HIGHLY INSULATED BUILDINGS AS A CRUCIAL ELEMENT FOR SMART CITIES, GRID BALANCING AND ENERGY STORAGE FOR RENEWABLES

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KNAUF INSULATION

We can count on highly energy efficient buildings as a key element of the energy transition in the European Union.

This is a pivotal moment for the EU and for the development of its actions on energy and climate. A swath of new energy legislation, known as the Clean Energy for all Europeans Package, is progressively being transposed into the laws and regulations of the Member States of the EU. Public opinion on the need to "act now!" on climate change has rocked the establishment and the new European Commission President, Ursula von der Leyen, has listened.

Challenging times lie ahead as administrators, politicians and decision-makers are forced to turn away from promises and fine words to take real actions and to instigate real change in all sectors of society to cope with the fallout from the COVID-19 crisis and the climate emergency that is still inadequately addressed.

There is a reason for optimism that the future priorities of the EU Institutions will be focused on making the EU the leading region on the globe in terms of actions for economic recovery, mitigation and adaptation to climate change. Success will mean that other regions can and will turn to it for inspiration. A European Green Deal was launched in December 2019, and the EU will spawn another round of legislative action that will, at the very least, see an increase in the energy and climate ambition of the EU for 2030.

Among the sectors that will be targeted is the buildings sector as its potential to make a meaningful and significant contribution to the challenges that lie ahead is very great. In its operational phase, our building stock consumes 40% of all primary energy produced, leading to around 36% of all CO_2 emissions. If we consider the whole life cycle of the building stock, then the figures go up to 50% of primary energy consumed, 50% of CO_2 emissions and 50% of all resources mined from the planet. It therefore goes without saying that unless we find a way to address these huge impacts, we cannot achieve long-term energy and climate goals such as those set out in the Paris Agreement at COP 21.

For these and other reasons, this short report makes very engaging reading. The partners to the Study set out to better understand and quantify the physical behaviour of highly insulated buildings in a cold (winter) climate zone, to verify if and to what extent they can contribute to energy system characteristics such as grid balancing, smartness and energy storage needs.

Buildings may not be the first thing that comes to mind when thinking about system-wide characteristics, but they have a great deal of potential.

This potential is contained in the fabric of our buildings and in how that fabric heats up when we create comfortable indoor conditions. Indeed, in a highly insulated building, the heat losses through the fabric are greatly reduced. This means that less heat is needed to bring the indoor environment to a comfortable temperature and that it holds that temperature for a longer time.

Most Europeans are familiar with the need to regulate heating systems so that they are always on when a building is occupied. This is needed as the heat loss from most buildings is so great, that occupants feel the cold in a matter of hours after the heating is switched off. What if this was not the case? What if the building retained the heat so effectively that only a small amount of heating is needed at long intervals of several days?

It is exactly these questions that this Study sets out to answer. The questions are comprehensively addressed for the first time and the results are astonishing. The researchers find that a building can be heated up to the higher end of a broadly accepted comfort zone and that they will not cool down to the lower end of the zone for a period of up to three or four days. This fact opens up a whole range of possibilities for our building stock and for the role that it can play in our future energy system.

Interestingly, the research shows that it is necessary to deploy multiple measures to achieve the best results. The measures are a combination of fabric improvements and controlled mechanical ventilation systems fitted with heat recovery mechanisms. It is a lesson to the designers of energy efficiency programmes that incentivising single measures will not deliver optimum results.

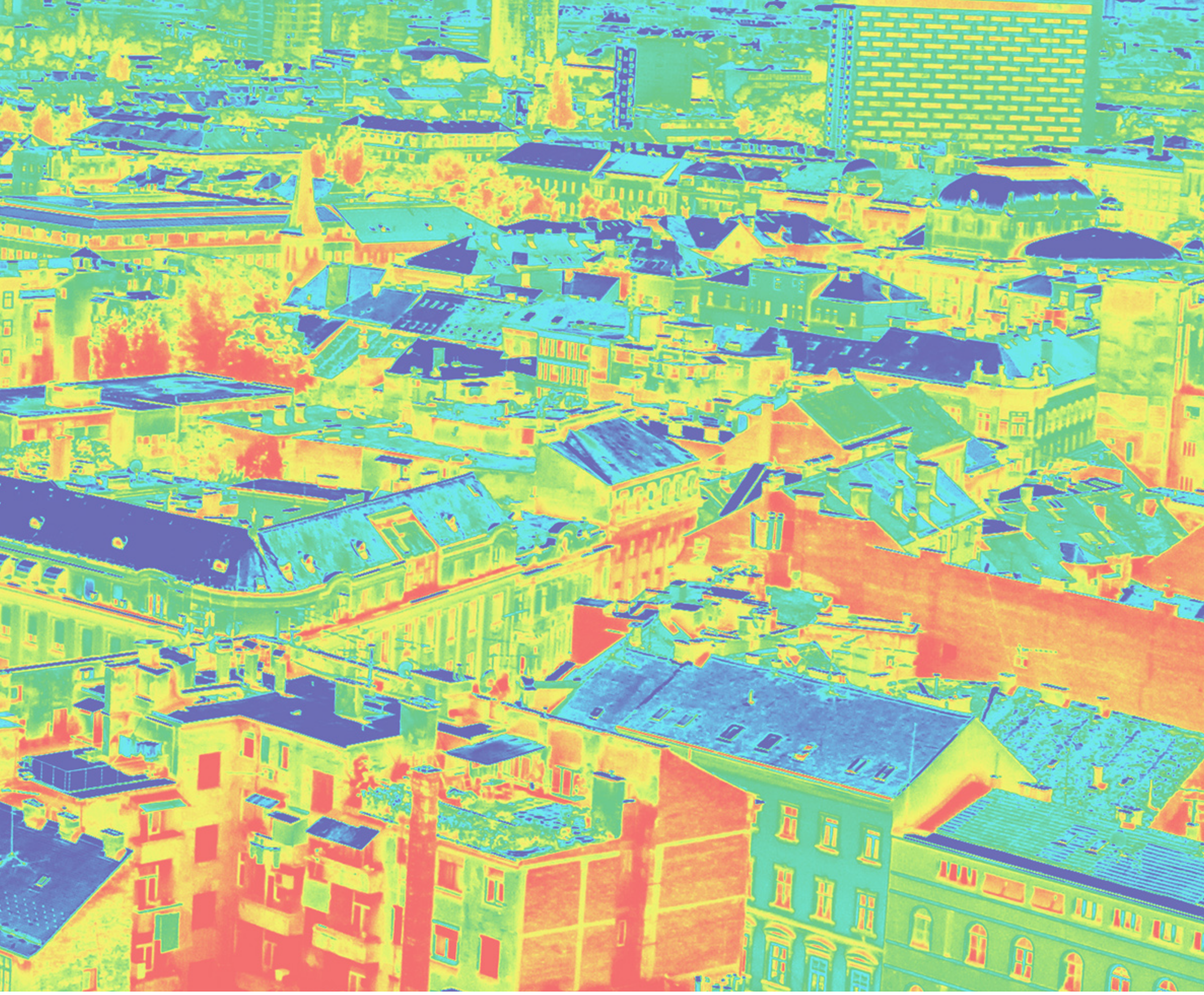
I trust that readers of this Study will learn something new, something surprising and that it will have the effect of bringing highly energy efficient buildings into the centre of policymaker's concerns as they move forward with planning for the needed economic recovery and energy transition in the EU.

I congratulate the research team on an excellent piece of work and I look forward to learning of the positive impacts that will arise from the implementation of the ideas contained herein.

Adrian Joyce

Secretary General
EuroACE (The European Alliance of Companies for Energy Efficiency in Buildings)

Brussels, May 2020



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THERMAL INSULATION OF BUILDINGS FOR FULL INTEGRATION OF RENEWABLES IN THE ENERGY SYSTEM

Deep and high quality renovation makes it possible to reduce energy consumption in our buildings by up to 80% and as a result reduce energy bills. But that is not all. Increasing the thermal insulation of walls and roofs considerably lengthens the time interval when the temperature inside a building remains comfortable after the heating has been switched off. The study conducted by the end-use Efficiency Research Group (eERG) of the Politecnico de Milano shows that heating for just one day to the upper end of the comfort zone is enough to maintain a comfortable temperature for a period of up to three or four days. This means that well insulated buildings offer the necessary flexibility to receive energy when it is available, attenuating the peaks in power demand on the electricity grid (when all inefficient buildings demand power) and properly exploiting moments of overabundance and scarcity of the supply of energy from renewable sources.

The work by Politecnico di Milano uses highly significant data to highlight the principle of energy efficiency first. It justifies rational strategies in which the reduction of the **energy needs for heating** from buildings is an indispensable prerequisite for a rapid transition to sources of renewable energy and the urgent decarbonisation of urban energy infrastructures.

At the heart of everything we do at Knauf Insulation is a commitment to the energy efficiency and sustainability of buildings. The Research Agreement we entered into with Politecnico di Milano underlines this commitment. My hope is that this work will provide expert insight to support the political, industrial and academic players involved in the energy transition process and the transformation of the building sector in Italy and beyond.

Paolo Curati

Managing Director, Knauf Insulation Italy

Executive summary

Findings

- This research paper offers breakthrough insight into how well-insulated buildings can maintain a comfortable interior temperature for up to three or four days after a single day of 'thermal charging' through heating.
- This long-term thermal energy storage creates flexible 'physically smart buildings' capable of tapping into the grid when intermittent renewable supplies are available. These findings provide evidence that a well-insulated building can work hand in hand with renewable energy supplies to effectively decarbonize the built environment.
- The study also shows that deep and high-quality building renovations could reduce energy use by up to 80% underlining the fundamental role that energy efficient building stock must play in urban decarbonization.
- In addition, this study reveals how deep renovation strategies reduce the capital cost of the equipment for heat generation, distribution and emission in a building by a factor of four as well as significantly improve comfort levels.
- Furthermore, if heat is delivered to the building by district heating or heat pumps, deep renovation also reduces by a factor of four the peak demand on the energy grids (district heating network, electricity network) – at the time when conventional inefficient buildings demand power – and related costs, and allows to displace that power demand to off-peak hours.
- These outcomes are accompanied by an analysis of current global energy use that shows there has been a constant increase in fossil energy use worldwide, despite the growth of renewable energies.
- Reducing **energy needs for heating and cooling** will not decrease demand for renewables, sensors and controls. On the contrary, energy efficient buildings will lead to the widespread use of renewables and controls.

Recommendation

Insulation of the building fabric and the resulting reduction of **energy needs for heating and cooling** are indispensable prerequisites for a rapid transition towards renewable energies and the urgent decarbonisation of urban areas.

Definitions and standardised terminology

Without having a shared and widely understood set of definitions and standardised terminology, a number of key issues about energy use by mankind and its impact on the environment remain exposed to ambiguity that can be used to avoid clear engagement to action. This risk of ambiguity is obviously present also in the area of energy performance of buildings. We therefore start by recalling the approach adopted by the internationally agreed Standard EN-ISO 52000-1. We have been careful to stick to its use of terms throughout this study. Please note that in this text the terms that have an explicit definition in EN or ISO standards are formatted in **bold.**

We then go on to look at the example of how to define the **energy need for heating** because this Study is centred around a simulation of the performance of a deep energy renovated building in Northern Italy in the winter, the objective of which is to test if the energy storage potential embedded in the mass of the **building fabric** can have a positive effect on the energy system as a whole.

THE CENTRAL ROLE OF THE CONCEPT OF ENERGY NEEDS FOR HEATING OR COOLING IN THE DEFINITION AND ASSESSMENT OF BUILDING PERFORMANCE

The **energy need for heating or cooling**[1] (defined in the Standard EN-ISO 52000-1 as the *"heat to be delivered to or extracted from a thermally conditioned space to maintain the intended space temperature conditions during a given period of time."*) is the starting point for any calculation of energy performance of buildings (European Commission, 2012) (EN ISO 52000-1).

This physical quantity, **energy need for heating or cooling,** is also required for the definition and assessment of nearly Zero Energy Buildings (NZEB for short) (L. Pagliano & Roscetti, 2019).

The Standard EN ISO 52000-2 (CEN & ISO, 2017b) states:
"The use of only one requirement, e.g. the numeric indicator of **primary energy** use, is misleading. In ISO 52000-1[2] different requirements are combined to a coherent assessment of nearly Zero-Energy Building (NZEB)."

More precisely:
"CEN proposes to combine the different requirements in a coherent assessment of NZEB. The proposed assessment methodology goes step by step 'from the needs to the overall energy performance expressed in primary energy use'. Only if the requirement of each step is reached, then the building can be qualified at the end as 'NZEB'. This approach is comparable to a hurdle race."

The goal of this sequence of indicators can be summarised as follows:

- the **energy need for heating** (or **for cooling**)[3] indicator quantifies the thermal quality of the **building fabric** in conditions that are typical of winter (or, respectively, summer); the reduction to very low values of the energy needs is a key point in the application of the "efficiency first" principle;

- the **total primary energy** indicator takes into account the equivalent amount of primary energy of all the renewable and non-renewable energy flows entering through the building boundary; setting a limit to the value of this indicator aims at improving the performance of the **technical building systems** and the quality of the energy sources;

- the **non-renewable primary energy** indicator takes into account the equivalent amount of primary energy *only* of the non-renewable energy flows entering through the building boundary; once the first two indicators have been reduced, setting a limit to the value of this indicator promotes greater share of use of renewable energy in percentage with respect to the (reduced) **total primary energy.**

[1] Please remind that in this text the terms that have an explicit definition in EN or ISO standards are formatted in **bold**
[2] (CEN & ISO, 2017a)
[3] Defined in the Standard EN-ISO 52000-1 as the *"heat to be delivered to or extracted from a thermally conditioned space to maintain the intended space temperature conditions during a given period of time."*

The definition of the main concepts and in particular of the **energy needs for heating or cooling** is often not accurate in public debate and in legislation and nomenclature is used often in a vague, non standardised, manner; this renders the commitments that accompany the declarations of promoting *Efficiency First* principle rather vague, and hinders the possibility of accurately monitoring progress. The EN 52000 series of standards supports accuracy, thus favouring certainty in environmental benefits and in the recognition of quality work in the construction industry, in building components manufacturing and in the renewables sector. A summary and examples of how indicators are calculated can be found in the chapter 5 of the "Guide to Implementation of the Energy Performance of Buildings Directive (EPBD)", published by the Building Performance Institute Europe (Lorenzo Pagliano & Roscetti, 2019).

As shown in Figure 1, e.g. the **energy need for heating** is given by the difference between the energy losses (by transmission through the envelope and through infiltration and ventilation) and the free energy gains from solar radiation and from the energy that is released inside the building by occupants, lighting and other sources that are not part of the heating system.

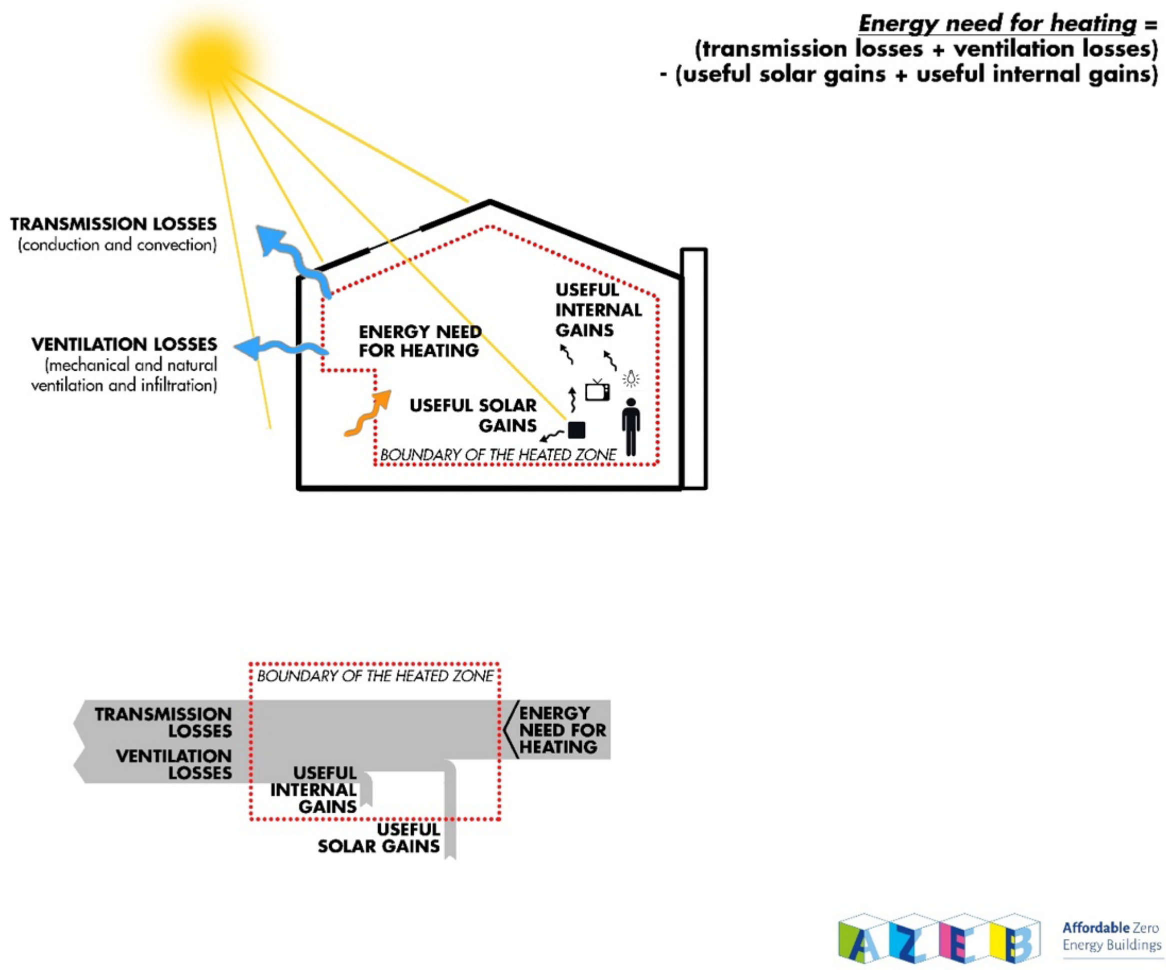


Figure 1: Visualisation of the physical quantity "Energy need for heating". Source: eERG within the Affordable Zero Energy Buildings (AZEB) project [4]

[4] European Union's H2020 project, grant agreement No 754174

THE URGENCY OF REDUCING ENERGY NEEDS FOR HEATING OR COOLING AS A NECESSARY PREREQUISITE FOR RAPID DECARBONISATION

Notwithstanding international commitments that have been repeatedly taken since the first International Climate Convention, 25 years ago, the data for the period 2000 - 2017 show at world level a growth rate in the use of energy that is far greater than the growth rate of energy supply from renewable sources of energy (Figure 2).

Essentially in those 17 years the world has been ***using a larger quantity of energy each year*** (partly from renewables but to a larger extent from fossil fuels) ***rather than substituting*** pre-existing levels of use of energy from ***fossil fuels*** with supply of energy from renewable sources (Jackson et al., 2018).

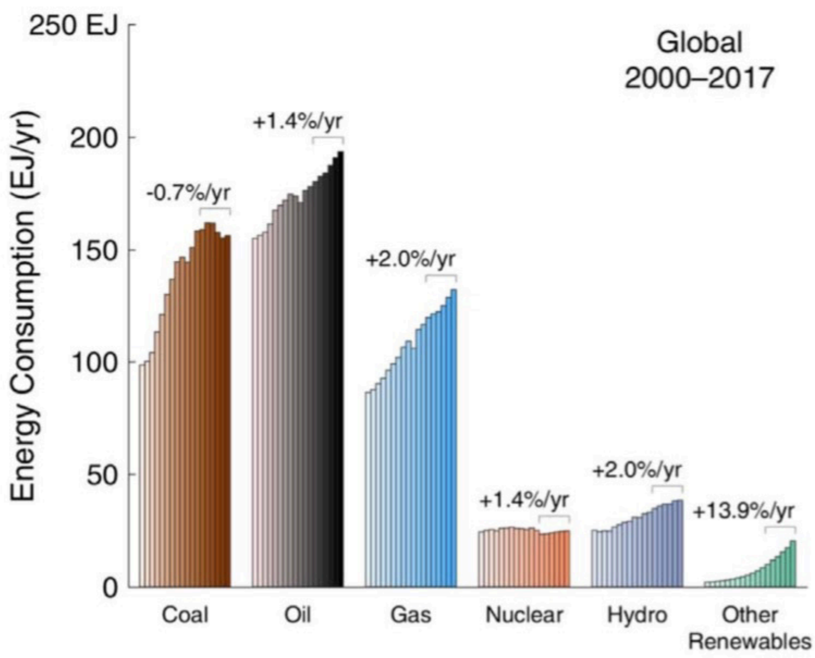


Figure 2: Growth of final energy use by source in the world from 2000 to 2017 in exaJoule/year. Source: (Jackson et al., 2018)

As for Europe the **total primary energy** use (excluding energy contained in imported goods) diminished during the economic crisis but has increased rapidly in the last three years (Figure 3).

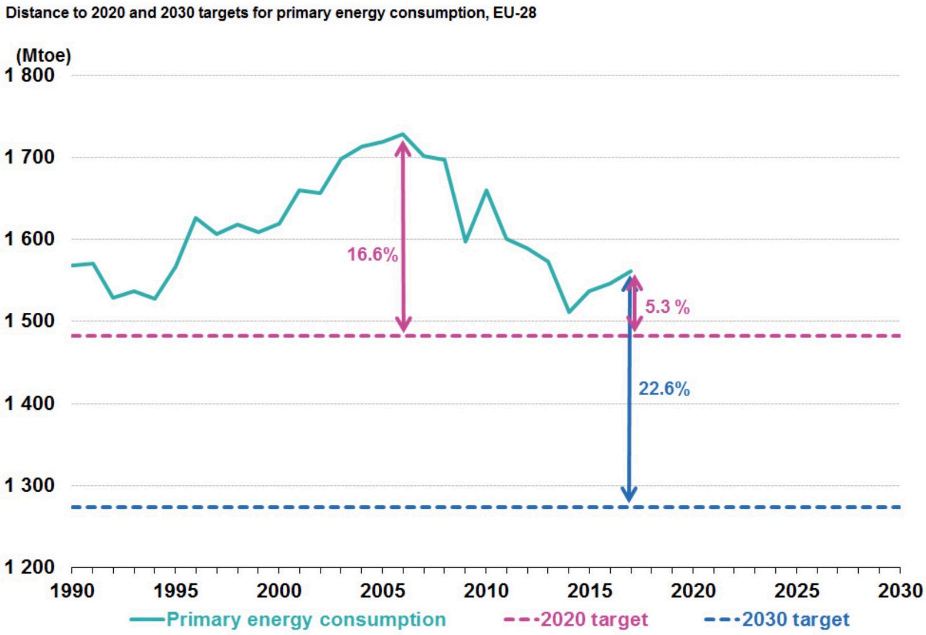


Figure 3: Variation over the years of **total primary energy** use in the European Union (excluding energy contained in imported goods) 1990-2017. Source: https://ec.europa.eu/eurostat/statistics-explained/index.php/Energy_saving_statistics

The only scenario that makes it possible to limit climate disruption to 1,5° C, without the risks and the injustice of burdening future generations with the task of removing CO_2 from the atmosphere (to way beyond the year 2100) using technologies of yet-to-be proven technical and economic feasibility, is one whereby the global **final energy** [1] use is reduced by 40% with respect to the *present* consumption level by the year 2050, in order to enable a rapid decarbonisation of the remaining demand (Grubler et al., 2018). Achieving a 40% reduction of **final energy** use at world level obviously involves a much higher percentage reduction in the Global North, including the EU and its Member States. At the same time reducing energy use will reduce not only CO_2 emissions, but also pollutants which directly harm human health (as PM10 and 2,5, NO_2, SO_2, which are unaffected by e.g. CCS)

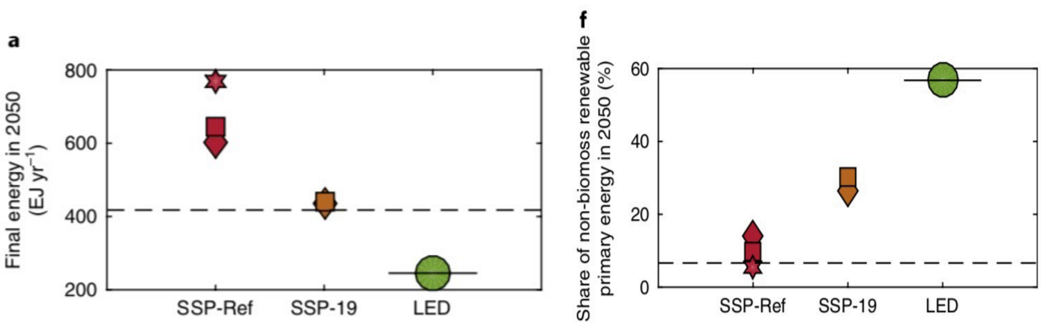


Figure 4: a) Global final energy use in various scenarios included in the IPCC 2018 report, including the Low Energy Demand (LED) scenario in ExaJoule/year in 2050; f) share of non-biomass renewable primary energy in 2050. Source: (Grubler et al., 2018).

Renewable sources are increasing in quantity but the path to make them a prevailing element in the supply of electric **and** thermal energy is a colossal transformation to be undertaken in a very short time interval.

It follows that in a rational strategy not even a single kWh from renewable sources should be used in an inefficient manner or diverted for uses that we shall soon deem to be outdated, such as "shallow" renovation of buildings or an excessive number of oversized electric cars.

[1] Final energy is the name sometimes used (e.g. in Eurostat documents) as a synonym of delivered energy (which is more specific to buildings, while final energy is a more general term for the energy flowing into any energy using device, often at national or regional level)

NEW BUILDINGS AND RETROFITS WITH A LOW ENERGY NEED FOR HEATING AS AN INFRASTRUCTURE PROJECTED INTO THE FUTURE

Thousands of new buildings with **energy need for heating** in the order of 15 kWh/(m^2/year) are completed every year and rigorously documented in the context of the voluntary ***PassivHaus*** labelling initiative and of some categories of ***Casaclima*** and ***Minergie*** (the more advanced ones). By comparison, existing buildings can have an **energy use for heating** that is up to ten to twenty times higher (in the order of 150 kWh/m^{2}y for existing buildings in Western Europe and 250 kWh/m^{2}y in Central and Eastern Europe (Harvey 2010) (Ürge-Vorsatz et al., 2012).

Not all building certification/labelling gives unambiguous and easily comparable information. For example, current Italian legislation for new buildings does not provide a unique comparison reference value for nearly Zero Energy Buildings (Attia et al., 2017). The energy need value against which to compare real buildings is not a number fixed once for all. On the contrary the above reference value is calculated for a reference virtual building with the same shape, orientation and window-to-wall ratio of the actual building. The reference building is only constrained to have prescribed values of steady state thermal transmittance of its components and performance of the technical building systems. As a consequence, the reference virtual building and the reference value of energy needs is different for each building to be assessed, thus making the comparison difficult for prospective buyers and building users.

The real building must have a value of **energy needs** lower than that of the reference virtual building. But the energy needs of the virtual building can assume a high value if the shape, orientation and the window-to-wall ratio of the real building (which are exactly mirrored in the virtual one) are chosen in an ineffective manner.

This is in contrast with Annex I of the Energy Performance of Buildings Directive which requires the calculation of performance to take into account shape and orientation. Using an approach which uses a virtual reference building implies that the calculated performance becomes independent of these essential parameters.

High quality renovation of existing building envelopes can reduce the energy need for heating of existing buildings by up to 80%. See, for example, the renovation of social housing buildings and schools carried out by the Municipality of Milan with the technical support of the end-use Efficiency Research Group (eERG) of Politecnico di Milano5. It is possible to renovate existing buildings to bring them close to the Passivhaus requirements for new buildings (L. Pagliano, Carlucci, Causone, Moazami, & Cattarin, 2016).

Given the situation described in the previous section, the construction of new buildings and retrofit projects that would not apply the best design strategies and the best materials and components would clearly diverge from the goal of decarbonisation. If this non-optimal path were taken, building stock would be locked for many decades in a level of **energy needs for heating and cooling** and of **delivered energy** that is higher than the level which is possible thanks to innovation in the building sector. The resulting wasted energy (because unnecessarily added) would be equivalent to approximately to 80% of global energy use by buildings in 2005.

This lock-in effect is estimated and featured in the 'Building' chapter of the Intergovernmental Panel on Climate Change Report 2014 (Lucon & Ürge-Vorsatz, 2014) and in (Ürge-Vorsatz et al., 2018).

[5] See http://eu-gugle.eu/it/citta-pilota/milano/ and http://www.eerg.it/index.php?p=Progetti_-_EU-GUGLE

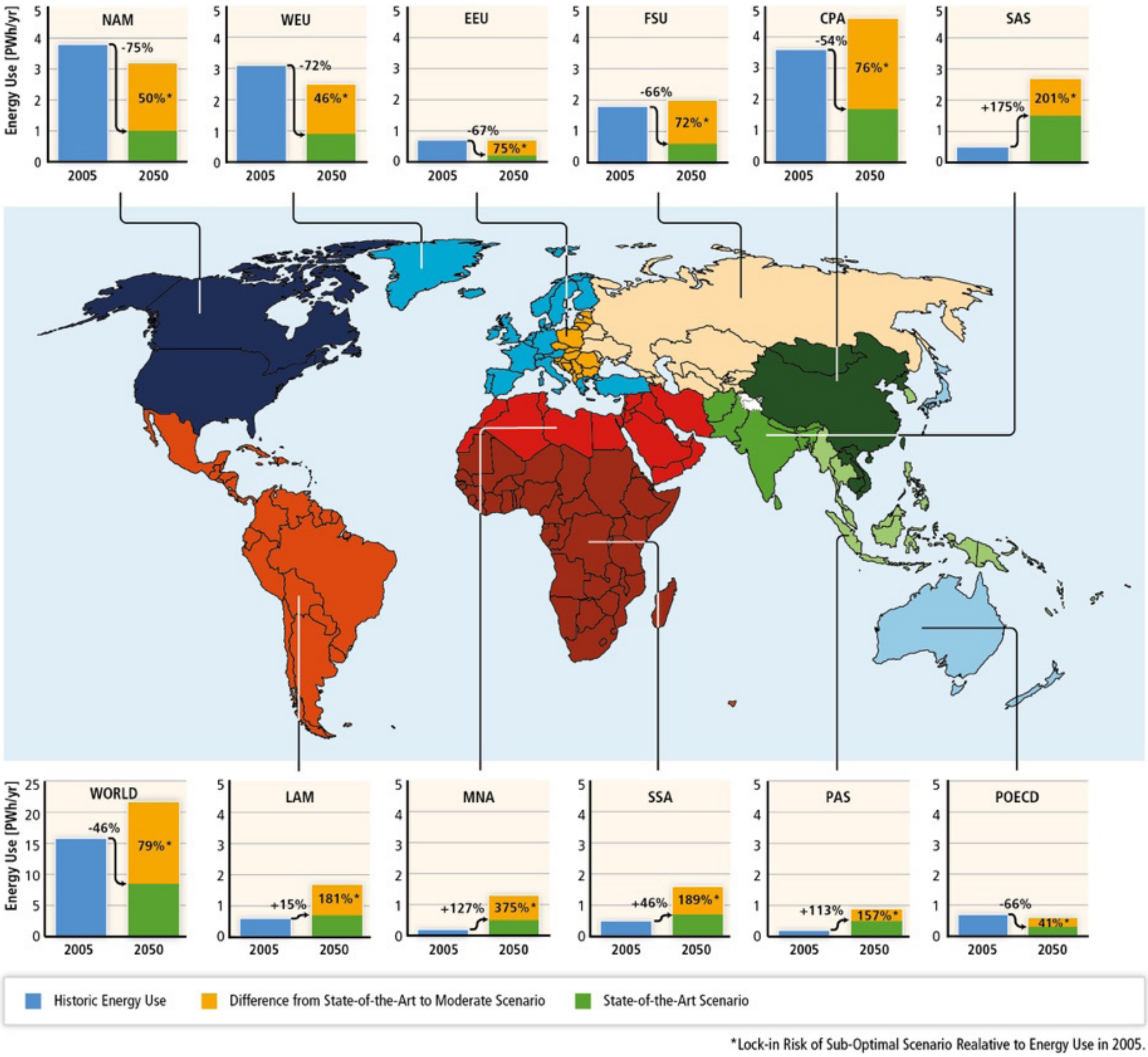


Figure 5: Lock-in effect due to failure to apply the best technologies in new buildings and renovation projects. In the graph the term "energy use" is employed as synonym of the term "**delivered energy**" of standard EN-ISO 52000-1. Source: (Lucon & Ürge-Vorsatz, 2014)

FLEXIBLE BUILDINGS AS AN INDISPENSABLE ELEMENT OF SMART CITIES AND MANAGEMENT OF VARIABILITY OF RENEWABLE SOURCES

The working hypothesis at the base of the research project that the eERG-PoliMI Group is developing in the context of a Research Agreement with Knauf Insulation Italia is that an increased external thermal insulation of walls, roofs and basements, considerably extends the time interval during which a building will maintain indoor conditions in the comfort range[6] . This will make it possible to:

- ***Match the demand with the supply of local energy*** by removing the current rigidity of energy demand from buildings and thus allow them to "ask for" energy precisely when it is available from local sources (renewable or recovered energy) or to exchange energy with other buildings in a flexible way. Most of the current communication on smart cities, micro-grids, etc. omits to mention the fact that making the **building fabric** "physically smart" is a *sine qua non* condition for the possibility to use other components such as sophisticated sensors and monitoring controls.

- ***Exploit moments of overabundance of renewable energy supply on the grid*** by making available energy storage capabilities (in the form of thermal capacity of the building fabric) when such moments occur.

- ***Manage conditions of energy supply shortage*** by attenuating peak power demand on the grid or district heating network (peak shaving, demand response, potential participation in the capacity market creating added value additionally to the value linked with energy savings and increased comfort).

[6] Established by international standards on the basis of thousands of interviews with building occupants and simultaneous measurement of physical parameters. Cf: ASHRAE Global Comfort Database I and II (Földváry Ličina et al., 2018).

ANALYSIS OF A RELATIVELY DEEP RETROFIT PROJECT (SOCIAL HOUSING BUILDING IN THE MUNICIPALITY OF MILAN)

Projects undertaken by the Municipality of Milan with the support of eERG-PoliMI, that are currently completed or under completion in a social housing building block7, include the application of an external insulation layer (25 cm with conductivity in the order of 0,035 to 0,040 W/(mK), thorough analysis and correction of the thermal bridges, substitution of window and door frames and glass panes, and installation of mechanical ventilation with heat recovery[7].

Figure 6: Residential social housing buildings before (photo) and after (model) deep renovation.

[7] Basic data gathered in the context of the EU-GUGLE (http://eu-gugle.eu/pilot-cities/milano/) and Sharing Cities (https://sharingcities.wixsite.com/milano) European projects, processing and analysis on "flexibility" carried out in the context of the Research Agreement by and between the Politecnico di Milano and Knauf Insulation Italia.

Table 1 illustrates the characteristics of the buildings that were analysed.

	Gross Floor Area [m²]	Useful Floor Area [m²]	Gross Volume [m³]	Gross Dissipating Surface Area [m²]	Surface/ Volume Ratio [m⁻¹]	Windows Surface Area / Dissipating Surface Area Ratio	Number of Floors
Building_1	2836	-	8462	4583	0.54	0.14	4
Building_2	1797	-	5361	2967	0.55	0.14	4
Total	4633	4170	13824	7549	0.55	0.14	4
Stairs and Lifts	543	-	.	.	.		.

Table 1: General Data (source: Technical office of the Municipality of Milan, Architects F.Manzoni and S.Bardeschi)

Table 2 illustrates the physical characteristics of the building fabric that were analysed, before and after deep renovation.

Physical characteristics of the building envelope		before renovation	after renovation
Thermal transmittance of opaque vertical structures	U [W/(m²K)]	1.15	0.13
Thermal transmittance of ceiling under the uninhabitable attic	U [W/(m²K)]	3.00	0.15
Thermal transmittance of pilotis supported attic	U [W/(m²K)]	2.40	0.17
Thermal transmittance of glass panes	U [W/(m²K)]	3.00	1.42
Thermal transmittance of the window frames	U [W/(m²K)]	5.00	1.6
Total solar transmittance of glass panes	%	0.75	0.52
Air changes per hour	n^{-1}	0.5 by day 0.25 at night	0.5 by day 0.25 at night
Mechanical ventilation with heat recovery	Recovery efficiency %	None 0%	Installed 75%
Thermal Bridges		high	Greatly attenuated

Table 2: Main physical characteristics of the building, before and after renovation (source: documentation by the Technical office of the Municipality of Milan)

The analysis of the effects of the retrofit measures is based on dynamic simulations, taking into account internal gains and useful solar contributions, and a detailed assessment of the comfort range.

The model of the building was created in an EnergyPlus simulation environment, where a detailed geometric model was developed, including internal partitions, in order to be able to assess the behaviour of the individual apartments including effect of orientation (see Figure 7).

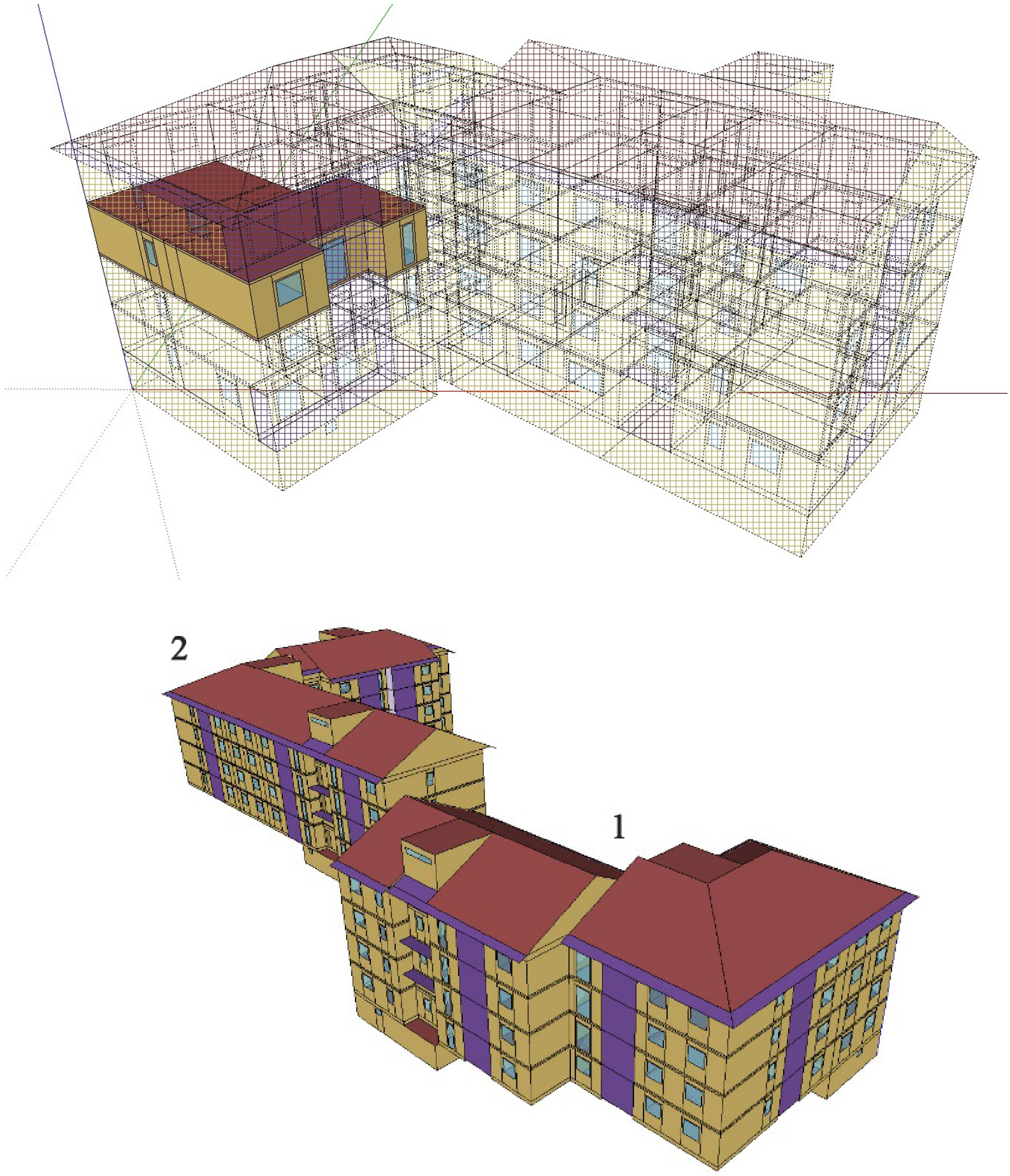


Figure 7: 3D modelling of buildings using the combination of Sketch-up and EnergyPlus software applications. Detail of the fine subdivision into thermal zones.

[8] It should be noted that according to EN 15251 and EN 16798-1:2019, category I is not a "better" category but a category for areas dedicated to vulnerable people (small children, the elderly, the sick), see e.g. (Lorenzo Pagliano & Zangheri, 2010).

[9] http://comfort.cbe.berkeley.edu

[10] The comfort tool also includes the Comfort Adaptive model in the versions of EN 16798-1:2019 and ASHRAE 55 (ASHRAE, 2017). The correlations between physical conditions of the building space and the comfort votes of the occupants are based on tens of thousands of interviews in real buildings, see e.g. (Földváry Ličina et al., 2018).

In order to determine the thermal comfort range in winter, reference was made to the Standard (EN 16798-1:2019) selecting category II (suggested for new buildings[8]). When adopting the Fanger model (suggested for conditioned spaces), comfort category II is defined as ranging between- 0,5 and + 0,5 PMV conditions (PMV is the Predicted Mean Vote, i.e. the average expected comfort vote by occupants). We assumed typical indoor winter clothing (1 clo), metabolic activity corresponding to office work (1,2 met), air velocity (0,1 m/s), and relative humidity (40 %), all typical values for indoors in winter. Under these conditions, using the online thermal comfort tool of the University of California, Berkeley[9], which incorporates the algorithm of the Fanger model10, one obtains that comfort category II ranges in winter, in terms of **operative temperature**, between 19,5 °C and 24,1 °C. **Operative temperature** is a major determinant of thermal comfort (Lorenzo Pagliano & Zangheri, 2010), is defined in Annex G of EN-ISO 7726:2001, and when air velocity is small it can be approximated as the mean value of air and mean radiant temperature, which in turn is a weighted average of the temperature of the surfaces of the room. It depends on the position within the room; here we have considered its value in the center of the heated space.

Internal gains due to occupants, appliances and lighting during the winter season in our energyplus simulation model account for about 26 kWh/m^2 in free gains, based on direct measurement of electric energy use in the selected buildings and plausible assumptions on occupancy. A similar value is obtained by applying Italian national standards for the building assessment mandated by law. Applying the Swiss SIA standard to this case study, one obtains winter internal gains of about 23 kWh/m^2. The PassivHaus calculation method applied to a single family house (lower occupation density) brings a result of about 9 kWh/m^2 winter internal gains. Given the variability in the value of internal gains (since they depend on the type and use of internal appliances and lighting and occupancy density and schedules), we performed a sensitivity analysis on two levels: 26 kWh/m^2 and 0 kWh/m^2 free gains.

As for solar gains through windows, our detailed simulations over an entire year performed using a weather file representing the local climate evaluates a gain of about 8 kWh/m^2 during winter. Italian National standard calculation rules bring a result of about 12 kWh/m^2. In any case, we performed a sensitivity analysis by considering two levels of solar irradiance: one referring to an average winter day and one referring to a “stress” winter day.

In fact, as illustrated in Figure 8 and Figure 9, we selected an "average winter day" that during a set of simulations is cyclically repeated in order to eliminate climate variability from the calculation.

A second set of simulations with EnergyPlus is made using a cyclical repetition of a 'stress' winter day where the outdoor air temperature is always below 0°C and solar irradiance approximately half as much as in the 'average' winter day (Ferrari et al, 2013).

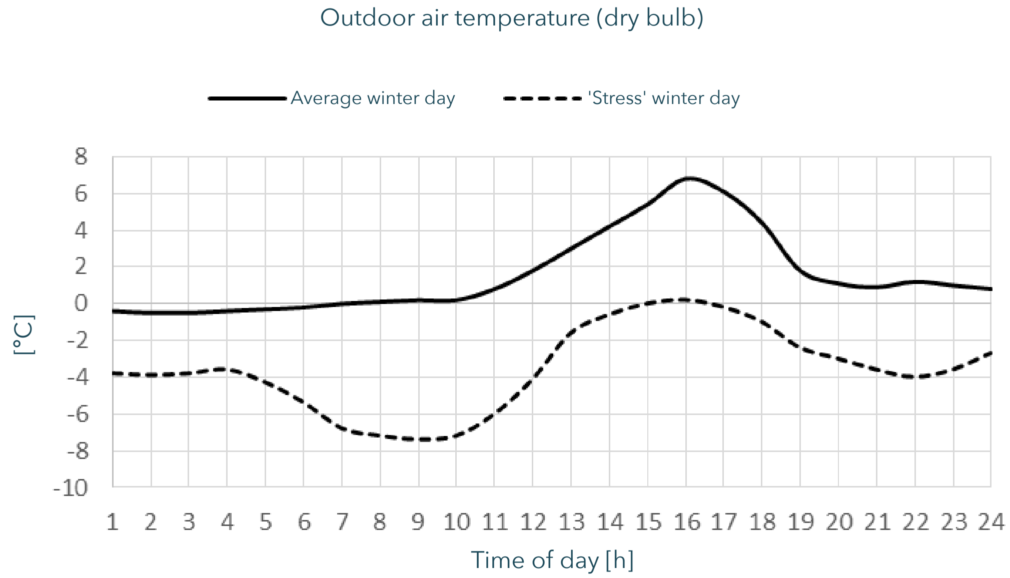


Figure 8: Air temperature (dry-bulb) during an average winter day and a "stress" winter day.

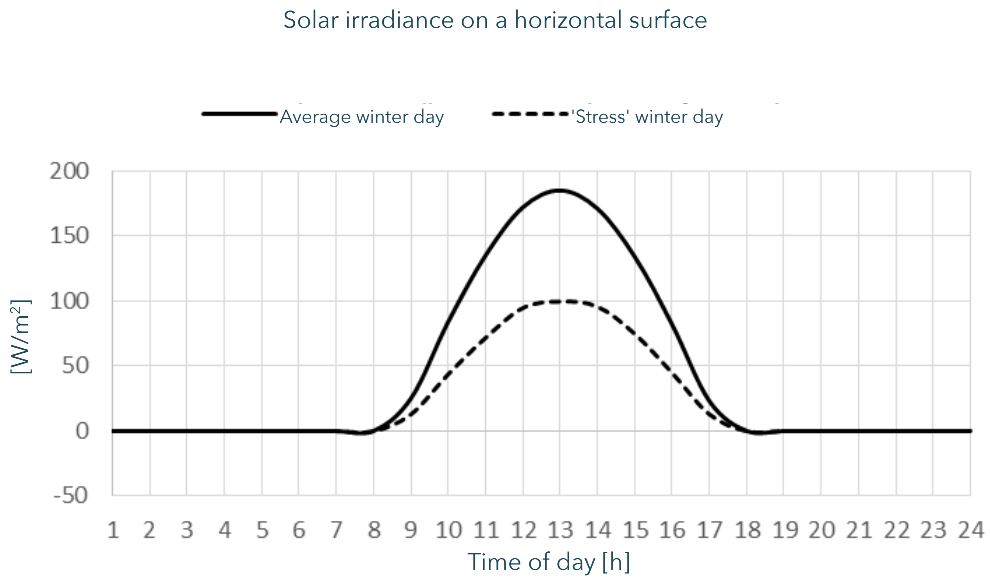


Figure 9: Global solar irradiance [W/m^2] on a horizontal surface in an average winter day and a "stress" winter day.

In the real buildings under analysis, energy is delivered to the conditioned spaces via a hydronic system and radiators. In the simulations, energy is delivered to the conditioned zones by using an all-air distribution system for the sake of simplicity. This choice of heating system errs on the safe side since it excludes the thermal capacity of the hydronic system from our calculation.

RESULTS

In order to communicate concisely and clearly the results of the analysis we have opted to present the results in a "question and answer" format.

FOR HOW LONG WILL A BUILDING THAT HAS BEEN SUBJECT TO DEEP RENOVATION REMAIN IN THE COMFORT ZONE AFTER THE HEATING IS TURNED OFF?

After a deep renovation as described above, in our simulations we heated the conditioned space to an **operative temperature** of 24.1°C (the upper value of the comfort range). This temperature was maintained for respectively 1, 2, 3, 4 and 5 days. Afterwards the heating system is turned off. The time interval during which the space remains in the comfort zone, under a climate given by the cyclic repetition of an average day, is different for each of the 5 cases, but the difference is limited.

Heating up (within the comfort zone) the envelope for 1 day, the conditioned space will remain in the comfort zone after turning off the heating system for approximately 4 days (96 hours, as shown in Figure 10).

Heating up the envelope for 2 days, the conditioned space will remain in the comfort zone after turning off the heating for more than 5 days (more than 120 hours, as shown in Figure 10).

A further increase in the time interval during which the heating is kept on produces marginal results showing that it is possible to activate a large part of the thermal storage potential by keeping the heating system turned on for just one day.

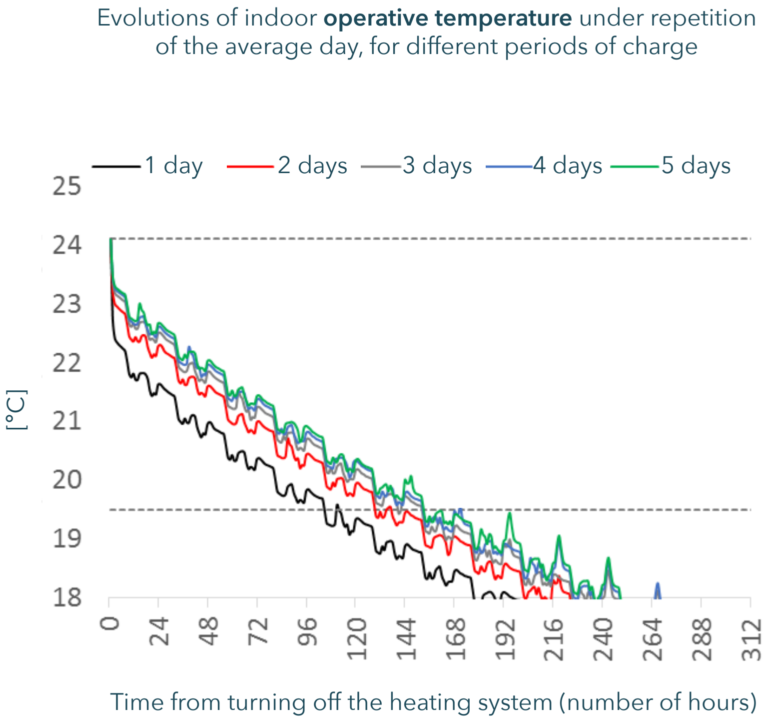


Figure 10: Variation over time of **operative temperature** in a reference indoor heated space as a function of the number of days (1 to 5) during which the heating system was kept on (before being turned off), with external conditions given by the cyclic repetition of an "average" day.

HOW DEEP MUST THE RENOVATION BE TO SIGNIFICANTLY INCREASE THE FLEXIBILITY OF A BUILDING?

Figure 11 shows that the substitution of windows and doors is not, by itself, enough to significantly modify the thermal dynamics of a building. Thermal insulation of the opaque parts of the **building fabric** to the level of quality taken under consideration in this case (conductivity in the order of 0,035 to 0,040 W/(m·K) and 25 cm thickness of external insulation) is indispensable for obtaining building flexibility (in addition to saving energy by reducing the **energy need for heating**).

Obviously, limiting the renovation to just the substitution of the thermal energy generation system, without any intervention on the **building fabric**, would have no effect on the flexibility.

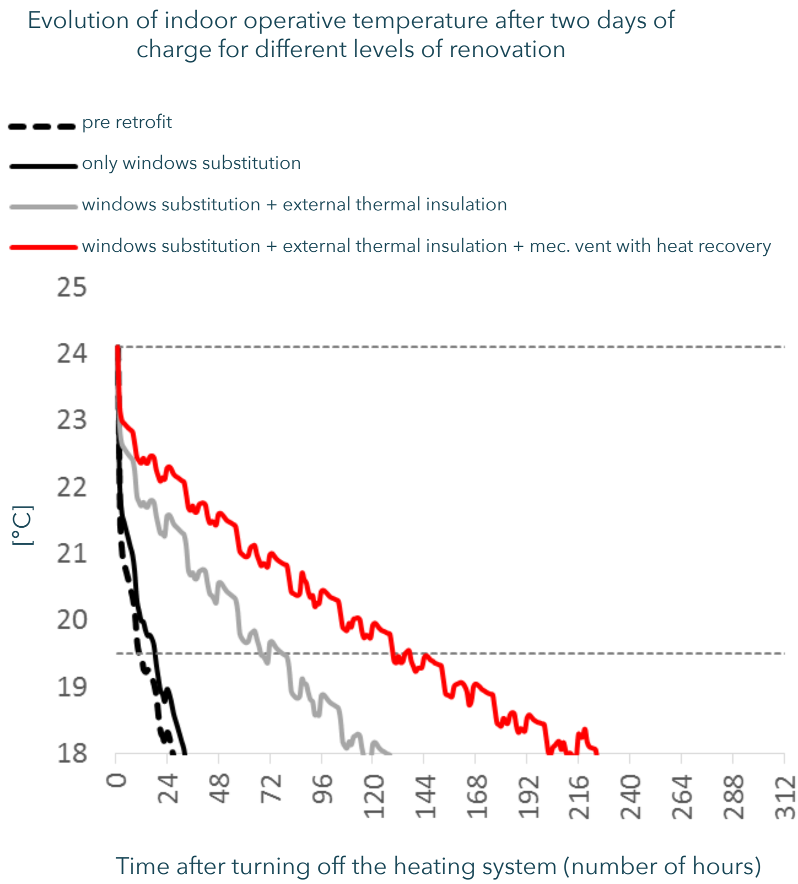


Figure 11: Variation over time of **operative temperature** in a reference heated space as a function of the retrofit measures undertaken, after two days during which the heating system was kept on (before being turned off) and with the cyclic repetition of an average winter day.

WHAT SORT OF VARIABILITY WILL THERE BE INSIDE THE BUILDING?

It is to be expected that in a multi-apartment building of a certain dimension there should be apartments which can exploit solar energy gains better than others thanks to better exposure to sun radiation, with positive effects with respect to the time interval during which adequate comfort conditions are maintained after turning off the heating system. Variability between apartments may come also by differences in the surface area exposed to the exterior or to non-heated spaces. Figure 12 shows the expected differences with respect to the reference apartment (in black) in the assessment of the time during which the indoor conditions remain in the comfort zone. The simulations show that after the retrofit work all the apartments behave in a similar way to each other. The time interval during which they remain in the comfort range varies to a very limited extent from one apartment to another.

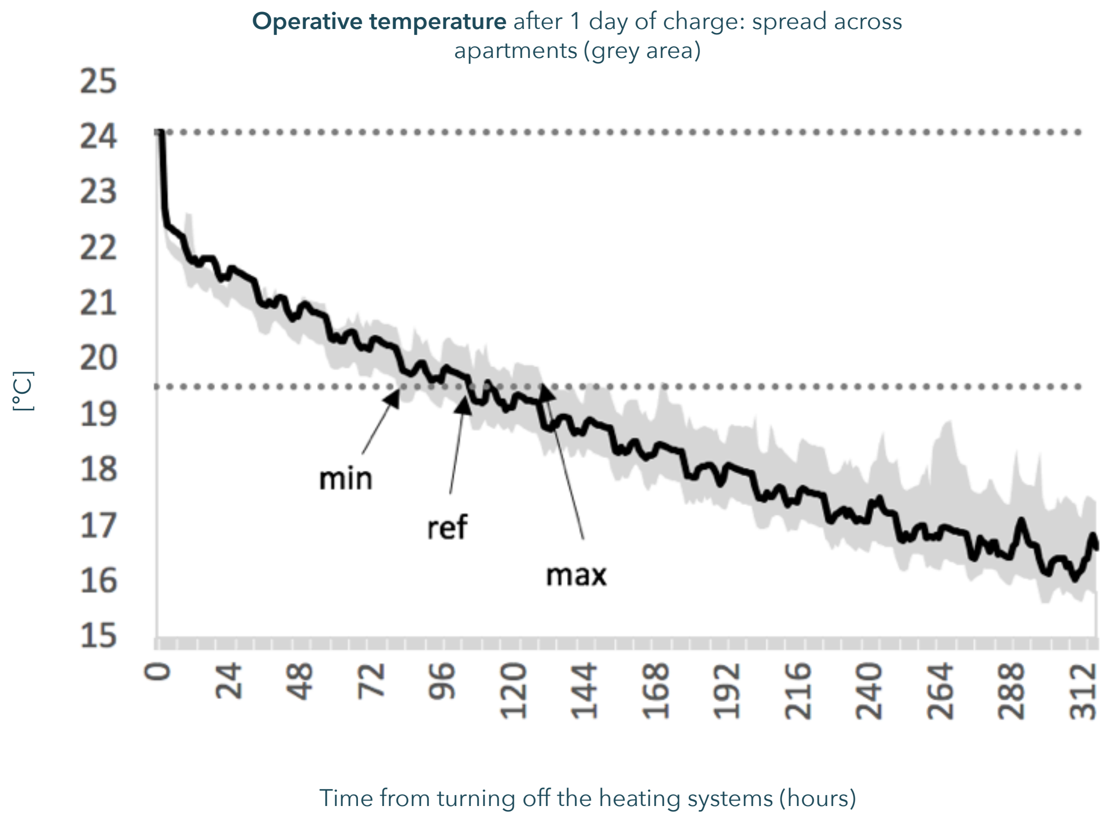


Figure 12: Variation over time of the **operative temperature** in various apartments (grey area) after 1 day during which the heating system was kept on before being turned off, under the cyclic repetition of an "average" winter day.

WHAT EFFECT WOULD A RIGID CLIMATE HAVE ON COMFORT AFTER TURNING OFF THE HEATING?

It is also necessary to check what happens in the event that after a period during which the heating was on and then turned off, unfavourable climatic conditions are experienced in the following days.

Figure 13 shows the result of dynamic simulations made assuming that the period of "thermal charging" is followed by a series of days with outdoor air temperature below 0 °C and limited solar irradiance (simulated by using a cyclical repetition for a number of days of "stress" winter conditions).

The time interval during which the **operative temperature** remains in the comfort zone is reduced with respect to the case shown in Figure 10, but it is still an interesting result (approximately 70 hours, i.e. nearly 3 days). Even in this case the retrofit of the **building fabric** creates previously inexistent opportunities to modulate the time and size of demand and reduce peak demand on the grid.

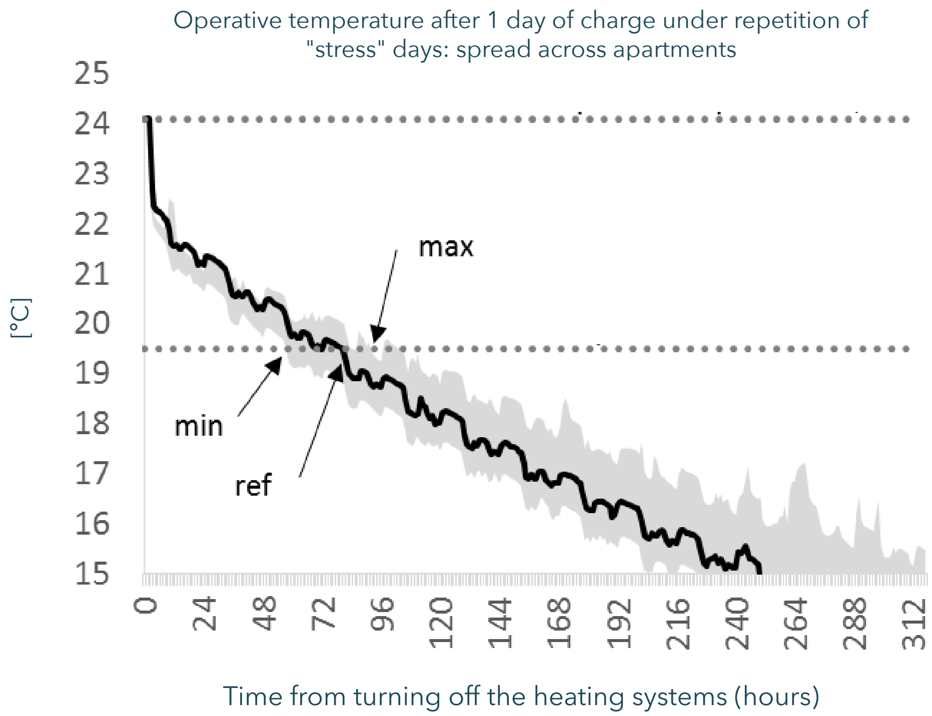


Figure 13: Variation over time of the **operative temperature** in various apartments (grey area) after 1 day during which the heating system was kept on before being turned off, under the cyclic repetition of a "stress" winter day (low outdoor air temperature and low solar irradiance).

WHAT WOULD BE THE EFFECT OF REDUCED INTERNAL GAINS DUE TO PEOPLE AND EQUIPMENT?

In order to assess the performance of the retrofitted buildings under various levels of internal gains due to occupants, appliances and lighting we have considered the extremely conservative case where those gains are completely non-existent due to the absence of occupants(in which case there would not be a need to maintain thermal comfort, by the way) and all appliances turned off. The result in terms of decay of **operative temperature** over time and variability across apartments are shown in Figure 13a and figure 13b. We note that this is only a sensitivity calculation and not a realistic scenario.

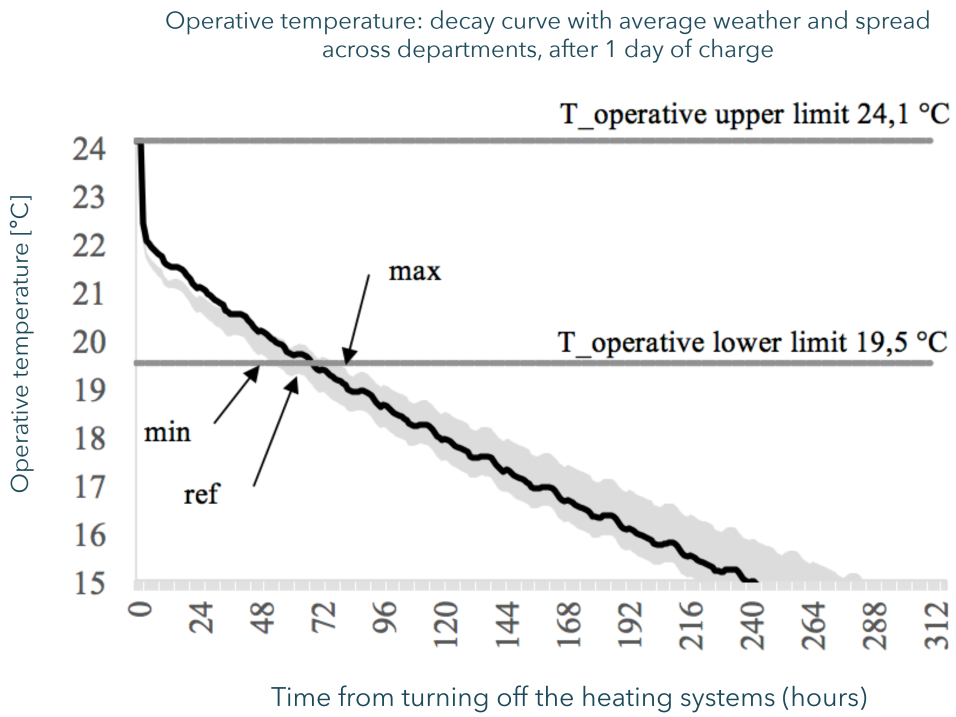


Figure 13a: Variation over time of the **operative temperature** in various apartments (grey area) after 1 day during which the heating system was kept on before being turned off, under the cyclic repetition of an average winter day, and with zero internal gains.

Operative temperature after 1 day of charge: spread across apartments (grey area)

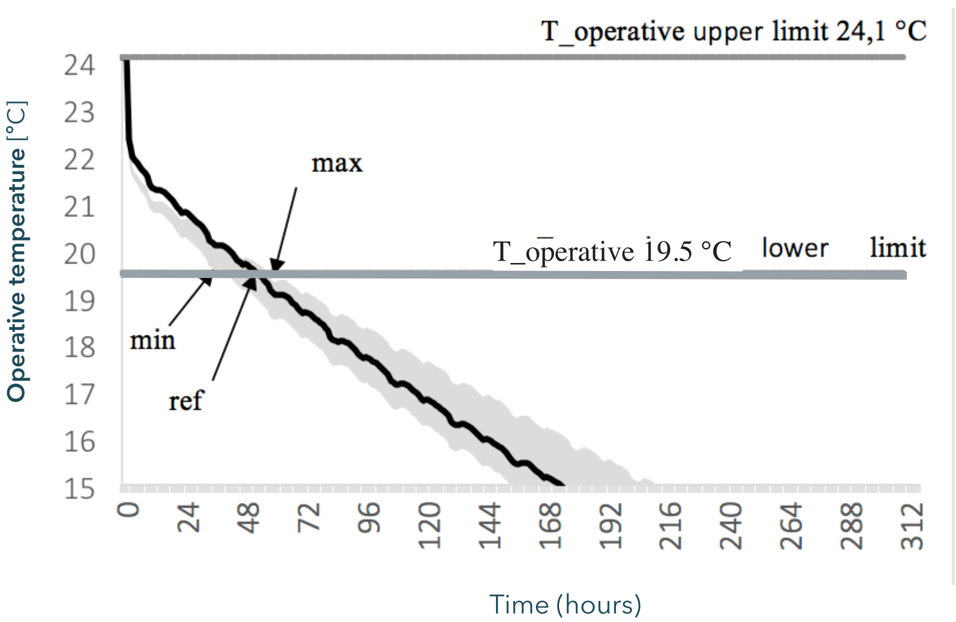


Figure 13b: Variation over time of the **operative temperature** in various apartments (grey area) after 1 day during which the heating system was kept on before being turned off, under the cyclic repetition of a “stress” winter day, and with zero internal gains.

WHY THE CURRENT BUILDING STOCK CANNOT CONTRIBUTE TO A SMART CITY WITHOUT DEEP RENOVATION?

Considering the situation before renovation of the building fabric, even delivering heat for one day with set-point temperature of 24°C, once the heating system is turned off the building will only remain in the comfort range for about ten hours (Figure 14). The effect of a potential shift of the demand is limited and very costly in terms of energy dissipation. In fact, most existing buildings behave like short-circuited (thermal) batteries. Thermal insulation of the building fabric, possibly with the addition of a mechanical ventilation system with heat recovery, proves to be an indispensable condition to enable the building to be flexible with respect to the moment in time when energy is required. Most of the current buildings are "rigid" in this respect and in winter they all need energy in the same morning time slot after the reduction of the set-point temperature at night.

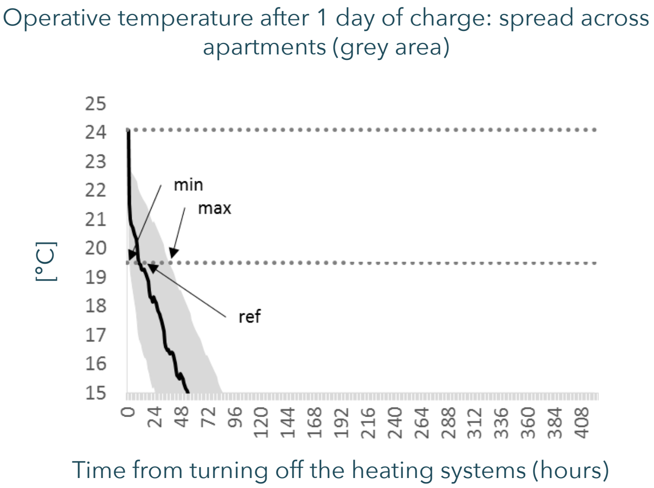


Figure 14: Variation over time of the **operative temperature** in a pre-retrofit case, with the heating turned off following a period of one day when it was on at 24 °C, with the cyclic repetition of an average day

HOW MUCH ENERGY CAN BE STORED?

The calculation for the amount of energy that is stored while the various layers that make up the building mass get warmed up (maintaining 24 °C **operative temperature** indoors) shows that 1-2 days with the heating system turned on are sufficient to activate a high percentage of the thermal storage potential of the structures. About 90% of the storage potential can be activated by keeping the heating system turned on for two days .

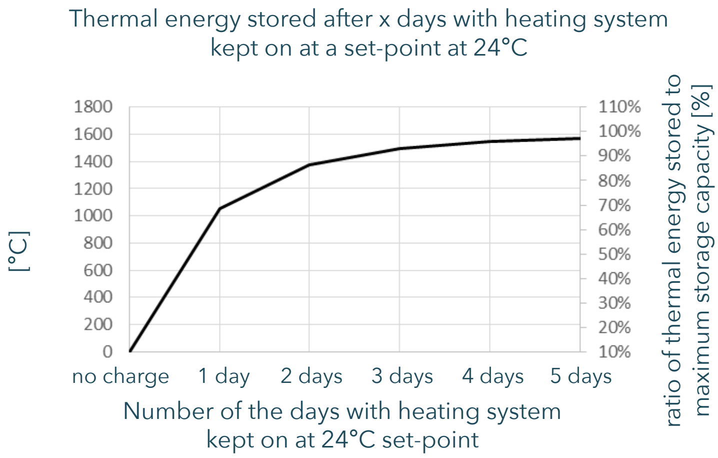
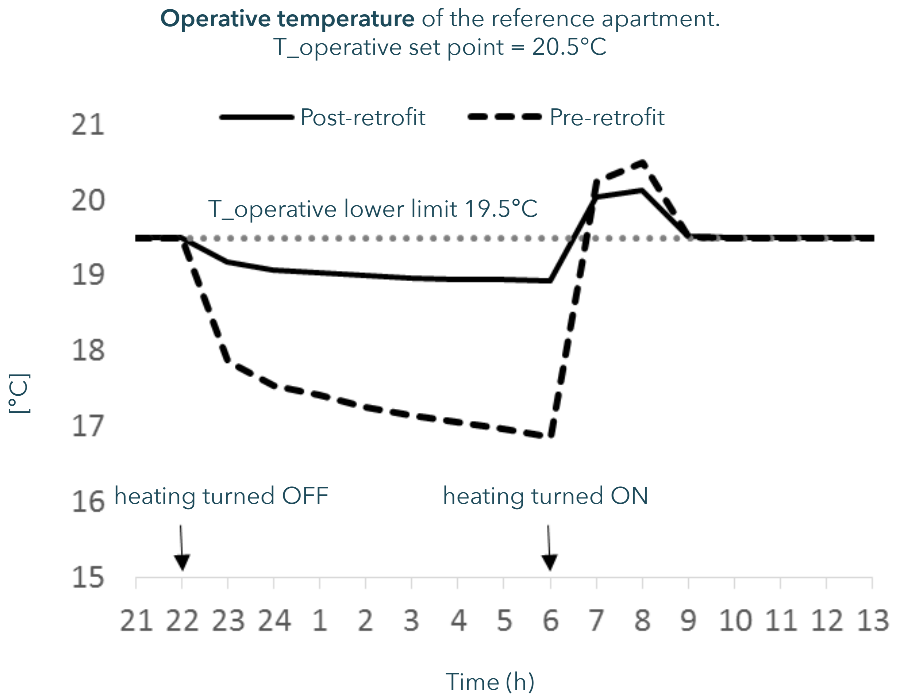


Figure 15: Energy stored in the thermal mass of one of the two buildings that were examined, as a function of the duration of the "charging" period, in absolute value (left) and as a percentage of the maximum storage capacity (right)

HOW MUCH THERMAL/ELECTRIC POWER CAN BE SAVED AS A RESULT OF DEEP RENOVATION?

The application of deep renovation strategies, while improving comfort levels, contributes towards a saving in the capital cost of the **technical building systems** for heat generation, distribution and emission (reduced by a factor of 4) and a reduction by a factor of 4 of the peak demand (when all the "conventional" buildings require heating power) on the grids if the building heat supply comes from District Heating or electric heat pumps, and therefore for the need to invest in power generation, transmission and distribution systems over the grids.



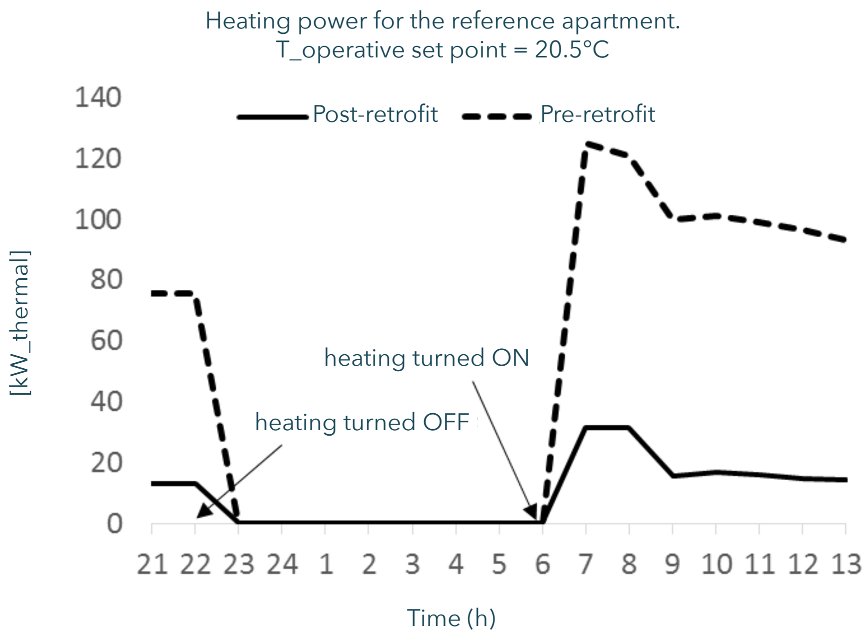
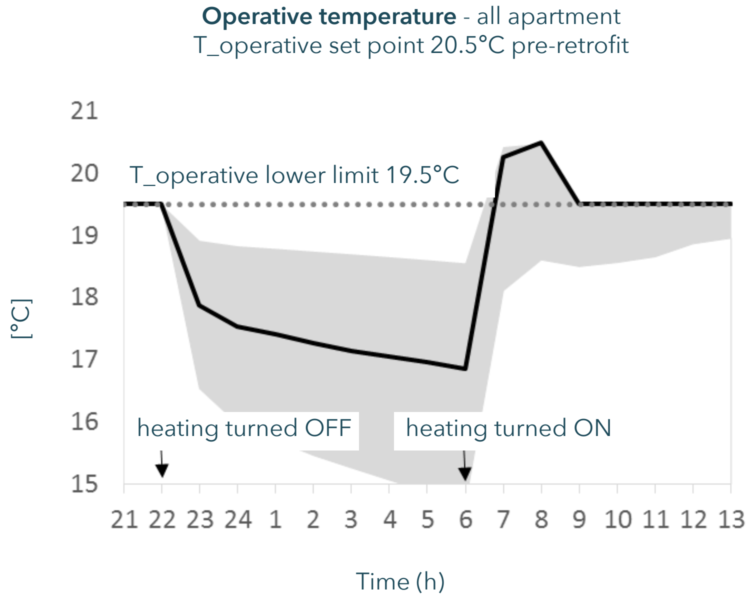


Figure 16: Evolution over time of **operative temperature** (top) and heating power demand (below) in a building during an]"average" winter day before and after a deep retrofit of the building fabric.

As shown in Figure 16, the thermal power peak demand for the whole building is reduced from 120 $kW_{thermal}$ before the retrofit to 30 $kW_{thermal}$ after the retrofit (i.e. in the order of 10 $kW_{electrical}$ with a heat pump with a COP = 3).

After deep renovation of the **building fabric** not only does the building require less power, but it is also flexible in relation to the time of that power demand (as described in the previous chapters).

Moreover, in the post-retrofit building all the apartments are rapidly back to the comfort zone when the heating system is turned on after the night-time attenuation, while in the pre-retrofit case many apartments would remain for hours below the comfort temperature (see Figure 17).



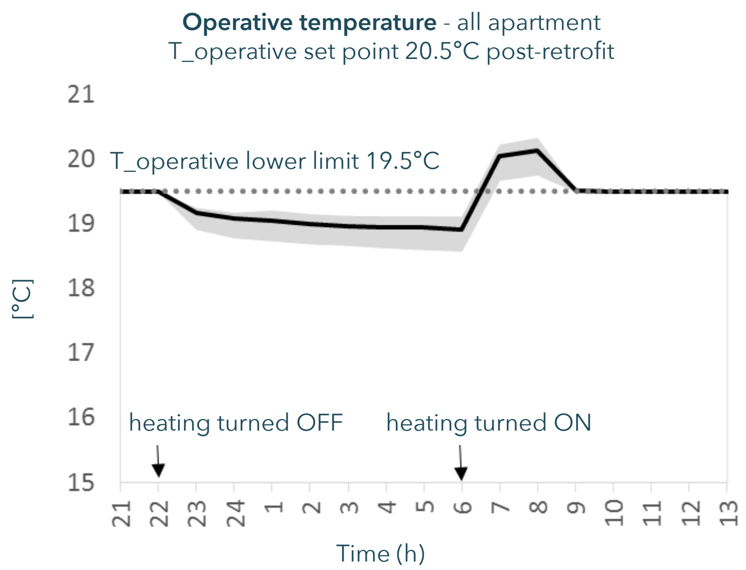


Figure 17: In a pre-retrofit situation there is a big difference in comfort conditions from one apartment to another, a difference that is significantly reduced post-retrofit.

CONCLUSIONS

One of the main obstacles for progressing towards so- called "smart cities" and the integration of renewables in buildings is the excessively high **energy need for heating and cooling** of our present building stock due to inadequate thermal quality of the **building fabric** and to ventilation losses.

A coherent and ambitious policy for the reduction of energy demand is confirmed by recent analyses to be the main route for:

- a rapid transition to renewables in order to avoid a catastrophic climate disruption (Grubler et al., 2018),
- the development of a strong renewable energy industry without the risk of encountering strong social opposition in territories with new excessively large installations for the generation, storage and transportation of energy.

Most roofs, external walls, ground floor slabs, glass panes and door and window frames in existing buildings have very low thermal resistance (i.e. excessively high values of both **stationary thermal transmittance**, which determines energy loss in winter, and **periodic thermal transmittance**, which is one of the determining variables of building's dynamic in summer). Sun shields are often missing or inefficient (for example internal sun shields are inherently ineffective to control solar gains in summer).

Current buildings are similar to a (thermal) battery that is short-circuited to ground: energy that is fed into the building is quickly discharged and wasted. We would never do anything of the sort with an electric battery, and it is indeed irrational to do so for the thermal storage available in the thermal capacity of walls and floors of the European building stock.

Good quality renovations of existing building envelopes can achieve a reduction in **energy need for heating and cooling** of up to 80% (see, for example the restructuring of social housing and schools made by the Municipality of Milan with the technical support of end-use Efficiency Research Group www.eerg.it[11]).

In a situation where the growth rate in the use of energy outpaces the rate of decarbonisation, the construction of new buildings and the execution of restructuring projects that do not apply the best design strategies and the best materials and components would be a net divergence from the goal of decarbonisation. If this non-optimal path is taken, the building stock will be locked-in for many decades in a level of **energy need for heating and coolin**g that is higher than that which has been made possible thanks to innovation in the building sector - by an amount that, e.g for Europe, is approximately equal to half of that consumed by the building stock in 2005. This excess amount would be wasted each year throughout the entire lifetime of those non-state of the art new or renovated buildings.

Not even a single kWh of precious renewable energy should be wasted, and even more we should carefully avoid creating situations that perpetuate energy waste for decades or divert energy to non-essential uses.

In addition to directly reducing the use of energy and climate-altering emissions, deep retrofit of **building fabrics** also has the effect of allowing a more rapid and effective penetration of renewable sources into the energy system. The increase of thermal insulation of walls and roofs, coupled with heat recovery ventilation, considerably increases the time interval during which a building remains in the comfort range[12] in the absence of energy input, making it possible to:

Coordinate the demand with the supply of local energy, by removing the current rigidity of energy demand from buildings and thus allow them to focus their use of energy at times when it is available from local sources (renewable or recovered energy) or to exchange energy with other buildings in a flexible way. Current literature on smart cities, micro-grids, etc. often omits to mention the fact that making the **building fabric** "physically smart" or "flexible" is a sine qua non factor for the possibility to use monitoring sensors and controls to manage demand.

[12] http://eu-gugle.eu/it/citta-pilota/milano/ http://www.eerg.it/index.php?p=Progetti_-_EU-GUGLE

[13] Comfort ranges are presented in International Standards on the basis of thousands of interviews with building occupants and simultaneous measurement of physical parameters. Cf.: ASHRAE Global Thermal Comfort Database I and II (Földváry Ličina et al., 2018)

Exploit moments of overabundance in the supply of renewable supply energy on the grid by making available energy storage capabilities in the buildings' thermal mass when such moments occur.

Manage conditions of energy supply shortage by attenuating peak power demand on the electric grid (connected to the foreseen penetration of heat pumps for space conditioning) or district heating network. This might take the form of peak shaving, peak shifting or demand response etc, with potential participation in the capacity market, thus creating further economic value which would be in addition to energy savings and increased comfort.

Far from being contradictory or conflicting, the various elements (reduction of the **energy need for heating and cooling**, deployment of sensors and controls, integration of renewables) are part of a framework where they are in close synergy with each other.

Reducing the **energy needs for heating and cooling** will not reduce the necessity to deploy renewables and sensors/controls. On the contrary, it is an indispensable prerequisite for renewables and controls to be productively deployed with environmentally and socially acceptable results, thus enabling their rapid penetration into our lives – something that we urgently need if we are to have any chance of seriously addressing the climate emergency.

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NOTE

Report produced in the context of the Research Agreement between Knauf Insulation Italia and the Politecnico di Milano (Public University) – Department of Energy

eERG
end-use Efficiency Research Group
Gruppo di ricerca sull'efficienza negli usi finali dell'energia

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