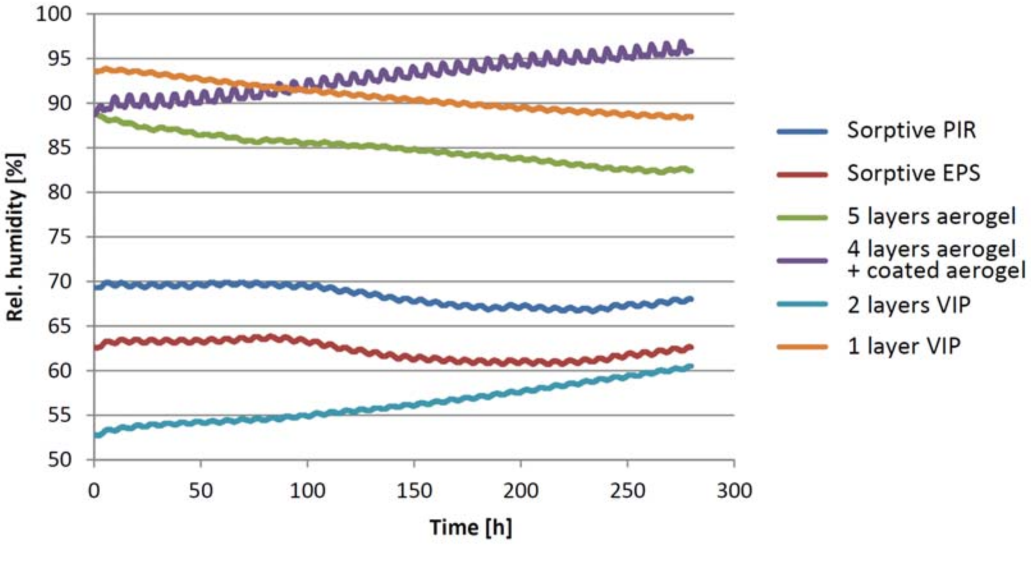


*Figure 25: Relative humidity measured during 300 h weathering test behind internal insulation layer of six different insulation systems*

The results of the weathering test are not yet conclusive. All systems – except one - show a trend towards a 75% equilibrium. The staring condition is mainly depending on the amount of water that was used during the application of the internal insulation. Only the aerogel insulation that was applied with a relatively vapour tight polymer coating shows an increasing relative humidity.

The tests included water spraying and sun drying in 3 hours cycles. Also frost cycles have been performed during a second weathering period. Probably, the testing period of 300 hours was too short for conclusive results. The test will be continued within a CTI project and carefully evaluated.

# 7. Internal climate control

In addition to systems simulation and development, also the potential of advanced room control strategies have been studied by EPFL-LESO-PB and Empa. The investigation should explain to what extent space heating, cooling and humidity control could avoid damage risk and save energy at the same time. Empa was focusing the work on the devices used for heating/cooling/ventilation, and LESO-PB/EPFL worked on how to control these building services in an optimal way.

The investigation [6] has clearly shown that the rain load on exposed façades is the dominant factor. A good rain protection is the best measure to prevent high moisture contents and moisture damages in these walls (Fig. 26). An outside render with low capillary absorption is important in order to reduce water absorption. In addition it was found that the aerogel insulation being vapour open is advantageous for the vapour transport and drying of the wall (Fig. 27). The results also show that a non-retrofitted wall is a considerable moisture source for the room. Applying an aerogel inside insulation substantially reduces the relative humidity in the room, especially in the case of a wall with limited rain protection.

On the other hand, the influence of space conditioning is rather limited. Optimised temperature and ventilation control can considerably reduce energy consumption but not significantly reduce moisture accumulation in the construction. An increase of the ventilation rate may help to dry-out the wall but it will increase heating energy consumption during winter. If applied, an efficient heat recovery system and a humidity control are recommended. Hence, at least for the residential cases considered, special or additional room conditioning is not required. However, special effects due to local thermal irregularities in external walls like window surroundings or wooden beam heads need probably special attention.

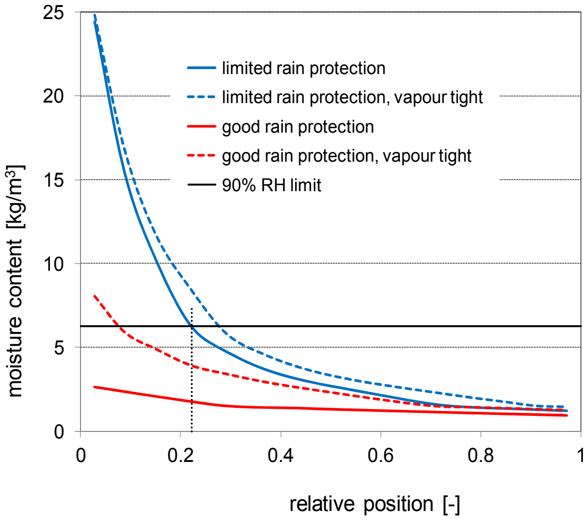


*Figure 26: Moisture content distribution in the aerogel insulation for limited and good rain protection. Comparison is made between vapour open and completely vapour tight inside finish to study the influence of inwards vapour flow on the moisture content distribution.*

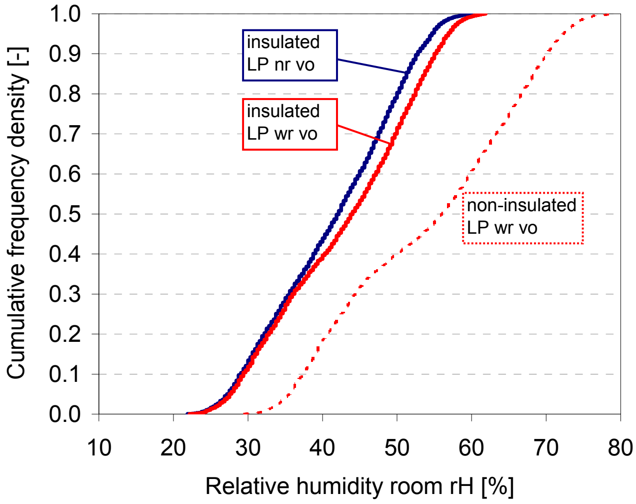


*Figure 27: Influence of inside insulation and rain on the cumulative frequency density of the room air relative humidity. Case with limited rain protection (LP) and vapour open inside finish (vo). Non-insulated wall is moisture source to the room, whereas with aerogel insulation is not: only small difference between variants with and without rain (wr / nr).*

# 8. Solar energy devices

Besides optimal building operation also the potential for renewable energy use was considered. If the energy savings potential of historical buildings is limited, the possibilities for covering the energy demand by solar energy should be considered. The technical implementation of solar energy – thermal or PV – is normally not the main problem. Much more critical is the architectural integration of these elements in a historical and therefore sensitive environment. Because solar energy systems could become standard during the next years, it is important to define what is needed to prevent an inharmonious development of such applications.

The investigation done by SUPSI concentrated therefore in a first step on the development of architectural guidelines for the integration of active solar technologies (photovoltaic and solar thermal) in buildings and specifically in historical constructions [7].

The criteria focussed mainly on the location and on the geometry of the solar collection area. These criteria can consequently be considered as the objective elements to take into account when planning where to install the solar thermal collectors and/or the photovoltaic modules, and how to shape them. However, the recommendations deal with more subjective aspects, especially concerning the visual characteristics of the installations, and are consequently conceived as a set of suggestions which can be helpful, but are not mandatory, when approaching the design and installation of a solar plant.

Finding good examples of solar technology integration is currently quite challenging. In fact in Switzerland it is still uncommon to use solar panels on buildings of a certain value. However, there are a couple of initiatives, specifically in Germany and England, which focus on applying or integrating photovoltaic modules on historical churches.

Regarding the technology, at the current state of art, finding examples of good photovoltaic integration is easier than finding cases of solar thermal integration. This is, as a matter of fact, because there is a greater choice of products suitable for the integration into buildings.

*Figure 28: Large PV installation on the Nervi Audience Hall of Vatican City*

*Figure 29: Good solar integration in an historical context is often a challenging task and creates extra costs: Substation of Electricité de France (EDF) built in 1929 and converted into an "Industrial Hotel" for start-up companies – 123 kWp [7]*

The second part was dealing with the opportunities for solar energy. A procedure for solar energy integration in historical buildings with different roof shapes is proposed (Fig. 30). Because solar energy systems could become standard during the next years, it is important to define what is needed to prevent an inharmonious development of such applications. Several buildings located in and near-by the historical centre of

Bellinzona were analysed. The buildings that are most suitable for solar installations proved to be flat roof buildings that were built around 1970. On these kind of buildings it is possible to install the panels both horizontally, in order to camouflage the installation (the orientation is irrelevant), or tilted, in order to optimize the energy production. The least suitable objects are the ones which feature strong architectural and historical characteristics (Headquarters of the Government and Parliament of Ticino and Banca Stato Headquarters). The roofs of these buildings are often occupied by a series of protruding objects such as chimney, dormers or additional volumes which can shade more or less relevantly the covering surface.

| | | skillion | gable | pyramidal hip | simple hip | mansard | monitor | sawtooth | flat | facade | annex construction | decentralized plant |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| CRITERIA | coplanarity | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟥 | 🟥 | 🟩 | 🟩 |
| | respect of the lines | 🟩 | 🟩 | 🟥 | 🟨 | 🟨 | 🟩 | 🟨 | 🟥 | 🟩 | 🟩 | 🟩 |
| | shape | 🟩 | 🟩 | 🟥 | 🟨 | 🟨 | 🟩 | 🟨 | 🟥 | 🟩 | 🟩 | 🟩 |
| | grouping | 🟩 | 🟩 | 🟥 | 🟨 | 🟨 | 🟩 | 🟨 | 🟥 | 🟩 | 🟩 | 🟩 |
| | accuracy | 🟨 | 🟨 | 🟨 | 🟨 | 🟨 | 🟨 | 🟨 | 🟨 | 🟨 | 🟨 | 🟨 |
| | visibility | 🟨 | 🟨 | 🟨 | 🟨 | 🟨 | 🟨 | 🟨 | 🟨 | 🟨 | 🟨 | 🟨 |
| RECOMMENDATIONS | cover the construction surface | 🟩 | 🟩 | 🟥 | 🟨 | 🟨 | 🟨 | 🟨 | 🟥 | 🟨 | 🟩 | 🟩 |
| | multifunctionality | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟥 | 🟥 | 🟥 | 🟥 | 🟥 |
| | application | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟥 | 🟥 | 🟩 | 🟩 |
| | aesthetics | 🟨 | 🟨 | 🟨 | 🟨 | 🟨 | 🟨 | 🟨 | 🟨 | 🟨 | 🟨 | 🟨 |
| | sizing | 🟨 | 🟨 | 🟨 | 🟨 | 🟨 | 🟨 | 🟨 | 🟨 | 🟨 | 🟨 | 🟨 |

*Figure 30: Summary table of feasibility criteria for solar collector installations. The criteria and recommendations which need to be fulfilled may vary depending on the typology of the building and the characteristics of the building surface where the solar installation is foreseen. Green: fulfilled, yellow: careful planning required, red: critical.*

The opportunities and difficulties of solar applications are presented as a case study [8]. Several buildings located in and near-by the historical centre of Bellinzona were analysed. The buildings that are most suitable for solar installations proved to be flat roof buildings that were built around 1970. On these kind of buildings it is possible to install the panels both horizontally, in order to camouflage the installation (the orientation is irrelevant), or tilted, in order to optimize the energy production. The least suitable objects are the ones which feature strong architectural and historical characteristics (Headquarters of the Government and Parliament of Ticino and Banca Stato Headquarters). The roofs of these buildings are often occupied by a series of protruding objects such as chimney, dormers or additional volumes which can shade more or less relevantly the covering surface.

Products whose technical and esthetical characteristics allow a good building integration have been listed in the document “Determination of Solar Opportunities” [8]. Integrating solar technologies into historical buildings requires a fair balance of preservation and technical installation. In these circumstances some products are better suitable than others. The choice of the module/collector should consider size, shape and colour of the panel that should be similar to traditional building covering elements.

*Figure 31: Various products try to optimize the integration of PV modules in roofs with tile covering, from left: Panotron, Sunstyle, Giellenergy tile, Swiss tile, Solarcentury C21*

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