Passive cooling strategies for better comfort during weather extremes – adapting the existing building stock in German cities to future climatic conditions

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Abstract

Global warming is causing a shift in climate zones. Focusing on German cities, this phenomenon is leading to changes in precipitation patterns, strengths of storms and to the duration and intensity of heat and cold periods. A large part of the built environment in German cities is not prepared to handle these changes. This paper aims to explore how existing buildings can be upgraded to incorporate passive cooling strategies to ensure comfortable indoor environments even during extremely hot periods. The study highlights the pressing need for such strategies and underscores their effectiveness. The techniques include thermal massing, cross ventilation, improved insulation, better window sealing and the use of suitable building materials. First, the passive enhancements are analyzed independently and subsequently evaluated in terms of their collective efficacy. Through a prioritisation process, it is demonstrated that the most efficient outcomes are achieved by relatively simple and cost-effective approaches. To substantiate the viability of the proposed interventions, a case study serves as demonstration and provides an illustrative model for retrofitting efforts aimed at adapting the existing building stock to the challenges which are expected to be posed by climate change. The findings underscore the feasibility of passive cooling strategies.

Keywords - Climate change adaptation, retrofitting, building performance analysis, passive cooling

1. Introduction – An unprepared built environment

In the context of German cities, a crucial aspect to underscore is the unpreparedness of the prevailing architectural inventory. The majority of structures lack appropriate provisions to mitigate the effects of these impending alterations. Remarkably, the absence of air conditioning systems or other cooling mechanisms exacerbates the situation. Given the projected surge in summer heat waves over the upcoming decades, a considerable number of residential and commercial spaces are projected to experience conditions that significantly exceed the bounds of comfort. The installation of conventional air conditioning units might appear as a quick fix, but it is neither a sustainable nor a feasible solution. Instead, a pressing requirement arises for the implementation of passive systems that offer a more environmentally conscious and enduring remedy. This emphasizes the necessity for innovative approaches that can ensure habitable indoor environments amidst the forthcoming climatic challenges.

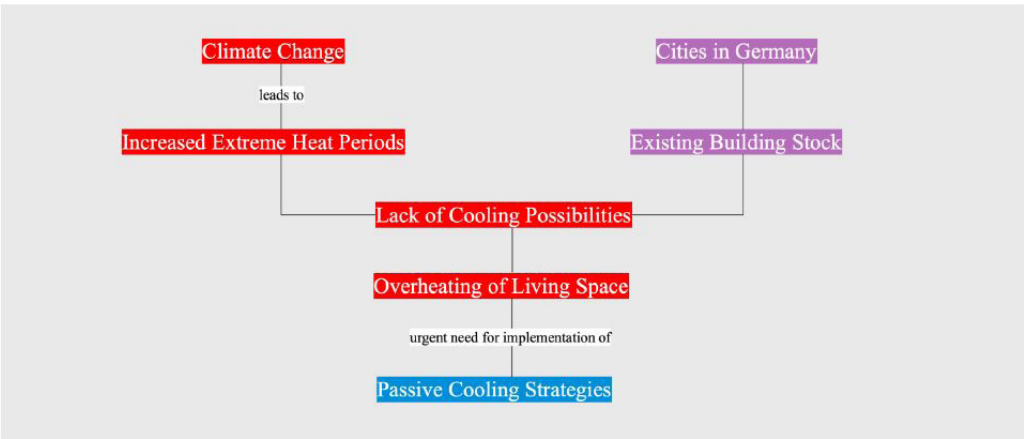

Figure 1: German cities are facing an increase in urban overheating and are not prepared enough

1.1 Rationale

This paper aims to investigate the retrofitting of existing building stock to enhance interior comfort during periods of summer heat. The investigation will focus on the implementation of passive cooling strategies to achieve this objective. Beyond the theoretical elucidation and advancement of principles for integrating passive cooling techniques into preexisting building frameworks, the paper also underscores practical implementation. This is achieved through a detailed showcase of how a selection of these principles is being effectively applied within the context of a retrofitting project involving two multifamily residences dating back to the early 20th century in Potsdam, Germany. The primary objective of this study is to investigate the potential retrofitting options that can ameliorate indoor comfort conditions amidst episodes of heightened summer temperatures. By investigating the deployment of passive cooling methodologies, the paper seeks to address the critical issue of maintaining pleasant interior environments without relying on energy-intensive solutions such as conventional air conditioning. In addition to this conceptual inquiry, the paper pivots towards a hands-on illustration, taking form through the retrofitting undertaking in Potsdam. The project in question encompasses a duo of multifamily dwellings, structures that carry the architectural heritage of the early 20th century. This case study encapsulates a practical application of the theoretical insights presented earlier in the paper. The overarching significance of this paper rests in its dual approach: it bridges the gap between theoretical considerations and practical execution, fostering a comprehensive understanding of how passive cooling strategies can be integrated into historical building contexts. This synthesis of theory and application stands as a testament to the viability and potential of passive cooling as a sustainable means to navigate the challenges posed by rising temperatures in our built environment.

1.2 Passive cooling

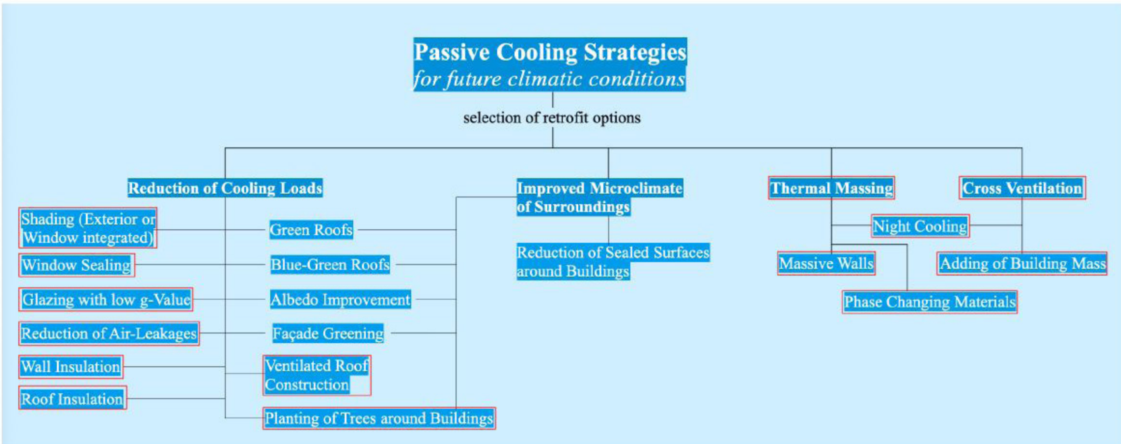

Figure 2: General passive cooling strategies which might be applicable to retrofits of existing buildings in Germany with selected strategies for the case study buildings in Potsdam indicated in red

Passive cooling strategies have been extensively used in hotter climate zones for thousands of years, but their application in northern European countries is gaining relevance only recently, generated by the new summerly weather conditions (heat waves) which are expected to significantly increase in the future. The implementation of passive cooling strategies on a broad scale in conventional existing buildings in German cities, may provide a solution to solve the problem of summer overheating many of the buildings will be faced to in the future, especially rooftop and upper floor apartments exposed to the sun. Already today every year many (mostly elderly) people die due to urban overheating during heat waves and the lack of the possibility to cool their apartments. Therefore, adaptation strategies for the transformation of existing buildings on a broad scale are urgently needed (Shukla et al., 2022). The implementation of passive cooling principles would provide an ideal solution for these buildings.

1.3 The case study buildings

Villa Moritz and Villa Michaelis in Potsdam represent typical examples of brick constructed buildings of the Wilhelminian era as they have been built in large quantities in German cities between 1890 and 1918. The two villas are multifamily residential houses with four floors and a total area of 1336 square meters of living space containing 17 apartments in total (Villa Moritz: seven apartments, Villa Michaelis: ten apartments). The buildings' heritage protection status allows only interventions which are not modifying the buildings' exterior appearance. This is a special challenge typical for the retrofits of many historical buildings in Germany. The improvement potential in many other, non heritage protected buildings is even higher, since measures like external sun protection, façade greening etc. might be applied additionally.

Figure 3: Villa Moritz in Potsdam

Figure 4: Villa Michaelis in Potsdam

1.4 Summer temperatures today and predicted for 2070

As the figure below shows, overheating of indoor spaces in typical German dwellings occurs only during the three summerly months of June, July and August. Within the graphic we can see the periods when indoor temperatures are rising above the comfort zone. In many multi-storey residential buildings, the rooftop apartments are most exposed to the sun and therefore most affected. For this reason, the values of the present case study are focused on the rooftop apartments.

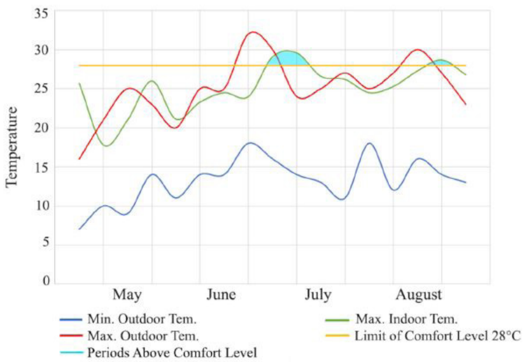

Figure 5: Outdoor and indoor temperatures during the summer months from May to August 2022 (before retrofit works have started) with illustration of indoor temperatures of the rooftop apartments above comfort level (ClimateStudio simulation)

In the case study buildings' rooftop apartments, it has been measured that around 262 hours on 17 days are beyond the comfort zone. The measurements have taken place during summer 2022 and, even though the values of 2022 have been typical and are not very different to previous years, an alignment to previous years still needs to be done to obtain a mean value for a more precise evaluation. With future climate change and rising temperatures, however, it is expected that the heat waves in Germany will significantly increase (Shukla et al., 2022).

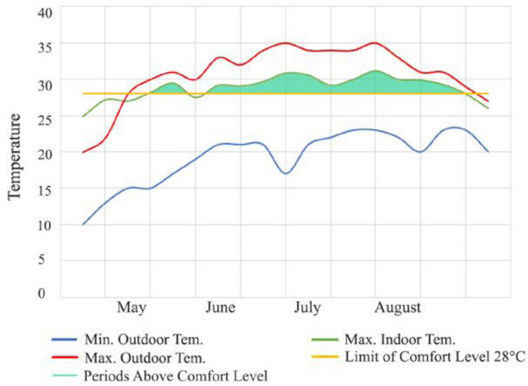

Figure 6: Expected outdoor and indoor temperatures during the summerly months from May to August for 2070 with illustration of indoor temperatures of the rooftop apartment above comfort level (ClimateStudio simulation)

The figure above is illustrating a future climate estimation of 2070 and showcases how this may have an effect on the indoor temperatures of the rooftop apartments of our case study buildings. As we can see in the figure, the hours and days during which the interior spaces of the rooftop apartments are in uncomfortable condition is dramatically higher than today. The predictions are vague and still need to be verified, but it is safe to assume that in general the occurrence, intensity and duration of heat periods will significantly increase in the future (Shukla et al., 2022). In our simulations, and as illustrated in the figure above, in 2070 the interior temperatures of our rooftop apartments of Villa Moritz and Villa Michaelis would be around 1082 hours on 68 days above the comfort zone of 28°C. Even though in the future we may get more used to higher interior temperatures, the interior spaces of the rooftop apartments could be seen as inhabitable future summer periods, if there would not be taken any measures against overheating.

2. Methods – Synthesis of theory and practice

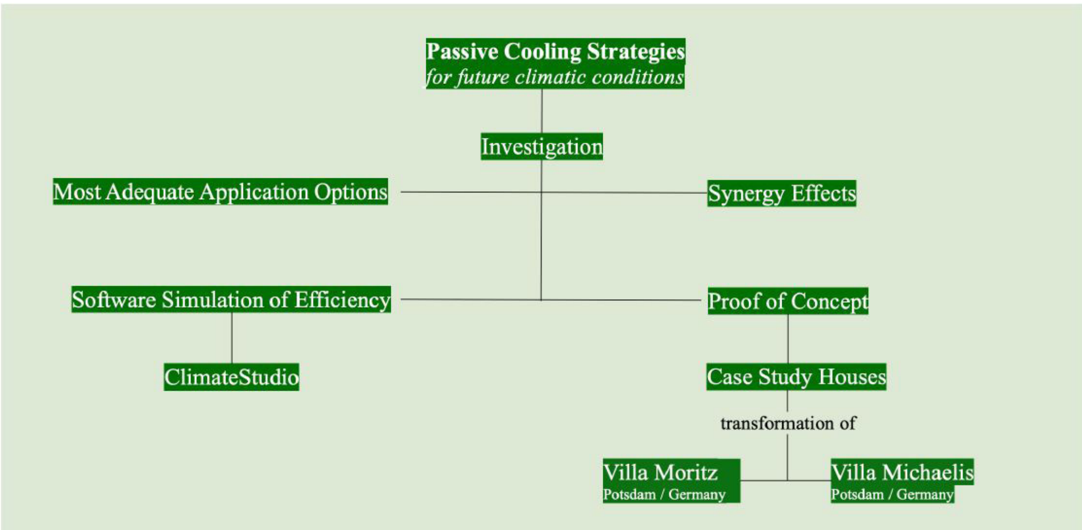

Figure 7: Diagram showing the study's methodological approach

After an introductory demonstration of the paper's rationale and an explanation of the urgent need to find ways of how to energetically retrofit our built environment with passive implementations, the focus will be set on an investigation of how the existing building stock can be retrofitted in order to provide a better interior comfort during summerly heat periods due to the implementation of passive cooling strategies. Besides the theoretical elaboration and further development of the principles to integrate passive cooling into existing building structures, it will be shown how some of these principles have been implemented as part of the retrofitting construction site in Potsdam.

Backed up with simulations by the environmental performance analysis software ClimateStudio, the planned cooling strategies have been integrated into a retrofit project of the two multifamily houses in Potsdam. Synergy effects of combinations of individual passive cooling techniques are highlighted. The actual cooling performance of the two case study buildings is compared with the simulation results in order to test and possibly verify the predicted performance results. Additionally, the feasibility in regard to costs and construction effort is evaluated and compared with techniques which are applied during conventional retrofit projects. The predicted construction costs and efforts are also proven by monitoring the real costs and efforts which are spent for the two exemplary retrofit construction projects. Last but not least, this study should help to clear the way to integrate passive cooling strategies into the German building regulations, which until today are not sufficiently considering passive cooling techniques in an adequate way.

3. Results – Passive cooling is a viable solution to keep our buildings comfortable in future climates

3.1 Implementation of passive retrofit strategies

Based on the energy performance analyses on one hand and the limits given by the legal requirements (e.g. heritage protection of the buildings) as well as financial limits, a series of enhancements to be implemented has been carefully selected. The major interventions, in regard to passive cooling, are: interior insulation, thermal massing, window improvements, enabling natural cross ventilation for all rooms (and thus the possibility of night cooling), and the installation of window integrated sun blinds. The following figures are illustrating more in detail the corresponding retrofit interventions.

Figure 8: Photo of installation of wall insulation from interior side

Figure 9: Photo of window enhancements

Figure 10: Installation of roof insulation (18 cm mineral wool)

Figure 11: Thermal massing with additional brick walls

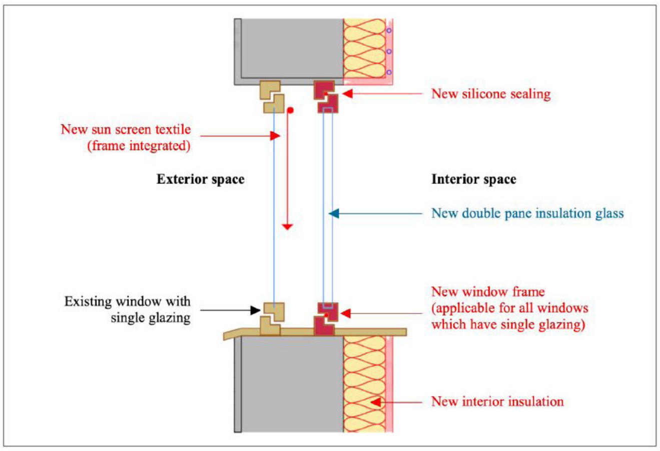

Figure 12: Window enhancement concept and installation of interior installation

3.2 Simulation results

The following figure illustrates the simulation results of the indoor temperatures after applying the above mentioned strategies of interior insulation, thermal massing, window enhancements, cross ventilation, and night cooling. The simulation has been made for the same estimated temperatures in Potsdam during 2070, as already presented in chapter 1.4. As we can see, the interior spaces could be kept within the comfort zone for the entire summer and conventional air conditioning systems would be unnecessary.

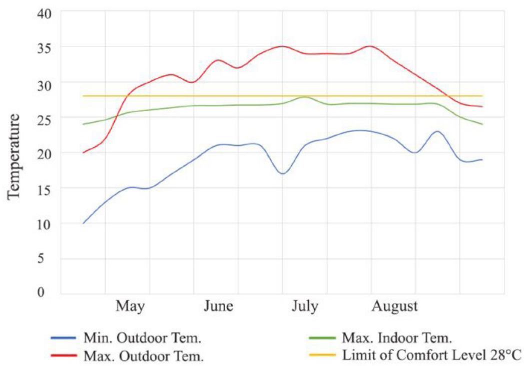

Figure 13: With the application of several passive cooling measures, the indoor temperatures could be kept low enough to completely maintain comfortable indoor temperatures also for temperatures predicted for 2070 (ClimateStudio simulation)

3.3 Analysis and comparison of savings, costs and carbon footprint

The figures below show the efficacy of each individual retrofit intervention in relation to the overall heat reduction achieved by the passive cooling measures. The aim is to envision the impact of each individual intervention on the total heat excess and then compare it with two other important factors: the related costs and the respective carbon footprint.

The figure at the left shows the total reduction of overheating subdivided into the five individual interventions. The figure in the middle contains a cost comparison of the individual interventions. The figure illustrates the proportion of each intervention from the total installation costs of the passive cooling implementations. The total costs for the implementation of the passive cooling interventions are 143,776 €. The highest spending has been made for the window enhancements (55,340 €), followed by the insulation of the exterior walls from the interior wall side (34,112 €) and the thermal massing (24,849 €). Significantly lower were the costs to enable cross ventilation (15,243 €) and for the installation of window integrated sun shading (14,232 €). The overall living space for the two buildings is 1,336 sqm. Therefore, the total cost for the passive cooling installations is 143

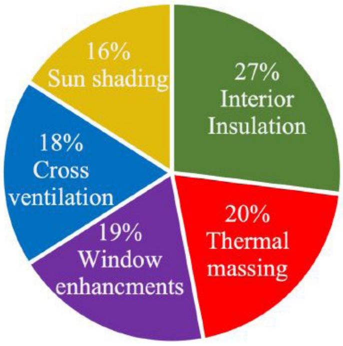

Figure 14: Percentage of reduction of overheating achieved by each intervention in relation to total

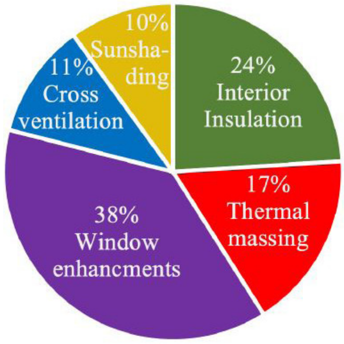

Figure 15: Percentage of cost of the individual cooling strategies in relation to their total expenditures

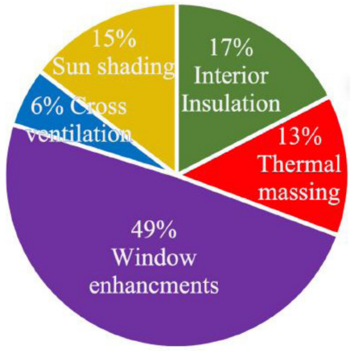

Figure 16: Percentage of carbon footprints of the single strategies in relation to their total footprint

€ / sqm living space. All costs indicated are exclusive to the German VAT which is currently 19%. And the figure on the right showcases an estimated carbon footprint comparison of the individual passive cooling interventions.

4. Discussion – How to develop the best passive cooling solution

An evaluation and development of a prioritization concept can become a powerful tool for the recognition of which combinations of interventions are most efficient in regard to energy and CO2 consumption as well as from an economical point of view. Thus, significant insights can be gained on which interventions to focus for the best overall outcomes.

4.1 Comparison of results

The efficiency of an intervention regarding the reduction of excess heat is not the only relevant factor to decide which strategy to choose. For sustainability aspects, the initial carbon footprint of the production, delivery and installation of a passive cooling component has to be as low as possible. Therefore, the carbon footprint has to be considered as well. A third aspect relevant for the decision which interventions to choose is a cost comparison. The next subchapter is providing the corresponding comparisons in the form of a table.

4.2 Prioritization of passive design implementation options

The following table shows which enhancements are most efficient in regard to savings, costs and embodied energy.

Table 1: Prioritisation of retrofit interventions in regard to efficiency, costs, carbon footprint

Priority	Type of retrofit intervention for passive cooling	Efficiency (percentage of total heat reduction)	Cost / sqm living space and percentage of total costs	Carbon footprint of intervention (metric tons of CO_2e) and percentage of total rank
1	Enhancements on windows, doors, ex- and interior walls to enable cross ventilation	18%	15 €, 11%	1.6 t, 6%
2	Thermal massing (incl. effect of night cooling)	20%	25 €, 17%	3.8 t, 13%
3	Wall insulation (from interior side)	27%	34 €, 24%	5.0 t, 17%
4	Installation of sun protection screen at window	16 %	14 €, 10%	4.2 t, 15%
5	Window enhancement by reduction of thermal heat gains through new glass layers with low u-values	19%	55 €, 38%	14.1 t, 49%
	total	**100%**	**143 €**	**28.7**

For the selection of the most reasonable cooling strategies, one has to consider all relevant factors, not only the efficiency in regard to cooling load reduction. Therefore, the costs and the carbon footprint of each intervention have been taken into consideration as well. Thus, it becomes evident that those interventions have to be preferred, which have the best relation between efficiency and costs (such as cross ventilation and thermal massing). And the intervention's carbon footprint is of relevance as well, since with a high carbon footprint, the duration time until the carbon savings have outbalanced the carbon spent for the production, delivery and installation, can extend to a very long time period. From the elaborated values it can be extracted that enabling cross ventilation is one of the most advisable implementation strategies for passive cooling. A relatively large reduction of the indoor temperature can be reached (18%) with proportionally low costs (11%) and a very low CO2 footprint (1.6 t). Thermal massing is another exceptionally effective cooling strategy. In the present case study, the overheating reductions achieved by thermal massing constitute 20% of total savings, with a cost of 17% and a CO2 footprint of only 13% (3.8 t). Wall insulation has a heat reduction of 27% from the total, while its costs are 24% of the total and the CO2 footprint is only 17%. The installation of sun blinds has 16% of savings but only 10% of the costs, while its carbon footprint is 4.2 tons, which equals to 15% of the total CO2 footprint. The overall lowest effectiveness has been observed in this study by the window enhancement strategy. Reason for this is not the amount of heat reduction (19%) but the high production cost (38%) and the large carbon footprint required for the manufacturing of the glass and frames (14.1 t, 49%).

4.3 Synergy effects by combining the implementation options

Some of the interventions can become most efficient in combination with each other. For example, can a window enhancement be combined with a window integrated sun shading roller blind, and it can be equipped with a tilt mechanism in order to facilitate the air flows necessary for cross ventilation and thus also significantly increase the effect of thermal massing. On the other hand, there are also interventions, which reduce the efficiency of other strategies. For example, can a wall insulation from the interior side reduce the thermal massing capacity since its mass is not anymore directly exposed to the interior space but separated by the insulation material.

4.4 Limitations of present study

The approach and depth of this paper is on a conceptual level and intends to show a path how we may use passive cooling strategies to transform our existing building stock to adapt to the future conditions. All data derived by calculations, software based simulations and measurements are on a conceptual level and need to be verified and intensified by deeper studies. Even though in this study only energy efficiency, costs and carbon footprint have been compared, there are several other very relevant factors as well, such as aesthetics, durability, re-usability and recyclability of the material, and maintenance effort. They also play an important role and may as well be considered in further studies.

5. Conclusion – How to pave the way for a successful implementation of passive cooling strategies on a large scale

This study aims to demonstrate ways how it is possible to retrofit our existing building stock in a way that it can respond to the new climatic conditions in a passive way without the need of installing conventional air conditioning systems. The fact that air conditioning systems are not yet installed in Germany on a broad scale, can be seen as an opportunity to go a more sustainable way to keep our buildings cool in the future and promote the installation of passive cooling systems instead. This would be an essential step of the climate neutral city of tomorrow. A prioritization, on which combinations of interventions are most efficient in regard to energy and CO2 consumption as well as from an economical point of view, proofs that the best outcomes can be reached with the combination of rather simple and less expensive interventions such as thermal massing, night cooling and night cross ventilation as well as the use of adequate materials. The presented case study construction site serves as a proof of practicability and constitutes an exemplary intervention proposal for the retrofitting in order to adapt our building stock to the impact of climate change.

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