Technical restrictions on retrofit insulation of buildings

Dipl.-Ing. (FH) Peter Mellwig & Dr. Martin Pehnt
ifeu – Institute for Energy and Environmental Research Heidelberg
(Institut für Energie- und Umweltforschung GmbH)
Wilckensstr. 3
D-69120 Heidelberg
Germany
peter.mellwig@ifeu.de
martin.pehnt@ifeu.de

Prof. Dr. Patrick Jochum
Beuth Hochschule für Technik Berlin
Luxemburger Straße 10
D-13353 Berlin
Germany
jochum@beuth-hochschule.de

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Abstract
During the process of retrofitting existing buildings, certain constructions and components cannot be insulated as required by national regulations. These restrictions on insulation have numerous reasons, such as sheltering architectural monuments, geometry, building physics, aesthetic aspects, and residential areas.

With a research project documented in this article, these restrictions were, for the first time, systematically identified and their share of the heat demand in the German building stock quantified. Furthermore, over 400 energy consultants and other experts were interviewed. The participants were asked to judge the frequency of restrictions on insulation in their daily work.

The results of the survey served as the basis for further calculations of the nationwide heat loss. The restrictions were weighted by survey ranking, typical area and typical "uninsulatability". A model for German building stock was programmed to calculate the heat loss.

As the restrictions concern energy refurbishments, their percentage rises in time with the on-going process of renovation. The course of the impact of restrictions was shown for four scenarios in a long-term perspective up to 2050. A fifth scenario was calculated to show the total potential of insulation measures and the share of restrictions on insulation. The model shows that even after an ambitious energy renovation of German building stock with high standards, a bottom heat demand of around 42 percent of today's heat demand remains.

About one third of the remaining heat demand consists of insulation restrictions. Most important are restrictions concerning the exterior wall (60 PJ/a heat losses due to restrictions), followed by restriction of the basement ceiling and the floor level (around 40 PJ/a) and listed building elements (20 PJ). Only future developments of insulation approaches and the use of renewable resources for heating will help to further lower the associated greenhouse gas emissions as long as the buildings are not dismantled.

Introduction
The German government set long-term aims for the country's building stock in its energy concept of 2010, which stipulates that the energy consumption for heating and hot water should be lowered by 80 percent by 2050. Most of the buildings that will exist in 2050 have already been built. About 75 percent of the residential building stock was built before 1978, when the first Thermal Insulation Regulation (1. Wärmeschutzverordnung) came into force. The structural thermal insulation of these buildings is about two to three times worse than in modern buildings.

Retrofit insulations are thus an important way of reaching the target. In daily practice, however, numerous construction situations cannot be insulated as required. The heat loss caused by these restrictions could not previously be quantified. Its share of the total heat loss was relatively small as long as the insulation standards were low. With increasing insulation standards, the restrictions become more important. The Beuth Hochschule für Technik Berlin and the IFEU Institut für Energie- und Umweltforschung Heidelberg cooperated in this project to analyse which kind of restrictions on insulation exist and what is their share of the heat demand of the German building stock. The final report documents the analysis (Mellwig et al. 2012) and can be downloaded from www.ifeu.de.

The project is divided into five phases. In the first phase, restrictions on insulation are defined in nomenclature. In the second phase, a survey was carried out amongst energy consultants and other experts to produce a ranking of the most effective restrictions on insulation. In the third phase, the quantity structure of the German building stock was researched and collated in a spread sheet containing both residential and non-residential buildings. The model can resolve single constructions with regard to their specific areas and energy quality. In the calculation phase, the model was adjusted to calculate the heat loss due to insulation restrictions. The earlier phases provide the basis for this specific, construction-wise calculation.

In the last phase, the results were revolved in four scenarios for analysis of the impact of the restrictions in the future, especially for the government's targets.

Nomenclature of Restrictions on Insulation

Insulation is considered to be restricted when an entire building or individual components either cannot be insulated enough to fulfil the current legal requirements for energy conservation at the time insulation is to be added – currently, Energy Conservation Ordinance 2009 (EnEV 2009) – or cannot be insulated at all.

As a result, insulation can only be restricted when existing buildings are to be retrofitted to improve their energy properties. There are no technical insulation restrictions on new buildings. Here, it is assumed that designs are selected in compliance with the minimum requirements in current law.

There is a risk of the terms "insulation restrictions" and "thermal bridges" being confused. Both concern weak points in a building's heat transmissivity. But while thermal bridges often occur where two building components are connected (such as at the joint between external walls and windows), insulation restrictions mainly concern the surfaces of individual building components (such as external walls). In other words, thermal bridges are lines or points, while insulation restrictions are surfaces.

Thermal bridges are the result of design and geometric issues. Unlike insulation restrictions, they occur in every building and are generally taken into consideration when a building's thermal performance is calculated. Thermal bridges refer to a relatively limited number of connection details. A large number of publications have looked onto the impact of thermal bridges on the energy balance of buildings. This study expressly does not further investigate this issue.

Furthermore, a distinction has to be made between technical and non-technical insulation restrictions. The focus of this study is on technical restrictions that affect construction.

A. TECHNICAL INSULATION RESTRICTIONS

Design-related insulation restrictions concern components that are no longer accessible for reworking. For example, when a basement is beneath a part-section of the house only, one or more of the basement's external walls are below the floor slab. In this case, external insulation (perimeter insulation) cannot be added to these basement walls without removing soil from below the building.

Insulation restrictions caused by construction physics focus on the risk of an insulation layer detrimentally affecting a component's properties in terms of construction physics. For instance, the temperature of masonry drops considerably when interior insulation is added to an external wall. When indoor air humidity comes into contact with this cold masonry, it condenses into water. Buildings that have timbered beams in the ceiling run the risk of having the ends of the beams, which are anchored in external masonry, exposed to high amounts of moisture, potentially resulting in considerable damage to the structure.

When interior insulation is added to post-and-beam structures, there is a risk of wind-driven rain and/or indoor humidity entering the structure and building up. Once again, the result can be considerable damage.

Geometry-related insulation restrictions occur when components cannot be retrofitted with insulation because of the building's geometry. For example, windows and doors directly next to a building's interior corner would be partly covered if insulation were added to the external wall. A thick layer of insulation could also greatly reduce the amount of space in open loggias.

B. NON-TECHNICAL INSULATION RESTRICTIONS

Insulation restrictions resulting from regulations occur when other regulations override the targets of the Energy Conservation Ordinance. For example, Section 24 EnEV stipulates that heritage buildings are exempt from the insulation requirement. Emergency exit balconies also have to have a minimum width, which must not be compromised by insulation thickness.

Aesthetics-related insulation restrictions. Some buildings have an appearance that would be particularly detrimentally affected by insulation. Examples include traditional construction methods that are not under heritage protection, such as masonry in northern Germany and decorative plaster façades on Wilhelminian style buildings.

Behaviour-related insulation restrictions concern building users whose behaviour prevents the addition of the insulation required by the Energy Conservation Ordinance. Examples include building owners who do much of the work themselves and may not know what is required by law. Elderly building owners may also believe that they will not be in the building long enough for the renovation to pay off.

One common insulation restriction is the alleged **economic inefficiency** of insulation. On closer inspection, however, the

Table 1. Types of insulation restrictions.

A. Technical insulation restrictions	B. Non-technical insulation restrictions
Design	Regulations
Construction physics	Economic disinterest
Geometry	Insufficient willingness to change

cost argument usually turns out to be the result of one of the aforementioned obstacles. Put differently, the inefficiency of insulation is not itself yet another cause of insulation restrictions, but rather quite often merely the result of the items listed above. Restrictions make it harder to add insulation; investment costs increase, and efficiency decreases. A lot of insulation restrictions would not exist if funding were available in unlimited quantities.

In extreme cases, an old building can be torn down and replaced by a new one not subject to insulation restrictions. This study therefore defines a building owner with maximum ambitions, but one who is nonetheless "reasonable." Construction measures that this fictitious building owner would not undertake define the insulation restrictions.

In defining insulation restrictions, considerations of efficiency come in between two extremes. On the one hand, a large number of technical insulation restrictions would not occur if efficiency were not considered. In other words, basically everything could be insulated if money were no object. On the other hand, it could be assumed that there is an economic optimum for insulation resulting from the (lowest possible) investment costs and the (highest possible) reduction of fuel costs. If this optimum is the goal, all types of insulation that would worsen this cost-benefit ratio should be avoided. These types of insulation would then also be considered insulation restrictions.

Of course, both of these extremes have little to do with reality on construction sites. In actual renovation projects, the calculation is mixed, with the more economical measures counterbalancing the less economical ones. A lot of insulation work is performed for more than just energy reasons. Often, for instance, the building's value is to be retained, indoor comfort is to be increased, and the building is to be made more attractive on the rental market. These factors are, however, hard to quantify when calculating economic efficiency. In other words, not every insulated building component has to pay for itself by offsetting fuel costs when a building is renovated to reduce energy consumption. It therefore does not make sense to break down the calculation of payback by individual building components.

Survey

A survey was taken among energy consultants, planners, and others in the construction sector to determine how often individual restrictions apply in practice. The survey was based on multiple-choice questions. Participants were asked to state how often 63 individual insulation restrictions occur in practice. They also had the opportunity to name and assess additional restrictions and write comments. A total of 496 people took part in the survey, 364 of whom filled out the entire survey (132 did not).

Figure 1 shows the participants' assessments by building component. The question was: "How often in practice do you have a situation in which a building component cannot be properly insulated or cannot be insulated at all?" Clearly, insulation restrictions affect windows the least (long dark bars). Overall, insulation restrictions affect walls and floors touching the ground the most (longest light bars).

The survey results were weighted according to the surface of the building component in question to see how relevant individual restrictions are. Furthermore, account was taken of whether the building components in question can be insulated at all and to what extent. The following insulation restrictions are highly relevant for heat demand in this assessment:

- Visible masonry with external insulation.
- External walls with heritage protection and external insulation.
- Risk of moisture damage with internal insulation for external walls.
- (Decorative) plaster with internal insulation on external wall.
- Topmost floor ceiling not accessible.
- Clearance insufficient if basement.
- Ceiling is insulated.
- Walls and floors touching soil.

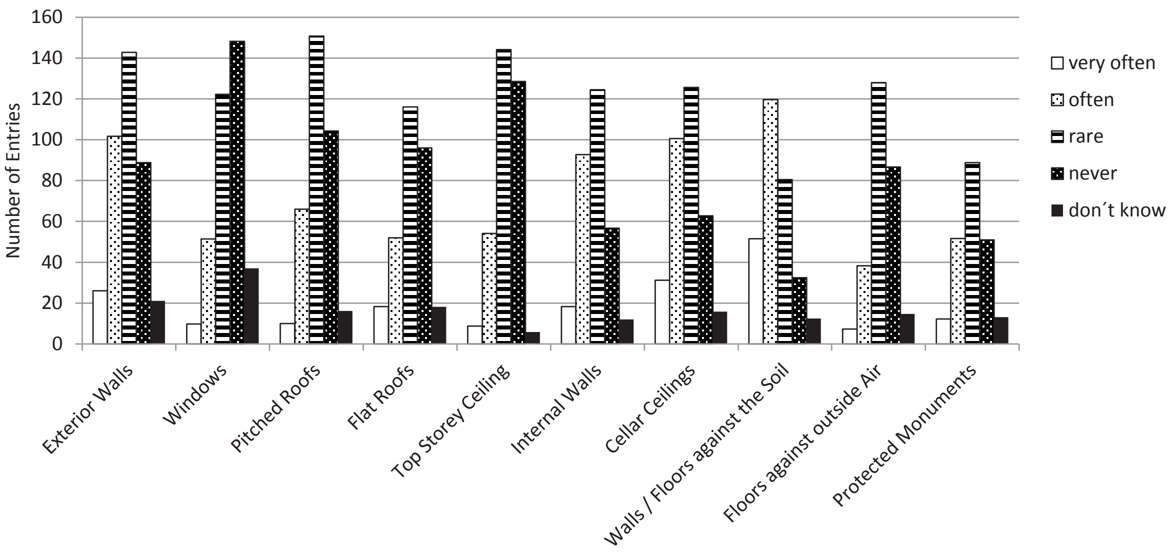

Figure 1. Assessments from all survey participants by building component affected by insulation restrictions.

- Architecture/appearance if external walls have external insulation.
- External walls with heritage protection and internal insulation.
- Plaster/ornamentation with external insulation.
- Piping below ceiling with insulation applied to basement ceiling.
- Architecture/appearance when windows are replaced.
- Insulation of vaulted ceilings.

The participants mainly mentioned non-technical insulation restrictions in their comments. The most common mentions were:

- Building owners not informed or motivated.
- Concern about unpleasantness/dirtiness during construction phase.
- Building owners too old.
- Requirements too strict and funding too scarce.
- Insulation already in place, retrofit inefficient.
- Costs cannot sufficiently be passed on to tenants.

Quantification of insulation restrictions

APPROACH

Insulation restrictions cause higher heat loss than regularly insulated building components do. The extent of heat losses caused by insulation restrictions is calculated using the common formula for thermal conductivity.

$$\Phi = U \cdot A \cdot \Delta\Theta$$

where
Φ is the heat output,
A is heat-conducting surface,
$\Delta\Theta$ is temperature difference on the two sides of the surface and
U the thermal transmittance coefficient.

The heat-conducting surface (A) depends on the kind of insulation restrictions. It can be very small or cover the entire building envelope. The temperature difference ($\Delta\Theta$) depends upon the outdoor and indoor temperatures. The indoor temperature is assumed to be 19 °C (in accordance with DIN 4108-6: Boundary conditions for monthly balances). Outdoor temperatures were calculated for each month based on the German reference climate (DIN 4108-6: Reference values for radiation intensities and outdoor temperatures for the German reference climate).

The thermal transmittance coefficient (U) results from the layer thickness and material values of the building component in question. To determine the heat losses caused by insulation restrictions, however, the difference between the target value for the thermal transmittance coefficient and the actual minimum value attained with the insulation restrictions must be used.

The approach described allows the amount of heat losses due to an insulation restriction to be calculated. To calculate the **difference of heat transmissivity coefficients (ΔU_{DR})** for all buildings in Germany, the following factors had to be addressed:

- What is the typical thermal transmittance coefficient for building components without insulation?
- Which requirements must be fulfilled when a component is insulated?
- How are components usually insulated?
- What kind of insulation restrictions occur?
- Which insulation thicknesses are feasible with specific insulation restrictions?

For the determination of the nation-wide **heat-conducting surfaces (A)**, these questions must be investigated**:**

- What kinds of buildings exist in Germany?
- Which insulation restrictions occur to what extent with these building types?
- How many buildings of each type are there?
- How large are the typical building component surfaces?
- How large are the typical surfaces for individual insulation restrictions?

Even one single type of component can contain several sub-types. As the sub-types may cause very specific insulation restrictions they need to be regarded separately. Figure 2 shows four subtypes of masonry walls which each cause specific restrictions.

To estimate heat losses caused by insulation restrictions in the way described, a calculation model was created to determine losses for each building component and building type. The model was based on a spreadsheet application. The data used for existing residential buildings are based on typologies from the Institut Wohnen und Umwelt (IWU 2005). As the available data for the stock of non-residential buildings and their heat-conducting surfaces is very poor, several studies and statistics were combined (Kleemann, Hansen 2005, BMVBS 2011, Kohler et al. 1999, BKI), and additional calculations had to be made. The model takes account of the size and number of buildings affected along with the surfaces and heat properties of the components. The individual insulation restrictions were quantified based on the availability of data.

For instance, the number of heated heritage sites was taken from state heritage registries. The frequency of visible masonry façades and other façades considered worthy of protection was determined based on aerial photos. Other insulation restrictions were assigned to specific building types or age groups. To the extent necessary, insulation restrictions were subdivided into categories, and account was taken of their frequency and maximum insulation thickness.

QUANTIFICATION EXAMPLE: HERITAGE BUILDINGS

The "heritage protection façade" restriction, for instance, was broken down into four subcategories. It is easier to assign individual subcategories to specific age classes and building types for quantification. The subcategories are shown in Table 2 with a description of the specific insulation restrictions. The total quantified heat demand that results from this insulation restrictions is shown in Figure 3.

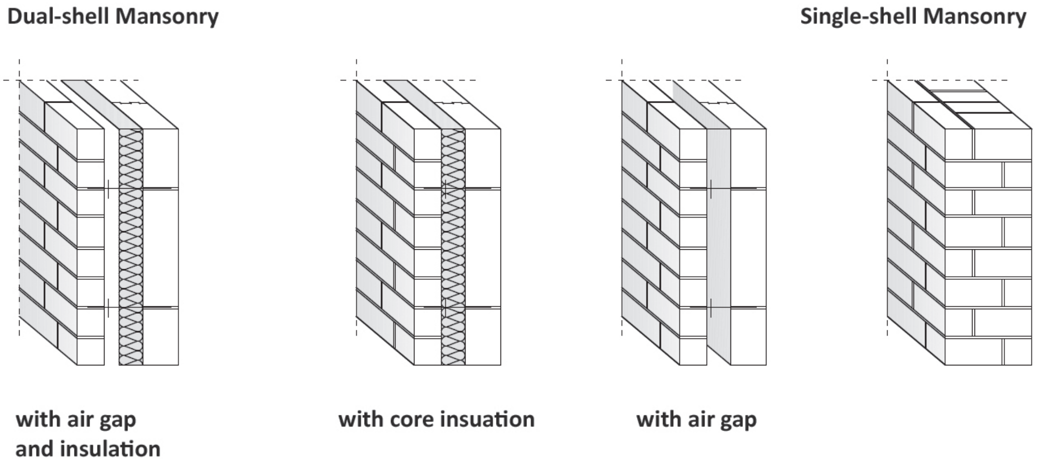

Figure 2. Options for a wall structure with single and dual-shell visible masonry.

Table 2. Subcategories of building insulation restrictions in heritage buildings.

Heritage buildings with ornamentation only on one external wall	This insulation restriction mainly concerns buildings from the Wilhelminian era (up to 1918). Here, there is a salient amount of decorated façades facing the street that cannot be insulated from the outside. It is assumed that the other external walls can have modern insulation added. It is also assumed that 15 percent of residential and non-residential buildings from this era are affected. From 1919 to 1957, it is assumed that 0.5 percent of buildings have this kind of ornamental façade.	
Heritage buildings that can be insulated with thin insulation on all sides	This insulation restriction especially concerns buildings constructed from 1919 to 1957 and, to a lesser extent, buildings constructed up to 1968. Generally, a three to four-centimeter layer of insulating plaster is added. Buildings constructed from 1919 to 1948 are the focal point of this type of insulation restriction, with five percent of them affected. Only four percent of buildings from 1949 to 1957 are affected, compared to only one percent of those up to 1968.	
Heritage buildings with restrictions on interior insulation	This insulation restriction especially affects buildings with timbered beams in the ceiling, generally in buildings up to 1957. While five percent of buildings up to 1918 are affected, only 0.5 percent of those from 1919 to 1957 are. In contrast, 67 percent of post-and-beam buildings, which are especially demanding in terms of construction physics, are assumed to be subject to this insulation restriction. A large number of post-and-beam buildings have heritage protection, and external insulation is generally not an option for such heritage-protected buildings; in addition, interior insulation in such buildings is always especially demanding. For all of the age groups specified, thinner insulation (four centimeters) is assumed, putting the insulation layer's thermal conductivity below 1.0 W/m²K, a target specified in several studies (Stopp, 2003).	
Heritage buildings that cannot be insulated	This restriction concerns buildings that are to be preserved both inside and outside, for instance to protect ornamentation on the façade and interior. No insulation can therefore be retrofitted. The share of buildings subject to this restriction is estimated at two percent for buildings from 1918 or earlier, compared to one percent of buildings from 1919 to 1948 and 0.5 percent of those from 1949 to 1957. The number is estimated at 20 percent of post-and-beam buildings.	

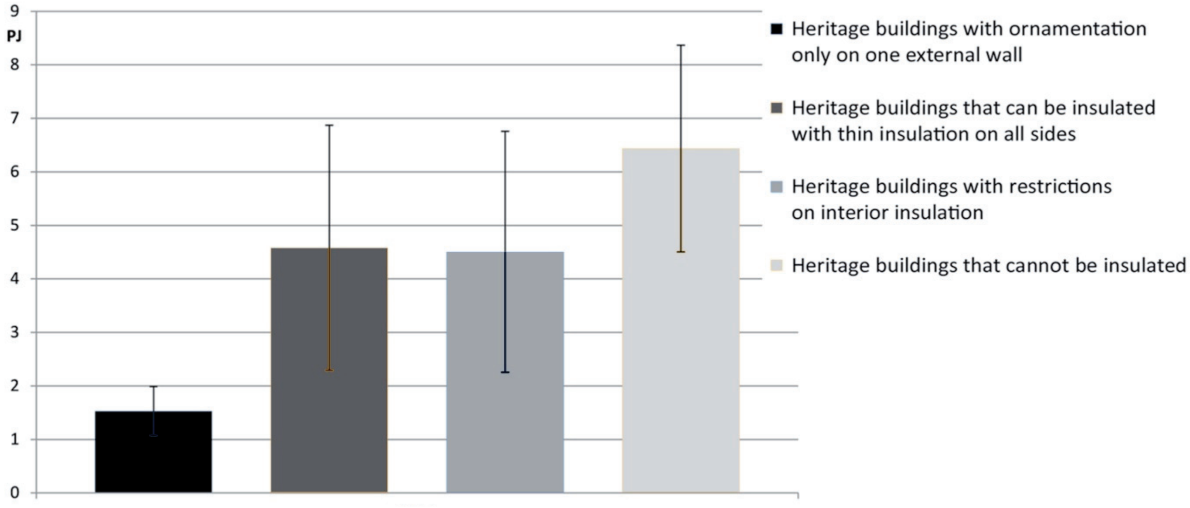

Figure 3. Effects of the "external wall (with heritage protection)" insulation restriction on the amount of heat that cannot be insulated in 2012 – equivalent to about 17 PJ, less than one percent of total demand for heating energy in Germany.

RESTRICTIONS FROM LOW REGULATORY REQUIREMENTS

In addition to insulation restrictions for individual building components, there are systematic insulation restrictions for entire buildings. They are derived from a requirement level that is simultaneously too low to fulfil the energy concept's future requirements and too high to ensure that further energy improvements are affordable in the next renovation cycle.

The payback on energy renovations largely depends upon the energy quality of the building before renovations. The worse a building is insulated to begin with, the greater the savings potential is. Because a large share of the renovation costs generally does not depend upon the building's condition (such as the cost of façade scaffolding, plasterwork, etc.), renovations of poorly insulated buildings usually have a faster payback than better insulated ones. Energy renovations of unrenovated buildings constructed before the first Insulation Ordinance (1977) frequently pay for themselves given current energy prices (dena 2011).

A complete renovation of such buildings to the standard for new buildings in EnEV 2009 improves heat transmissivity losses (H_T') by around 70 percent. Buildings constructed after the second Insulation Ordinance (1984) are now entering their first round of renovations. Because their starting point is better, the payback on energy renovations is generally slower.

The thermal transmittance coefficient of a renovation project in compliance with the standard for new buildings in EnEV 2009 would be improved by around 50 percent. Buildings constructed in accordance with EnEV 2002 are scheduled to enter their first round of renovations before 2050. The savings potential from these buildings, however, is considerably lower than with older buildings. The thermal transmittance coefficient of a renovation project in compliance with the standard for new buildings in EnEV 2009 would be improved by around 33 percent. The cost of additional insulation will not pay for itself in terms of offset energy costs. Even if we assume that energy prices will increase during this timeframe far faster than the cost of renovations, the affordability of such future insulation work is very questionable.

When standards for currently built or renovated buildings are too low, these buildings become "locked in" to their energy level.

Comparison of Restrictions

The greatest losses caused by insulation restrictions occur on external walls. Basement ceilings and components touching the soil are the second biggest group. In contrast, topmost story ceilings that cannot be insulated play only a minor role (Figure 5).

At present, insulation restrictions only make up around five percent of demand for heating energy in Germany. However, insulation restrictions only crop up when the building is to be renovated – in other words, the more extensive the renovation, the greater the share of restrictions.

Figure 6 shows the temporal trend. Renovations reduce demand for heat, and heat losses from insulation restrictions simultaneously increase. However, the calculation assumed that buildings entering their second renovation cycle are renovated more thoroughly, thereby reducing a wide range of insulation restrictions. This contrary effect means that heat losses from insulation restrictions will taper off at a certain level.

Figure 6 shows the progression until a plateau is reached. At that point, Germany's entire building stock has been renovated to an ambitious energy level. Demand for heat will then drop to around 42 percent of the current level, at which point insulation restrictions will make up 28 percent of total demand for heating energy.

Outlook

The analysis shows that the government's targets – reducing the current primary energy demand by 80 percent – cannot be reached only by means of insulation. Renewable energies and efficient technologies need to provide high energy savings. The political framework has to anticipate and promote this process.

The heat loss from insulation restrictions has to be compensated in constructions without restrictions as far as possible.

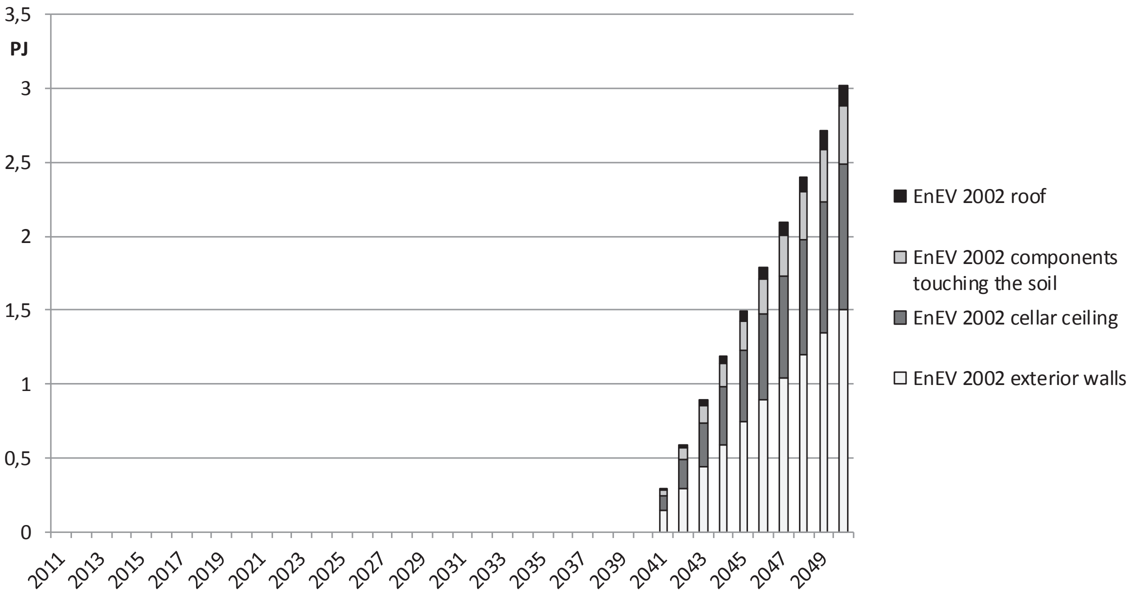

Figure 4. Lock-in effect: Insulation restriction due to requirements in the 2002 building code (EnEV: Energy Savings Ordinance) become effective in a few decades.

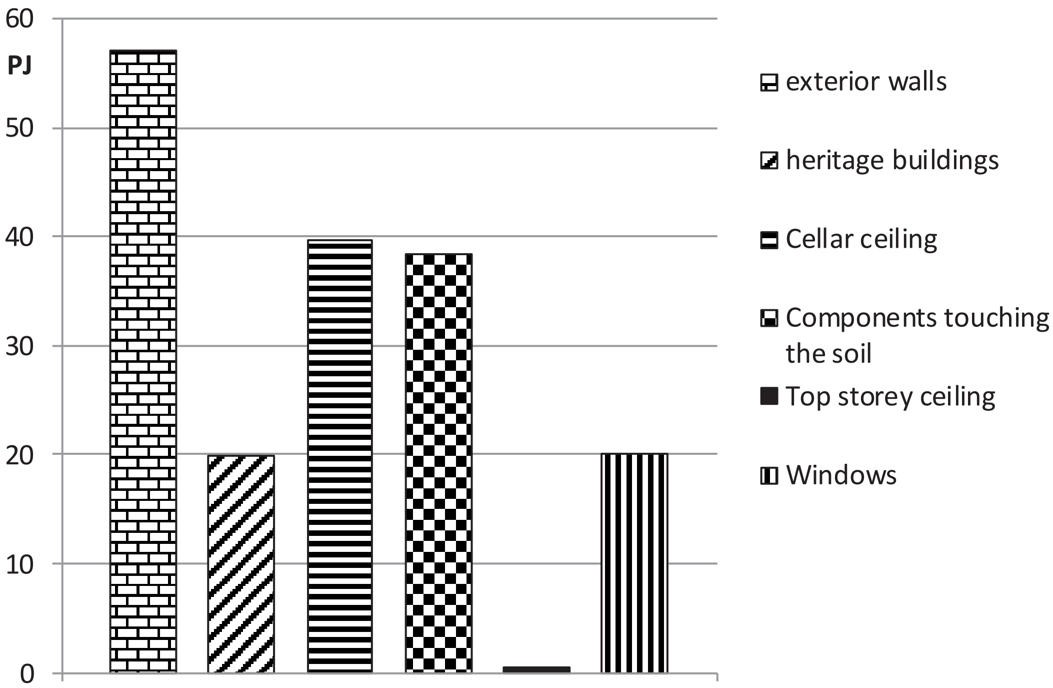

Figure 5. Comparison of insulation restrictions by components affected.

This means that higher standards are needed even for retrofit insulations. The energy standards for new buildings have to be orientated at future standards to avoid that these buildings become "locked in" in low-class energy performance. New buildings at today's standards will be economic insulation restrictions in 2050. In other words, insulations can be assigned to the categories "helpful to reach the aims in 2050" and "not helpful to reach the aims in 2050".

As many insulation restrictions refer to non-technical causes, such as insufficient willingness and insight, a higher level of information and education is needed as well. Motivating the people also includes concerted policy actions and targeted approach. This means effective funding programs, ambitious legislation, and comprehensive information. Details of such policy packages are documented in another eceee paper (Pehnt et al. 2013).

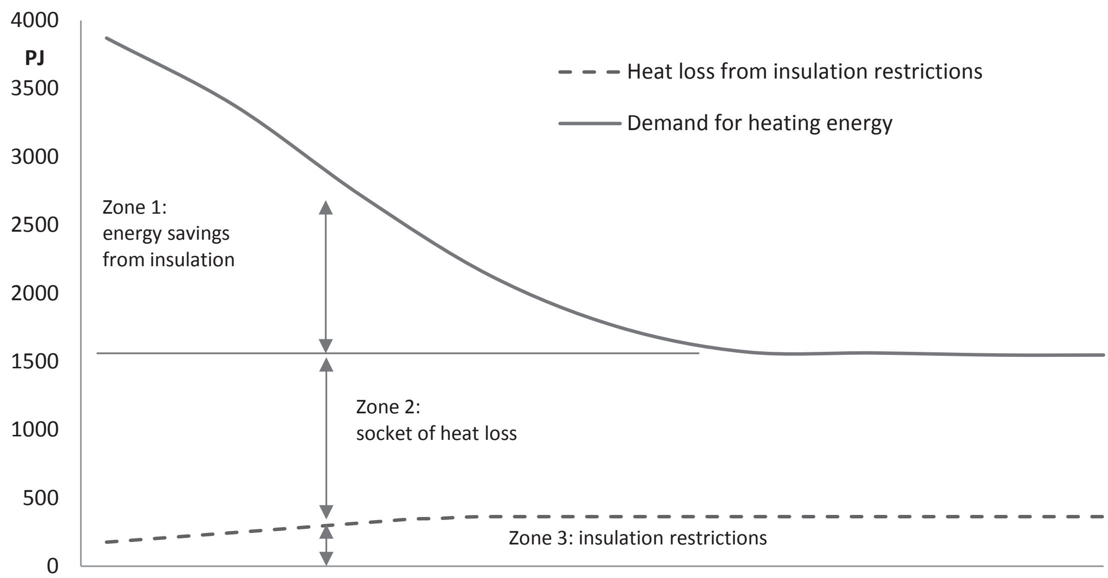

Figure 6. The development of heat demand and heat losses from insulation restrictions up to a saturation phase.

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