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Article

Comprehensive Energy Renovation of Two Danish Heritage Buildings within IEA SHC Task 59

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Abstract: Historic and heritage buildings present a significant challenge when it comes to reducing energy consumption to mitigate climate change. These buildings need careful renovation, and increasing their energy efficiency is often associated with a high level of complexity, because consideration for heritage values can often reduce and impede possibilities and sometimes even rule out certain improvements completely. Despite these issues, many such renovation projects have already been carried out, and therefore the IEA SHC Task 59 project (Renovating Historic Buildings Towards Zero Energy) in cooperation with Interreg Alpine Space ATLAS has developed a tool for sharing these best-practice examples—the HiBERAtlas (Historical Building Energy Retrofit Atlas). The Internet serves as a best-practice database for both individual energy efficiency measures and whole-building renovation projects. This paper presents two of the Danish projects featured in HiBERAtlas. The first project, Ryesgade 30, is a Copenhagen apartment building with a preservation-worthy period brick façade. The second project is the Osram Building, a listed Copenhagen office building from 1959 with a protected façade, which today acts as a culture centre. Both renovation projects achieved significant energy savings and consequently CO₂-emission reductions, and the indoor climate in both buildings have also improved significantly. Furthermore, a detailed analysis was carried out regarding possible window solutions and ventilation systems in Ryesgade 30, and for the Osram Building regarding daylighting technologies. This paper investigates the two renovation cases through the available measurement and calculation results before and after renovations and demonstrates that it is possible to reduce energy consumption significantly and at the same time improve the indoor climate without compromising the cultural values of buildings.



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Keywords: historic buildings; energy renovation; energy savings; HiBERAtlas; IEA Task 59; best-practice database; indoor climate; daylight; windows; ventilation

1. Introduction

The European building stock accounts for approx. 40% of the total energy consumption in Europe [1]. In order to reduce this and thereby mitigate climate change, there is a need for significantly increasing the energy efficiency of the existing building stock. In this respect, historic and cultural heritage buildings are special. They need careful renovation and restoration, and increasing their energy efficiency is often associated with a high level of complexity because consideration for heritage values can often reduce and impede possibilities and sometimes even rule out certain improvements completely. Lidelöw et al. carried out a literature review on energy efficiency measures for heritage buildings, which clearly underlines this fact [2].

Buda et al. [3] presented an approach to support decision makers in selecting relevant retrofit solutions. Their paper focuses on best practices for walls, windows, HVAC systems and solar thermal and PV technologies and, as a main result, the paper encourages decision makers to opt for specifically tailored energy retrofits to solve the conflict between conservation and energy performance requirements.

Harrestrup and Svendsen have investigated the use of internal insulation in a heritage building block with wooden beam construction and masonry brick walls as part of an energy renovation. The risk of mould growth in the wooden beams and in the interface between the insulation and the brick wall was evaluated, and it transpired that a 200 mm gap in the insulation can be a moisture-safe solution for some orientations. It is not recommended to apply internal insulation at thin walls towards north, and a 200 mm gap in the insulation results in increased heating consumption of 3 kWh/m²/yr. Energy-savings of 39–61% were obtained, which was strongly influenced by occupant behaviour [4,5].

Rieser et al. [6] provided a systematic approach to pair appropriate ventilation system solutions with historical buildings. The paper provided both a review and an overview of the interrelationships between heritage conservation and the need for ventilation in energy-efficient buildings, regarding building physics and indoor environmental quality.

Despite these issues, many renovation projects related to heritage buildings have already been carried out and therefore it makes sense to promote some of the best-practice examples that can serve as inspiration for, e.g., architects, building owners and people involved in heritage protection. To this end, the IEA SHC Task 59 project (Renovating Historic Buildings Towards Zero Energy) [7] and Interreg Alpine Space ATLAS [8] jointly developed a tool for sharing best-practice examples—the HiBERAtlas (Historical Building Energy Retrofit Atlas) [9]. The Internet can be used for sharing best-practice examples of both individual energy efficiency measures and whole-building renovation projects.

IEA SHC Task 59 can be viewed as being in connection with the EU project RiBuild (www.ribuild.eu accessed 10 September 2021) [10], which focused on the internal insulation of historic buildings. RiBuild began 1 January 2015 and ended 30 June 2020.

Grytli et al. presents an integrated analysis method in [11]. Energy improvement measures can destroy the historical and architectural values of existing buildings. From a broader environmental perspective, extensive energy efficiency measures may even lead to increased greenhouse gas emissions from demolition, waste production and transportation of new materials. The complexity of the consequences of energy-saving measures on existing buildings calls for more holistic methods when discussing solutions.

This paper presents two of the Danish projects featured in HiBERAtlas:

Ryesgade 30, a Copenhagen apartment building with a preservation-worthy period brick façade which featured internal insulation of facades and external insulation of the gable, new energy efficient windows, central mechanical ventilation with heat recovery, roof insulation and a roof-installed photovoltaic system, and established new attractive penthouse apartments with roof terraces overlooking Copenhagen. Due to the building's status as worthy of preservation, the renovation could not change the appearance of the facade. However, the municipality accepted that windows were replaced with new and energy efficient replicas of the old windows. A test apartment had demonstrated that this solution was the cheapest and most energy efficient.

In the initial phase of the project, a number of solutions were tested in this so-called “test apartment” and were measured and evaluated over a full heating season, e.g., different window solutions, different ventilation strategies, etc. After the renovation, measurements of the energy consumption were made and simulations were carried out using the whole-building energy simulation software IDA-ICE. Simulations were based on the renovation measures that were selected and implemented based on the experiences from the “test apartment”, which largely correspond to the originally projected solution.

The Osram Building, a listed Copenhagen office building from 1959 with a protected façade which featured insulation of the thermal envelope using alternative methods, energy saving lighting systems, solar thermal collectors, new energy efficient windows and improved use of daylighting and automatically controlled natural ventilation. Today the building acts as a culture centre. The renovation of the Osram Building was part of a strategic cooperation with a number of Danish enterprises for the purpose of mutual profiling on climate-friendly buildings and should therefore present a spearhead for possibilities and methods of renovating old industrial and commercial buildings that are worth preserving.

In order to achieve this, high ambitions were necessary. Prior to the renovation, in addition to focusing on the level of insulation, many detailed analyses of the daylight performance of the building were also made.

The main purpose of this paper is to demonstrate that it is possible to reduce energy consumption and at the same time improve the indoor climate without compromising the cultural values of buildings.

Both renovation projects achieved significant energy savings and consequently CO₂-emission reductions. The indoor climate in both buildings have also improved significantly; for the Osram Building, natural ventilation provides fresh air and helps to avoid high indoor temperatures, while new roof windows provide increased daylighting levels. In Ryesgade 30, the new windows and insulation of the façade have improved airtightness and thereby removed draughts and risks of condensation, while the new mechanical ventilation system provides fresh air.

2. Renovation Project Descriptions

2.1. Ryesgade 30

Ryesgade 30 is a very well-documented renovation case. It was part of a research-project lead by the Technical University of Denmark, and the renovation won the 2013 “RENOVER-prisen”, an award given to extraordinary renovation projects. For these reasons, most of the information given in this paper has already been published in papers, reports, etc.; however, most of it in Danish [12–14].

Ryesgade 30 is a multi-storey apartment building located in Copenhagen, Denmark. It was built in 1896 and has six floors with 32 apartments divided in three different stairwells (block A, B and C) and a total heated area of 2760 m². On the ground floor, the building has commercial premises. The building has an unheated basement and an unheated attic. Ryesgade 30 has a heritage value corresponding to Class 4 in the SAVE classification system [15], which means that the façade of the building cannot be changed (the period masonry with horizontal cornices and bands are protected). Figure 1 shows the façade of the building and Figure 2 shows a horizontal cross section of the apartment layout.

Before the renovation, the exterior walls were solid brick masonry with a thickness varying from 350–710 mm (1½–3 bricks). Windows had one pane of glass in a wooden frame, were very energy-inefficient and gave rise to cold draughts in the apartments. The horizontal division above the basement was uninsulated and the roof had 50 mm insulation. The building is heated by district heating and had natural ventilation through leaks in the building envelope and opening of the windows.

As mentioned, the Ryesgade 30 renovation was part of a research project, and therefore several different solutions were investigated regarding possible energy improvements. All pre-renovation measurements and tests are described in detail in [14].



Figure 1. Façade of Ryesgade 30 after renovation, including new roof and penthouse apartments. Ground floor has commercial premises.



Figure 2. Horizontal cross section showing the apartment layout of the building. Blue is stairwell A, red is stairwell B and green is stairwell C.

For the façade, internal insulation was tested in one apartment. This test involved measuring temperature and relative humidity behind the insulation and at two beam ends and measuring temperature behind insulation in window reveals. These tests showed that internal insulation was a viable solution and suggested that 40 mm insulation could be added to the walls and 20 mm to the reveals, and therefore this was chosen as the solution for the building.

For the windows, four different solutions were tested: three different variations of renovating the existing windows and one solution where windows were replaced with new replicas. The conclusion was that the new replicas had the best energy performance while also being the cheapest solution, and the Municipality of Copenhagen approved this choice for the full renovation.

For the ventilation, decentral balanced mechanical ventilation with heat recovery was tested in one apartment. Unfortunately, the test gave no unequivocal answers. However, all apartments were fitted with mechanical ventilation with heat recovery, but different systems were used in each stairwell: Stairwell A, traditional central system; Stairwell B, central demand controlled system; Stairwell C, decentral system. This way the three systems could be compared through detailed measurements.

For the floor over the basement, 100 mm insulation was added from beneath, and for the part of the masonry wall acting as fire protection (gable), 200 mm of mineral wool was added to the outside. Finally, photovoltaic panels were added to the roof. The photovoltaic system is expected to produce 8950 kWh per year, more or less covering the electricity consumption of the new ventilation systems.

In addition to the energy improvements, a series of general improvements were carried out during the renovation. New kitchens and bathrooms were installed, and all facades, the basement and stairwells were renovated. All installations were replaced, except for parts of the heating system. Four new penthouse apartments with individual roof terraces were added to the top of the building, which increased the heated floor area by 20% to 3310 m² and significantly increased the value of the building.

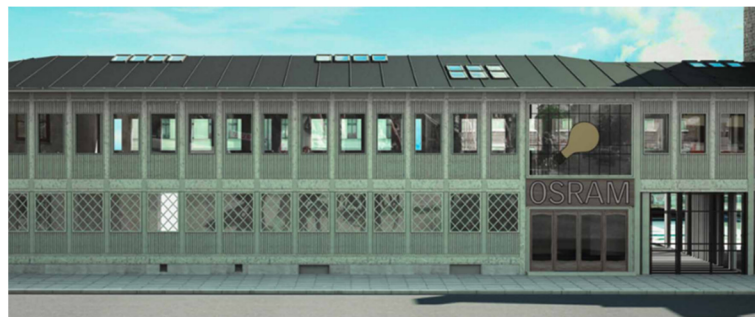
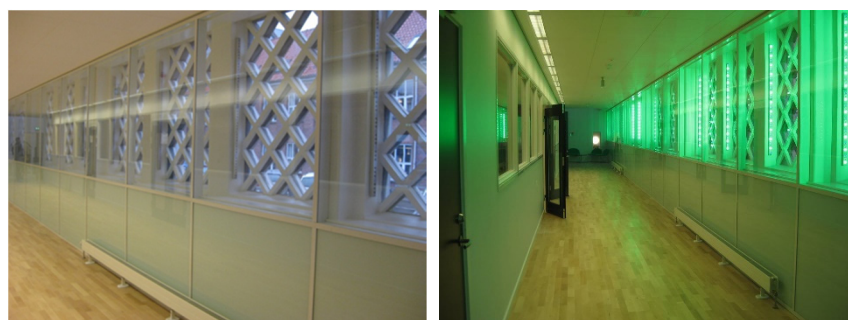
The energy improvements of Ryesgade 30 are summed up in Table 1.

Table 1. Energy improvements in Ryesgade 30 [12]. Calculated values.

Construction	U-Value (W/m ² K)	
	Before	After
Brick wall (mean)	1.40	0.37
Windows	4.20	0.89
Floor over basement	1.50	0.30
Roof	0.52	0.15
System		
Ventilation	Natural	Mechanical with heat recovery
Photovoltaics	None	80 m ²

2.2. The Osram Building

The Osram Building was built in 1953 as an industrial building. It was the first prefabricated house in Copenhagen, built as an office and warehouse for Nordisk Glødelampe Industri A/S. As part of a Neighbourhood Development Project in a former semi-industrial area of Copenhagen, the City of Copenhagen initiated an energy renovation of the cultural centre “OSRAM”. The facade of the building is listed. The building was renovated in 2009 (see Figures 3 and 4).

**Figure 3.** Façade facing the main street after renovation.**Figure 4.** Façade facing inside after renovation. LEDs, off (left) and on (right).

The objectives of the renovation were:

- To energy renovate a former industrial building, now in use as a culture centre, by utilizing daylight and combining mechanical and natural ventilation to improve the indoor climate;
- To minimize energy consumption by improving the thermal envelope and utilizing energy saving lighting;
- To minimize the resources required (and the CO₂-emissions) during both construction and upkeep.

Table 2 shows the U-values before and after renovation of the Osram Building. Before the renovation, the roof insulation was performed with mineral granules later supplemented with batts to a total thickness of 150 mm. The centre of the roof had a footbridge with an extra 100 mm insulation. To the deck above the gate (to the right of the entrance), 120 mm concrete and 380 mm insulation was added on the outside.

Table 2. Osram Building. U-values before/after renovation. Calculated values.

Construction	U-Value (W/m ² K)	
	Before	After
Roof	0.20–0.30	0.20–0.30
Deck above the gate	3.90	0.09
Walls	1.65–3.73	0.09
Windows	2.70–5.90	1.20
Doors	1.00–5.20	1.00–1.50
Slab floor and basement deck	0.57–2.37	0.57–2.37

The walls were a mix of prefabricated concrete elements, concrete columns and uninsulated brick walls, and 380 mm insulation was added on the inside. The lower part of the back façade was insulated on the outside (see Figures 5 and 6).



Figure 5. Façade facing the garden before renovation. The façade was originally the division between the office area (existing) and the factory area (which was torn down many years ago). The façade is not protected.



Figure 6. Façade facing the garden after renovation.

The windows in the building ranged from single glass windows with different levels of sash to standard windows with two layers of glass. The main entrance door had a single layer of glass. The two other entrance doors to the building were relatively new. All windows were replaced by low energy windows with thin frames, except for the façade windows on the ground floor. Here, floor-to-ceiling glazing was added on the inside to preserve the expression of the façade. Skylights were installed in the roof.

Before renovation, half of the ground floor was a deck construction facing the building's grounds. It consisted of 120 mm concrete on 120 mm cinder. The remaining part faced the partially heated basement and consisted of 200 mm reinforced concrete. No insulation was added to the slab/deck, but 100 mm insulation was added to the outside of the foundation to reduce thermal bridge effects.

The original heating system was based on district heating using a steam supply. The heat distribution system was a single-pipe system. The new heating system is based on district heating using a hot water supply. The heat distribution system is a two-pipe system, and thermostat valves have been added to all radiators.

In addition to the existing windows, the renovated building has an added 24 m² of roof windows, 16 roof windows of 0.66 m × 1.40 m and 12 roof windows of 0.66 m × 1.18 m, to increase the amount of daylighting in the building. In the stairwell, the horizontal division was removed to allow for the daylight from the roof windows to penetrate all the way to the ground floor.

The original ventilation system was a simple mechanical exhaust system where air was removed from toilets and kitchens. In the renovated building, mechanical ventilation with heat recovery was installed, and this was supplemented by natural ventilation via the roof windows. The natural ventilation through the roof windows is controlled by electric motors and is based on the indoor climate.

Solar heating was added to the building to supplement the district heating from the hot water supply. Furthermore, decorative LED lighting has been added to the windowsills in the original façade windows of the building, making it possible to set the scene for any arrangement in the building as a cultural centre.

3. Calculated and Measured Energy Savings

3.1. Ryesgade 30

The data given in the following was taken from [13].

For Ryesgade 30, the heat consumption before the renovation was measured as 155.5 kWh/m² per year (average for 2007–2009). This was compared to the results of an IDA ICE [16] simulation model, which predicted the consumption as 151.6 kWh/m² per year based on an indoor temperature of 20 °C.

After the renovation, the consumption was measured as 83.0 kWh/m² (September 2013 to September 2014), and during the same period the photovoltaic system produced approx. 11,000 kWh, corresponding to 3.3 kWh/m² per year. The electricity production was approx. 20% higher than expected. The IDA ICE model had predicted a heat consumption of 60.6 kWh/m² per year, so the actual consumption was significantly higher than expected. Figure 7 shows the results of measurements and calculations.

One of the main reasons for not achieving the expected savings in heat consumption was the fact that the indoor temperature after the renovation was significantly higher than what is usually used in these types of calculations. The temperature was measured during the heating season of 2013–2014 in blocks A and B (20 different sensors in total), and the result showed an average indoor temperature of 22.5 °C.

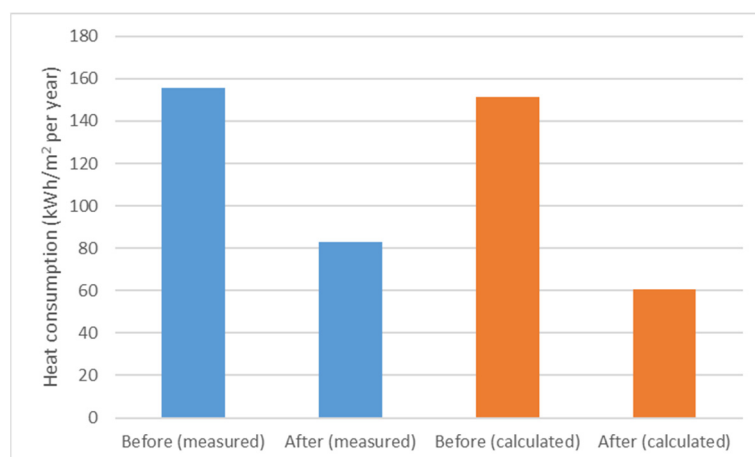


Figure 7. Measured and calculated heat consumption before and after renovation of Ryesgade 30.

If the IDA ICE calculation model is revised to take the actual indoor temperature into account, the expected heat consumption increases from 60.6 to 77.3 kWh/m² per year.

Another possible explanation for the difference between measured and calculated heat consumption is the infiltration and ventilation of the building. In the calculations, it was assumed that the heat recovery rate was 85% in average and that the infiltration was very low, i.e., 0.05 L/s per m². Parametric calculations with the calculation model show that, in particular, an underestimation of the infiltration rate can influence the heat consumption, and because the opening of windows and doors is part of the infiltration, this parameter is heavily dependent on user behaviour.

Unfortunately, for Ryesgade 30, no detailed economic data is readily available. However, in a test apartment, approximate prices were calculated as: windows EUR 4665 (one 3-pane, three 2-pane and two 1-pane), ventilation system EUR 5900, internal insulation EUR 6660 (approx. 25 m² total), consultancy, labour, etc., EUR 5240, i.e., totalling approx. EUR 22,465 per apartment. This does not cover the cost of external insulation of the gable, the new penthouse apartments and photovoltaics.

3.2. The Osram Building

The primary energy use (including the primary energy factors) was calculated as 288 kWh/m² per year before renovation and 153 kWh/m² per year after, i.e., a total reduction of 47%. The electricity consumption before renovation was 45 kWh/m² per year, and after renovation it was 40 kWh/m² per year. The heating consumption decreased from 158 to 37 kWh/m² per year, and the domestic hot water from 18 to 16 kWh/m² per year.

The energy savings for the building is 9500 and 181,000 kWh per year for electricity and heating, respectively. The savings from the façade insulation and the windows account for 150,000 kWh per year, and the rest are from the heating and lighting systems, the controls and the solar panels (see Figure 8).

The Osram Building was renovated in 2009, so the prices, etc., are from this time period. The total investment for the renovation project was approximately EUR 564,000, of which EUR 212,000 was directly aimed at energy reductions. The expected total savings per year were EUR 13,000, i.e., resulting in a simple payback time for the entire project of approximately 18 years. Energy savings should result in CO₂-reductions of approximately 29 tons per year for the entire renovation.

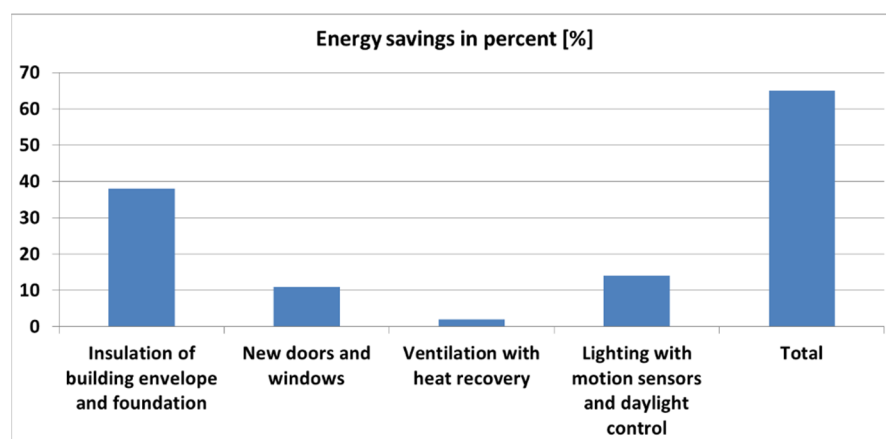


Figure 8. Energy savings in percent divided into the different parts of the renovation.

4. Detailed Analysis

Both renovation projects involved a deeper analysis of individual renovation solutions, including their impact on, e.g., energy efficiency, indoor climate, moisture safety and the overall economy of the projects. Thereby, these detailed investigations made by the consultants helped to determine and select the best solutions for the projects.

4.1. Ryesgade 30—Ventilation Systems and Window Solutions

Ryesgade 30 was part of a research project which facilitated the use of very detailed investigations of a wide range of renovation measures, including, e.g., detailed in-situ measurements on the performance of different solutions for the internal insulation of exterior walls. The following describes the solutions that were considered and tested regarding the ventilation systems and window solutions for Ryesgade 30. Before the renovation, Ryesgade 30 had natural ventilation (through leaks in the building envelope and open windows). Three different solutions were installed in the building, as explained below.

In stairwell A, a traditional central mechanical ventilation system is located in the basement. The system has a fresh air intake at the basement level by the stairwell. Existing chimneys are used to carry air exhaust ducts from bathrooms and kitchens to the basement. In addition, existing chimneys are used for the return of used air over the roof. Fresh air is fed to apartments via new ducts. The supplied air to the remaining rooms has a constant air flow of 140 m³/h. Exhaust air from the bathrooms is constant at 20 m³/h when the relative humidity is below 55%, and 54 m³/h when it exceeds 55%. In the kitchen, the exhaust is generally at 72 m³/h, but rises to 144 m³/h when the cooker hood is activated.

In stairwell B, the central ventilation system unit is located in the basement. The system has a fresh air intake at the basement level by the stairwell. There are new main channels for both fresh air and extraction from apartments. Existing chimneys are used for the return of used air over the roof. The use of existing chimneys for the return of used air over the roof has proven problematic in stairway B. Although the chimney is sealed very thoroughly in connection with the renovation, one apartment experienced minor odour nuisances due to leakage of exhaust air. This clearly shows that the use of existing chimneys for the return of air can be risky. The ventilation system is demand-controlled based on CO₂, relative humidity and temperature. In addition, there is a user panel to regulate specific user needs. When no one is present in the apartment, the municipality has granted dispensation to deviate from the requirements in the building regulations, making it possible to reduce the air change to 22 m³/h.

In stairwell C, the ventilation systems are decentral systems at the apartment level. This means that each apartment has its own unit. The systems are wall-hung and placed in cupboards in the kitchen. Each system has a fresh air intake via the facade. On one

side of the building, returns are managed over the roof and, on the other side, returns go through the end wall. The ventilation systems do not need management (user intervention to control extraction levels); however, the system can be forced to maximum capacity by activating the cooker hood. The plant has a capacity limited of approx. 180 m³/h.

Extensive user surveys have been conducted to get feedback on the ventilation systems in the three stairwells. Overall, the residents are satisfied with the ventilation in Ryesgade 30; however, there are still problems that need to be addressed, which are, primarily:

- Ventilation noise (valves and unit noise);
- The cooker hood works poorly;
- Residents do not understand how the ventilation (and the system) works.

Regarding operational reliability, the decentralized facilities in stairwell C have proven to be clearly better than the central systems in stairwells A and B. The decentralized systems have also proven to be significantly easier to troubleshoot, because a given error is only related to a single apartment and unit, and service work will only affect a single lease at a time.

The electricity consumption of the three different ventilation systems has been measured from August 2013 to the end of August 2014. However, the systems have not had a stable operation throughout the period, but since January 2014, the operation seems to be relatively stable. Based on the measurements, the expected annual electricity consumption can be determined as shown in Table 3.

Table 3. Annual electricity consumption for mechanical ventilation systems.

	Stairwell A	Stairwell B	Stairwell C
Electricity consumption (kWh/m ²)	9.9	2.4	2.3

As can be seen, there is a large electricity consumption for ventilation in stairwell A, which is partially due to the fact that the heat recovery units are located in the basement and return happens over the roof. This results in large pressure losses, as the air has to travel a long way. In stairwell B, the air must travel the same distance, but in the demand-controlled ventilation, the air volume is significantly lower and the electricity consumption is therefore also lower than in the plant with constant air flow.

Regarding the windows, four different solutions were tested. The windows were ready for replacement, but the municipality wanted to preserve the windows for reasons of principle. The solution with a coupled frame, however, met resistance from tenants who did not want windows that opened inward because the solution is cumbersome and limits the use of the windowsill. Furthermore, this solution also proved problematic because the existing window frames had significant moisture damage.

The first solution was a 1 + 1 + 1 solution, which includes an extra layer of glass fitted on the outside of the existing window so that there is one plain of glass and two individual energy glasses. The distance between the two individual energy glasses in the test window was 23 mm. This should be at least 20 mm, because smaller cavities significantly reduces the insulating ability.

The second solution was a 1 + 1 solution, i.e., corresponding to a refurbishment of the existing solution, with installation of an extension energy glass on the inside in a separate frame.

The third solution was a 1 + 1 solution, where 4 mm tempered glass was mounted directly on the inside of the window frame using patented special hinges and fittings. The advantage of this special solution is that the air tightness does not depend on the behaviour of the residents and that the windowsill does not need to be cleared when opening the window.

The fourth solution was a complete replacement of the window with a replica of the original. This was a 1 + 2 solution with two energy glasses (inner and outer panes) and energy panes with “warm” pane edge and krypton filling.

Table 4 shows the energy data for the various window solutions. The overall energy efficiency is expressed as the energy balance, E_{ref} , for the windows, i.e., the solar heat gains minus the heat loss over a heating season (based on Danish weather data). E_{ref} is a relevant term to compare the performance of different windows during the heating season and is based on reference dimensions of 1.23×1.48 m.

Table 4. Energy data for the investigated window solutions.

#	Window Solution	U (W/m ² K)	g [-]	E_{ref} (kWh/m ² per Year)	LT (-)
1	1 + 1 + 1 secondary glazing (refurb.)	1.08	0.37	−26	0.37
2	1 + 1 secondary glazing (refurb.)	1.62	0.44	−58	0.45
3	1 + 1 coupled frame (refurb.)	1.76	0.44	−73	0.45
4	1 + 2 coupled frame (new)	1.13	0.29	−45	0.39

The prices for the different solutions were also compared and are specified in Table 5.

Table 5. Cost for different window solutions in EUR (2013 prices).

#	Description	Price	Total 2-Pane window	Total 3-Pane Window
1	Repair and paint	467		
	Secondary glazing 2 layers	1163	1630	
2	Repair and paint	467		
	Secondary glazing 1 layer	1100	1567	
3	Repair and paint	467		
	Coupled frame 1 + 1	1679	2146	
4	New window 2 + 1	1193		
	Installation	380		1573

Comparing the window solutions in Table 4, it is clear that solutions 1 and 4 perform best regarding energy efficiency. The U-values are quite low and, due to the three layers of glass in both solutions, the g-value is also quite low. Light transmittances are similar for all solutions. The energy balance (E_{ref}) is negative in general, which means that transmission losses outweigh solar gains. From Table 5, it is evident that solution 4 is the cheapest. Please note that for solution 4 the prices are for a 3-pane window as opposed to the other solutions that are for 2-pane windows, i.e., the price for solution 4 is valid for a window that is approximately 50% larger than the others.

Based on this information, it was concluded that solution 4 was the cheapest, while at the same time being highly energy efficient. The solution was also very user friendly, i.e., all the glass was fitted in one frame, and they had been manufactured to replicate, from the outside, the originals. Project participants presented these findings to the municipality who gave permission to replace the windows of the building. The new windows are shown in Figure 9.



(a)



(b)

Figure 9. New windows from the inside (left) and from the outside (right). Source: Leif Rönby.

4.2. The Osram Building—Daylighting Technologies

In connection with the renovation, a new and more appropriate layout of the ground floor was considered. There are two main entrances; the new one from the courtyard includes a gate in the access/escape route. In the large entrance hall, penetration of the ceiling creates double room height in part of the room. From the entrance hall, a passage along the street facade gives access to two large flex rooms and three smaller activity rooms. The large rooms open towards the garden, and the activity rooms have glazing placed high in the walls, allowing “used” daylight to enter, while prohibiting seeing in from the other rooms. Lavatories and a bathroom are located in the eastern corner. In the southern corner, there is an office facing the garden and new window slits to the gateway (see Figure 10).

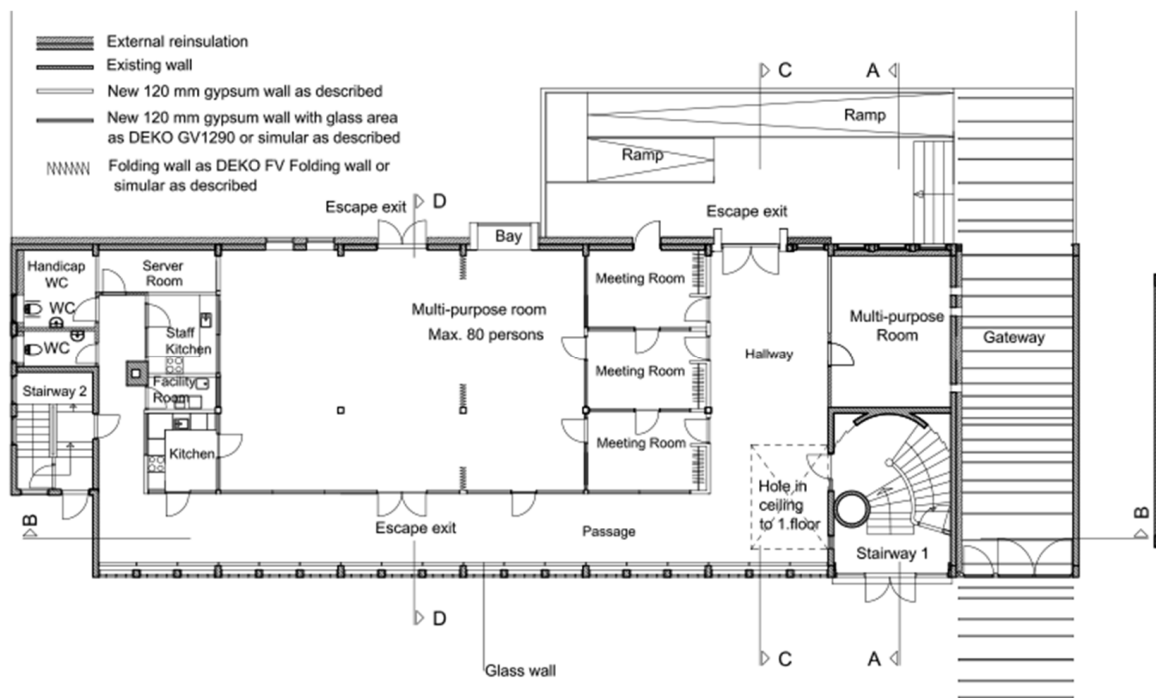


Figure 10. Ground floor layout.

This layout of the building presents several advantages. The passage along the facade is a partly heated room, which will reduce the heat loss through the facade. As this facade symbolizes the house architectonically, it would be hard to insulate it without damaging the present expression. By replacing insulation with a room-high double wall of energy efficient glass, the architectonic expression will be maintained and the heat loss reduced, though somewhat less than by traditional, external insulation.

On the first floor, the present layout is maintained, apart from the area around the front stairs where it is now possible to look towards and communicate with the entrance hall and the passage downstairs.

On the first floor, there is access to the great hall and the three offices making up the primary rooms on this floor. Roof windows are installed above the great hall, the offices and the hallway and are fitted with electrically-operated sun screening and opening devices for natural ventilation (see Figure 11).

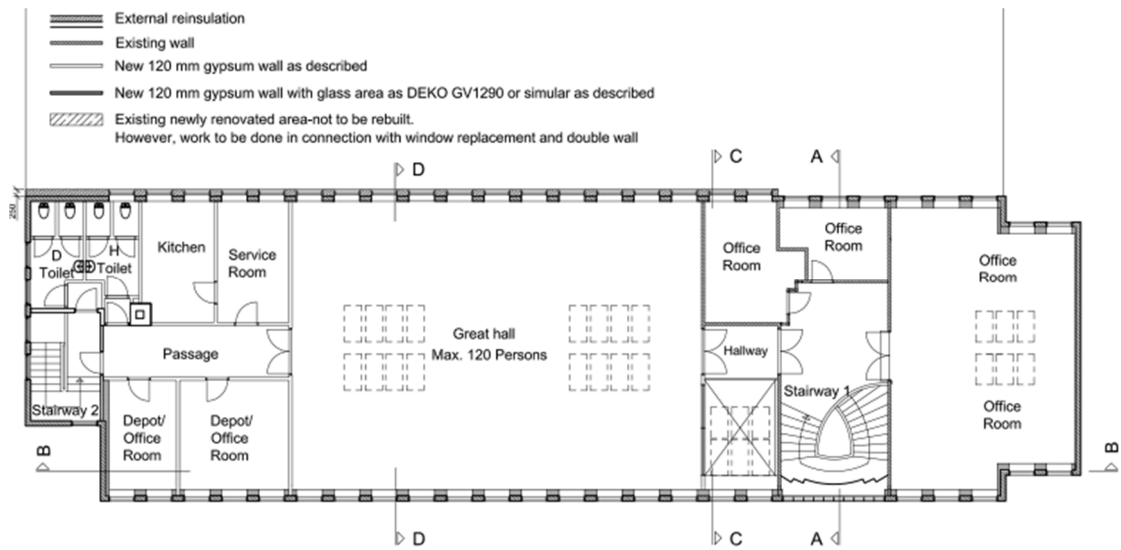


Figure 11. First floor layout.

The roof windows in the hallway will contribute significantly to creating a lighter and more inviting entrance area and to make the passage more open. The windows in the great hall are relatively small, but the roof windows will improve the daylight conditions considerably in this area. At the same time, the roof windows will contribute actively to adjusting the indoor climate when a large amount of people are gathered for activities such as folk dancing, lectures or private parties.

The daylighting performance of the Osram Building has been specified using the daylight factor (DF) as a performance indicator. The calculations of the daylight given below were performed by Velux [17]. Please note that there are slight differences between the drawings used in the daylight calculations (Figures 12 and 13) and the drawings of the first-floor layout in Figure 11. The daylight calculations were performed at an early stage of the design phase.

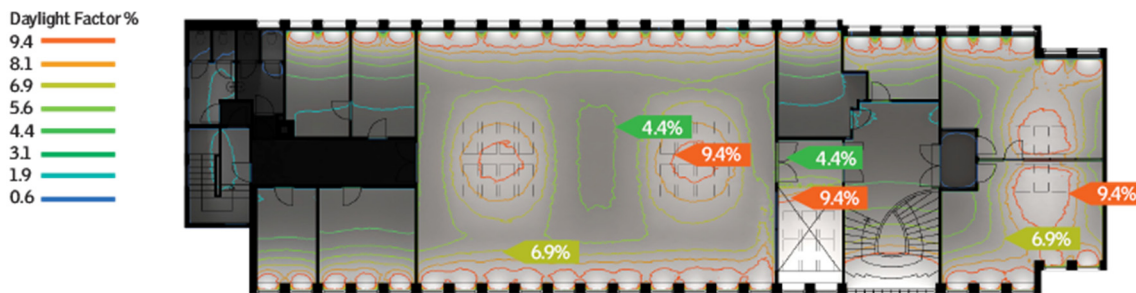


Figure 12. First floor with roof windows.

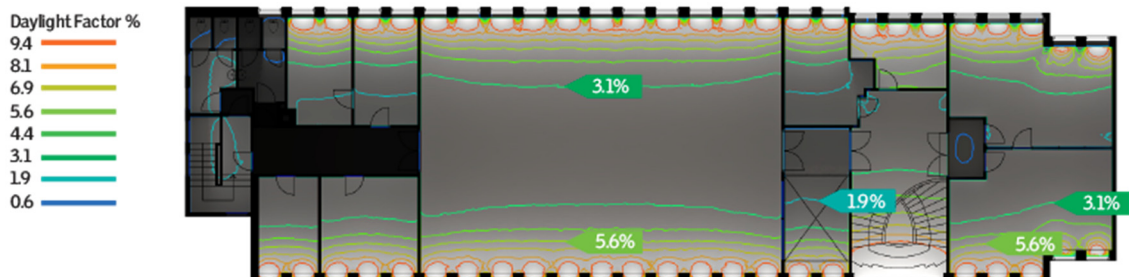


Figure 13. First floor without roof windows.

The daylight factor is a common and easy to use measure for the available amount of daylight in a room. It expresses the percentage of daylight available in the interiors, on a work plane, compared to the amount of daylight available at the exterior of the building under known overcast sky conditions. The higher the DF, the more daylight is available in the room. Rooms with an average DF of 2% or more are considered daylit. A room will appear strongly daylit when the average DF is above 5%.

The daylight factor analysis has been performed using computer simulations of Radiance. Figures 12–15 show the daylight factor levels obtained on each floor for two different variants evaluating the impact of the installed roof windows on the finalized design.

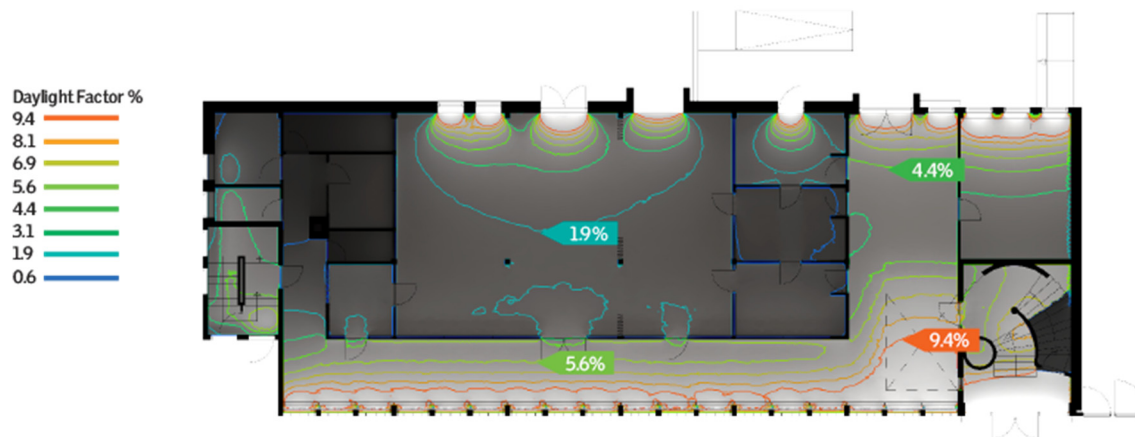


Figure 14. Ground floor with roof windows.

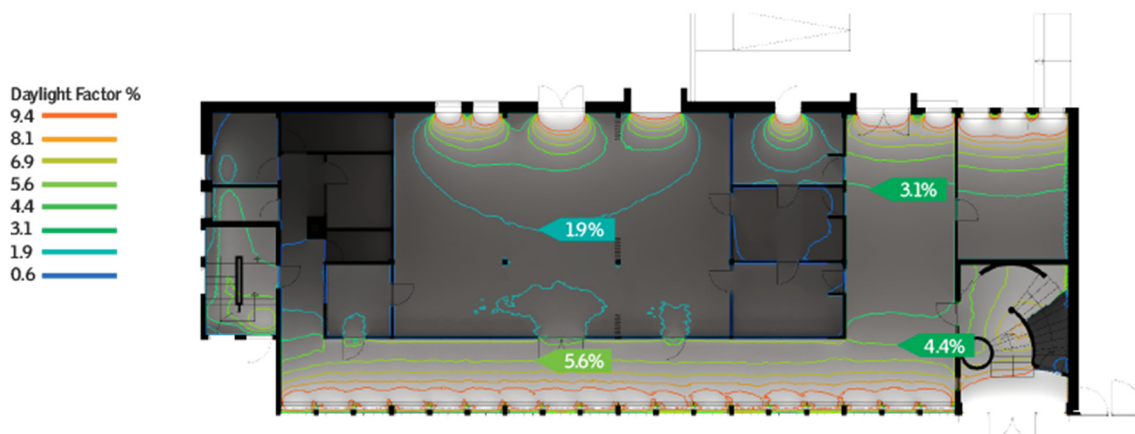


Figure 15. Ground floor without roof windows.

The comparison of results shows the positive effects of adding roof windows on the daylight conditions of the first floor. The roof windows deliver high levels of daylight in the centre part of the main room, as well as in the meeting rooms at the end of the building. The use of roof windows also contributes to raising the daylight levels on the lower floor via a new opening in the existing structural floor situated below the skylights in the hallway, as shown in Figure 16.



Figure 16. The roof lights provide a significant amount of daylight to the first floor in the building.

5. Lessons Learned

5.1. Ryesgade 30

Since the renovation, extensive user surveys have been conducted to receive feedback from tenants on ventilation system performance and indoor climate improvements in general. The residents of Ryesgade 30 are generally very satisfied with the renovation and, in particular, are experiencing major comfort improvements. Areas within the apartments that previously could not be used due to cold and draughts can now be fully utilized.

Another important lesson learned from the Ryesgade 30 project—and from a number of other renovation projects—is that individual user behaviour is reflected in the achieved energy savings. The Ryesgade project clearly demonstrates that there are still major challenges in getting residents in newly renovated homes to use the homes appropriately in relation to energy consumption.

The three different ventilation solutions installed in Ryesgade have shown that there are some issues with noise, and also that the decentral solution is more appropriate in apartment buildings because repairs and servicing will only influence one tenant at a time. For the windows, it is clear that refurbishment which includes energy improvement is more expensive than new windows, and it can be difficult to achieve the same energy standards. However, replacing the windows will often require permission from relevant authorities.

Finally, it is also worth noting that the Ryesgade project is also a clear-cut example of the so-called rebound effect. Before the renovation, it was expensive to heat the apartments so residents maintained a temperature close to 20 °C on average, but after the renovation, when the heat demand is significantly reduced, indoor temperature is increased and part of the energy savings are converted to comfort.

5.2. The Osram Building

The indoor climate in the Osram Building was improved significantly by the renovation process. Daylight levels in the building were raised by introducing roof windows that would help raise daylight levels on both the first floor and on the ground floor.

The indoor air quality has also been improved significantly by the introduction of a combined mechanical and natural ventilation system. The mechanical system has heat recovery and ventilates the building during winter. When indoor temperatures or CO₂-levels in the building get too high, the automatic natural ventilation will be initiated (opening of roof windows). Furthermore, the lighting systems in the building have also been improved with motion sensors and automatic control, so that the electric lighting is dependent on daylight levels in the building.

The insulation of the building envelope, along with the installation of new windows, increased the thermal comfort in the building. The increase in airtightness and the removal of cold surfaces (windows and walls) have helped to remove draught and general discomfort in the building. Another important aspect of the building renovation is the improved layout of the building and the flexibility with which the building can now be used. The improved indoor climate has also helped to make the entire building area useable.

6. Conclusions

This paper has documented two Danish renovation projects where buildings with heritage significance have undergone major renovation. Both buildings had protected facades, which restricted the possibilities of the renovations. However, both cases demonstrate that it is possible to achieve significant reductions in energy consumption and improve indoor climate in historic buildings. It has been demonstrated how careful planning, detailed analysis and innovative strategies can lead to very successful renovation projects, even in heritage buildings with constraints in terms of possible renovation measures.

For Ryesgade 30, the new photovoltaic system produces electricity that more or less covers the electricity use of the new ventilation systems, and therefore electricity use before and after renovation are approximately the same. This case demonstrated that, quite often, the expected reductions in heat consumption were not fulfilled. Originally, calculations pointed to expected savings of approximately 56%, but it turned out that savings were a little below 50%. The main reason for this was that residents exchanged some of the savings for improved comfort, i.e., by increasing the indoor temperature. This is also known as the rebound effect.

In the Osram Building, an innovative solution was used for insulating the façade of the building where a combination of internal insulation and a floor-to-ceiling layer of glass was added. This meant that the measure is not readily visible from the outside, but the insulation of the façade is a significant improvement, particularly to the indoor climate in the building because it has removed drafts. The electricity consumption is reduced by 11%, primarily due to replacing existing lighting systems with motion sensors and daylight controls, and the heat consumption is reduced by 77% as a result of an overall insulation of the thermal envelope and new windows.

The two Danish projects only had minor restrictions regarding possible renovation measures, but still demonstrate how careful planning, detailed analysis and innovative strategies can lead to very successful renovation projects where reduction of energy use and improvement of indoor climate go hand in hand.

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References

1. European Commission. Energy, Transport and Environment Indicators. Eurostat. 2012. Available online: <https://ec.europa.eu/eurostat/web/products-statistical-books/-/KS-DK-20-001> (accessed on 10 September 2021).
2. Lidelöw, S.; Örn, T.; Luciani, A.; Rizzo, A. Energy-efficiency measures for heritage buildings: A literature review. *Sustain. Cities Soc.* **2019**, *45*, 231–242. [CrossRef]
3. Buda, A.; Hansen, E.J.d.P.; Rieser, A.; Giancola, E.; Pracchi, V.N.; Mauri, S.; Marincioni, V.; Gori, V.; Fouseki, K.; López, C.S.P.; et al. Conservation-Compatible Retrofit Solutions in Historic Buildings: An Integrated Approach. *Sustainability* **2021**, *13*, 2927. [CrossRef]
4. Harrestrup, M.; Svendsen, S. Full-scale test of an old heritage multi-storey building undergoing energy retrofitting with focus on internal insulation and moisture. *Build. Environ.* **2015**, *85*, 123–133. [CrossRef]
5. Harrestrup, M.; Svendsen, S. Internal insulation applied in heritage multi-storey buildings with wooden beams embedded in solid masonry brick façades. *Build. Environ.* **2016**, *99*, 59–72. [CrossRef]
6. Rieser, A.; Pfluger, R.; Troi, A.; Herrera-Avellanosa, D.; Thomsen, K.E.; Rose, J.; Arsan, Z.D.; Akkurt, G.G.; Kopeinig, G.; Guyot, G.; et al. Integration of Energy-Efficient Ventilation Systems in Historic Buildings—Review and Proposal of a Systematic Intervention Approach. *Sustainability* **2021**, *13*, 2325. [CrossRef]
7. IEA-SHC Task 59. Deep Renovation of Historic Buildings towards Lowest Possible Energy Demand and CO2 Emission (NZEB). Available online: <http://task59.iea-shc.org/> (accessed on 10 September 2021).
8. ATLAS Interreg Alpine Space Project. Advanced Tools for Low-Carbon, High Value Development of Historic Architecture in the Alpine Space. Available online: <https://www.alpine-space.eu/projects/atlas/en/home> (accessed on 10 September 2021).
9. HiBERAtlas (Historic Buildings Energy Regrofit-Atlas). Available online: <https://www.hiberatlas.com/en/welcome-1.html> (accessed on 10 September 2021).
10. RiBuild. Available online: www.ribuild.eu (accessed on 10 September 2021).
11. Grytli, E.; Kværness, L.; Rokseth, L.; Ygre, K. The impact of energy improvement measures on heritage buildings. *J. Archit. Conserv.* **2012**, *18*, 89–106. [CrossRef]
12. Harrestrup, M.; Svendsen, S.; Papadopoulos, A.M. Energy retrofitting of an old multi-storey building with heritage value. A case study in Copenhagen with full-scale measurements. *Nord. Symp. Build. Phys.* **2014**. Available online: https://www.researchgate.net/publication/269820942_Full-scale_test_of_an_old_heritage_multi-storey_building_undergoing_energy_retrofitting_with_focus_on_internal_insulation_and_moisture (accessed on 5 December 2014).
13. Pedersen, L.R.; Harrestrup, M.; Kildemoes, T.; Mikkelsen, S.E.; Minzari, M.G. Resultater og Erfaringer fra Energirenovering af Ryesgade 30. Project Report Unpublished. 2014. Available online: <https://docplayer.dk/295190-Resultater-og-erfaringer-fra-energirenovering-af-ryesgade-30.html> (accessed on 21 September 2021).
14. Pedersen, L.R.; Tommerup, H.; Kildemoes, T.; Mikkelsen, S.E.; Christensen, M.G. Erfaringer fra Prøvelejlighed Ryesgade 30C 1tv. Project Report Unpublished. 2011. Available online: <https://www.innobyg.dk/media/43493/erfaringer%20fra%20pr%C3%B8velejlighed%20ryesgade%2030c%201tv%20-%20juni%202011.pdf> (accessed on 10 September 2021).
15. SAVE. Kortlægning og Registrering af Bymiljøers og Bygningers Bevaringsværdi Ministry of Culture. Cultural Heritage Board. 2011. Available online: https://slks.dk/fileadmin/user_upload/kulturarv/fysisk_planlaegning/dokumenter/SAVE_vejledning.pdf (accessed on 27 September 2021).
16. Equa Simulation AB. User Manual, IDA Indoor Climate and Energy, Version 4.5. 2014. Available online: <http://www.equaonline.com/iceuser/pdf/ICE45eng.pdf> (accessed on 6 January 2021).
17. Available online: https://velcdn.azureedge.net/-/media/marketing/master/professional/cases/osram%20culture%20centre%20-%20denmark/120543-01_r544-007.pdf (accessed on 10 September 2021).