Bayerisches Landesamt für
Umwelt

Abstract for the presentation
"Life cycle analysis of residential buildings"
during the cooperation forum
"Nachhaltiges und energieeffizientes Bauen im Alpenraum 2017"
("Sustainable and energy-efficient construction in the Alpine region 2017")

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Summary of the study "Life cycle of residential buildings"

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1. Background of the study "Life cycle analysis"

Mr. Holger König and his company Ascona GbR have, on behalf of the Bavarian State Office for the Environment and funded by the Bavarian Ministry of Economic Affairs carried out a study on the life cycle analysis of residential buildings. The study's aim is to contribute to the debate about sustainability of construction works. Apart from considering the ecological and economical aspects, it also offers an overview of the specific advantages of the different construction methods and is thus an aid for citizens when building a house.

2. Scientific base for the calculation of the life cycle analysis

A representative sample house was examined according to the criteria of DIN EN 15978[3] and DIN EN 15804[4] in the sense of a comprehensive life cycle assessment. The following life cycle phases were included in the study: Production phase A1 - A3 (raw material supply, transport, production), usage phase B2, B4, B6 (maintenance, replacement, operational energy consumption) and disposal phase C3, C4 (waste management, disposal). Additionally, the advantages and burdens outside of the system limits (module D) were considered, which contain potential for reuse, recovery and recycling in the shape of credits. The examination period was defined as 50 years.

3. Scope and method of the life cycle analysis

A single-family house without a cellar with a net floor area (Nettoraumfläche[5]) of 150 m² of which 135 m² are pure living space, was the basis for the investigations. Its surface-to-volume ratio (A/V) of 0.73 represents compact design without projecting elements. The building is divided into two floors, and with the stairs moved next to the entrance and sanitary installations on both floors, it is possible

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[1] Ökoenergie-Institut Bayern, Bayerisches Landesamt für Umwelt (Bavarian State Office for the Environment)

[2] Ascona GbR

[3] DIN EN 15978: "Sustainability of construction works - Assessment of environmental performance of buildings - Calculation method"

[4] DIN EN 15804: "Sustainability of construction works - Environmental product declarations - Core rules for the product category of construction products"

[5] Nettoraumfläche (NRF) = sum of the usable floor spaces of a building

to divide the house into two separate apartments. 33% of the window areas face south, the ceiling to the attic floor is insulated and thus forms the top rim of the thermal envelope. The concept provides for a technical room on the ground floor for the technical equipment instead of a cellar. Image 1 below gives an overview of the building.

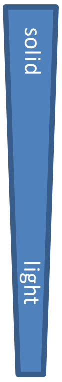
South

Section – West

Image 1: South and west view of the single-family house examined

Six different construction methods were examined for the life cycle analysis, all with rendered facades. Apart from that, the house was modelled and analysed with three different energy levels and four different heating technologies, calculated according to the German Energy Saving Ordinance (Energieeinsparverordnung – EnEV).

Construction methods:



- Brick construction and monolithic design with or without insulating material filling
- Sand-lime brick construction with rendered exterior insulation and finishing system (EPS-EIFS)
- Monolithic and multi-layer autoclaved aerated concrete
- Hybrid construction with heavy construction in the building core and light enveloping surfaces
- Solid wood system with rendered exterior insulation and finishing system (wood fibre-EIFS)
- Timber frame construction with rendered exterior insulation and finishing system (wood fibre-EIFS)

Heating systems:

- Gas condensing boiler with solar thermal hot water heating
- Wood pellet boiler
- Air-to-water heat pump
- Water-to-water heat pump

Energy levels:

- EnEV new building requirement[6] (since 1.1.2016), without ventilation system
- 30 kWh / (m²·a) heat energy requirement, with exhaust air system
- 15 kWh / (m²·a) heat energy requirement, with ventilation system including heat recovery system

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[6] according to the calculation bases of DIN 4108 and DIN 4701

The resulting 72 different varieties were examined thermally-dynamically via a computer-aided simulation with the simulation software TRNSYS17 using a seven-zone model. This allowed for the examination of heat storage effects as well as night-time ventilation and solar gains and thus their influence on the heat energy requirement and the thermal comfort of the building in the summer. The life cycle assessments were rated using the software LEGEP and data from German data base ÖKO-BAUDAT 2016.

4. Rating criteria

Apart from the quantifiable aspects from the areas ecology and economy, the rating criteria also include further quality aspects. In the area of ecology, the environmental impact in terms of the resource consumption (primary energy renewable, non-renewable and total energy), the greenhouse gas, eutrophication, photochemical smog and acidification potential were examined. The quality aspects focus on thermal comfort, longevity, acoustics, presence of pollutants in the room air and fire resistance. In the area of economics, the costs of different construction methods (only for EnEV standard) were examined.

5. Heat energy requirement

Using a thermal-dynamic simulation, the heat energy requirement of the respective building types were determined based on the U-values of the envelope surfaces, taking the heat storage effects of materials of different weights into account. For this, the target room temperature was specified as 20°C and the data of the test reference year 13 (Munich) was used as weather input.

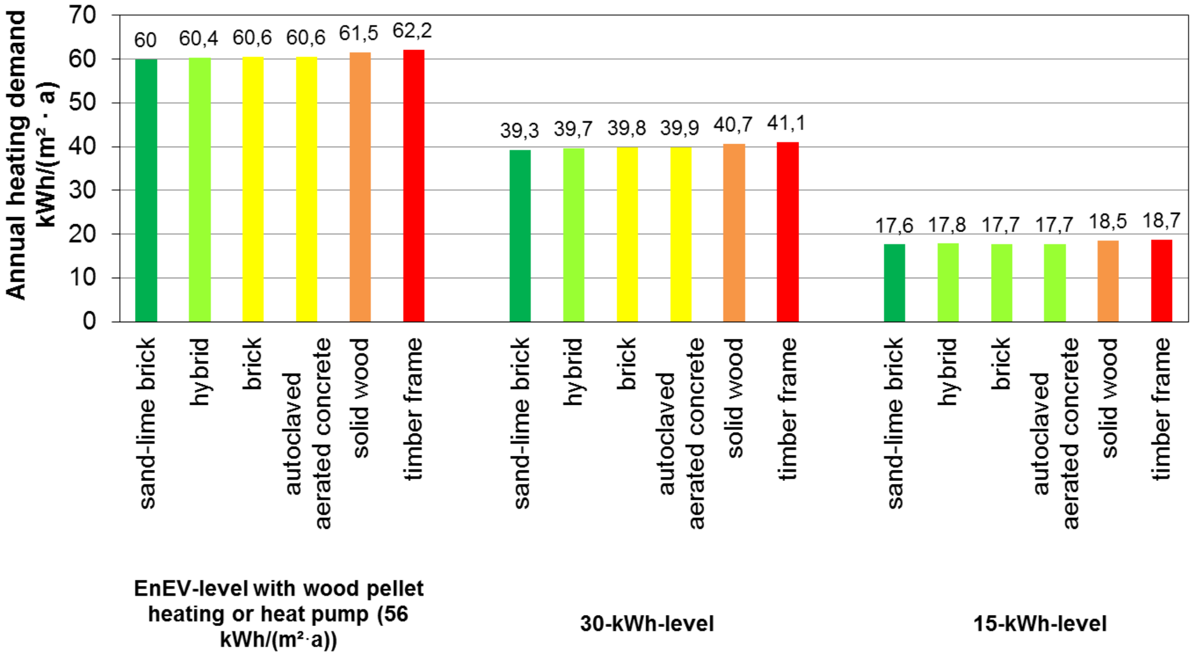

Image 2: Heat energy requirement data of the different construction methods and energy levels

It showed that the construction methods with lower efficient thermal mass cause slightly higher heat energy requirements than the solid construction methods (image 2). Depending on the energy standard, the spread is between 3.6% and 6.3%. The better the selected energy standard, the higher the percentage difference between the highest and lowest heat energy requirement. In the best case it will be possible to save more than 10% of the heat energy requirement compared to lightweight constructions due to the heat storage effect between the warm and the cold phases. Also with hybrid construction in comparison a lower heat energy requirement is achieved across the different energy levels.

Furthermore, a significant decrease of the heat energy requirement from EnEV to 15 kWh level of around 70% can be observed.

6. Life cycle assessment

After detailed modelling of the building, the effects of the processes during construction, maintenance and demolition (= building) of the different construction methods and during the operation were examined by a life cycle assessment. For this, the life cycle assessments were prepared based on energetic and ecological parameters.

6.1. Primary energy consumption

Looking at the primary energy consumption of the life cycle assessment, the result is contrary to that of the heat energy requirement of point 5 (image 3). Here, the lightweight construction methods perform better than the solid construction methods in terms of non-renewable and total primary energy consumption necessary for the processes of *construction, maintenance and demolition*. For lightweight constructions the share of renewable primary energy consumption is higher than that of the solid construction method. When considering the primary energy consumption, the hybrid construction method ranks between the other two construction methods.

With increasing efficiency levels, the construction costs increase slightly when a lower energy consumption of a building is to be achieved, which results in an increased primary energy consumption depending on the construction method: for wood pellet heating by 10 - 18%, for gas-fired condensing technology with solar thermal energy by 1 - 13%, for air-to-water heat pumps by 9 - 19% and for water-to-water heat pumps by 9 - 17%.

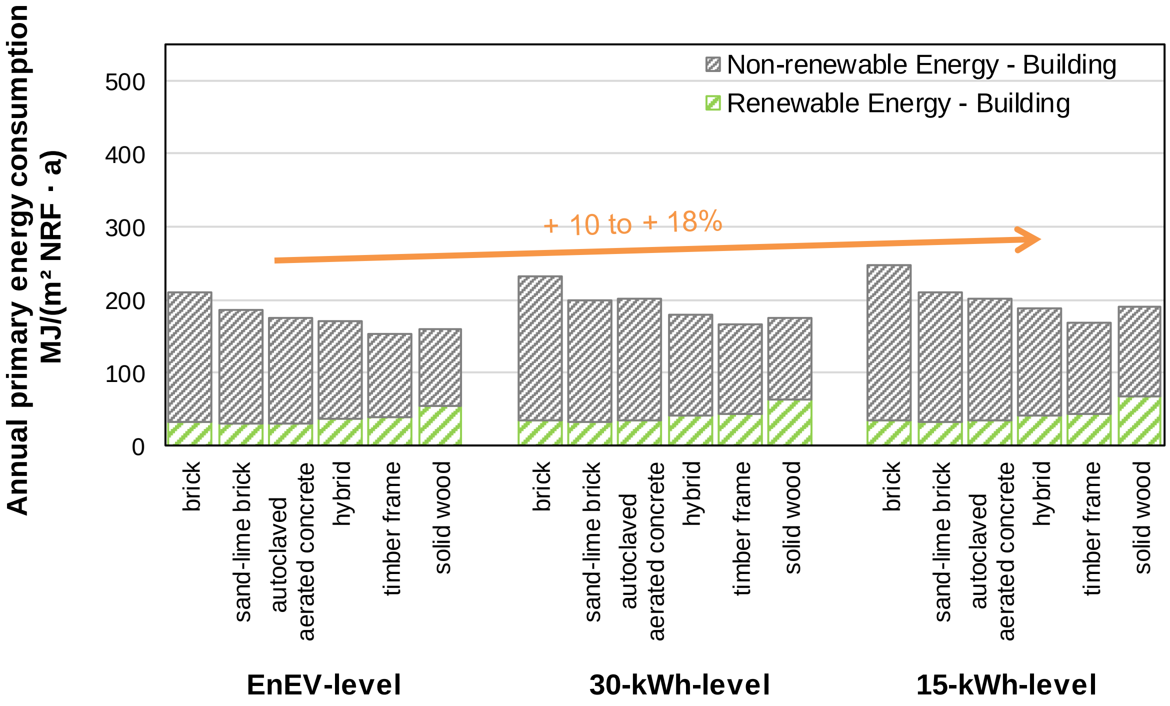

Image 3: Primary energy consumption of the building (construction, maintenance, disposal) for the different construction methods and energy levels based on the example of wood pellet heating

When comparing the primary energy consumption values required for the *construction, maintenance and demolition* as well as *operation* of the building, it, however, shows that the operational energy consumption which can be saved by a higher energy efficiency level, can not only compensate the additional costs for the building, but that there will eventually be a potential for further savings (image 4). For wood pellet heating this is, depending on the construction method 8 - 16% between the EnEV and the 15 kWh level. By using the other examined heating technology methods even bigger savings potentials can be achieved: 27 - 34% for air-to-water heat pumps, 15 - 22% for water-to-water heat pumps and 25 - 32% for gas-fired condensing heating with solar thermal energy.
The higher the energy efficiency of the building, the less influence the different heating technologies have on the primary energy consumption.

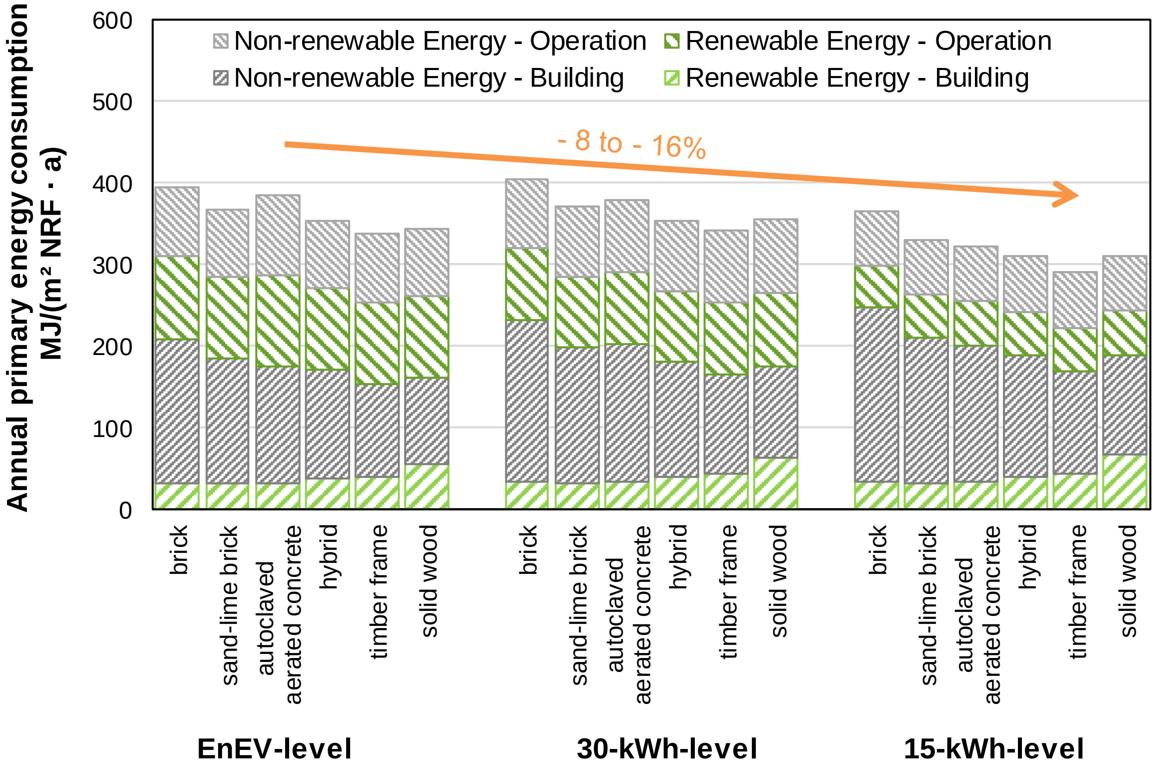

Image 4: Primary energy consumption values (building + operation) of the different construction methods and energy levels based on the example of wood pellet heating

6.2. Environmental indicator – greenhouse gas potential

The focus is put on the greenhouse gas potential as an environmental indicator, as in absolute terms the other indicators are of subordinate importance. The greenhouse gas potential for the production of lightweight construction buildings is lower than for solid construction buildings (image 5). As for the result of the total primary energy consumption, the hybrid construction method ranges between the other two construction methods. The additional greenhouse gas emissions caused by the construction of significantly more efficient buildings are easily compensated during a 50-year period by the reduction of greenhouse gas emissions during operation (22 - 34% reduction depending on the construction and heating method).

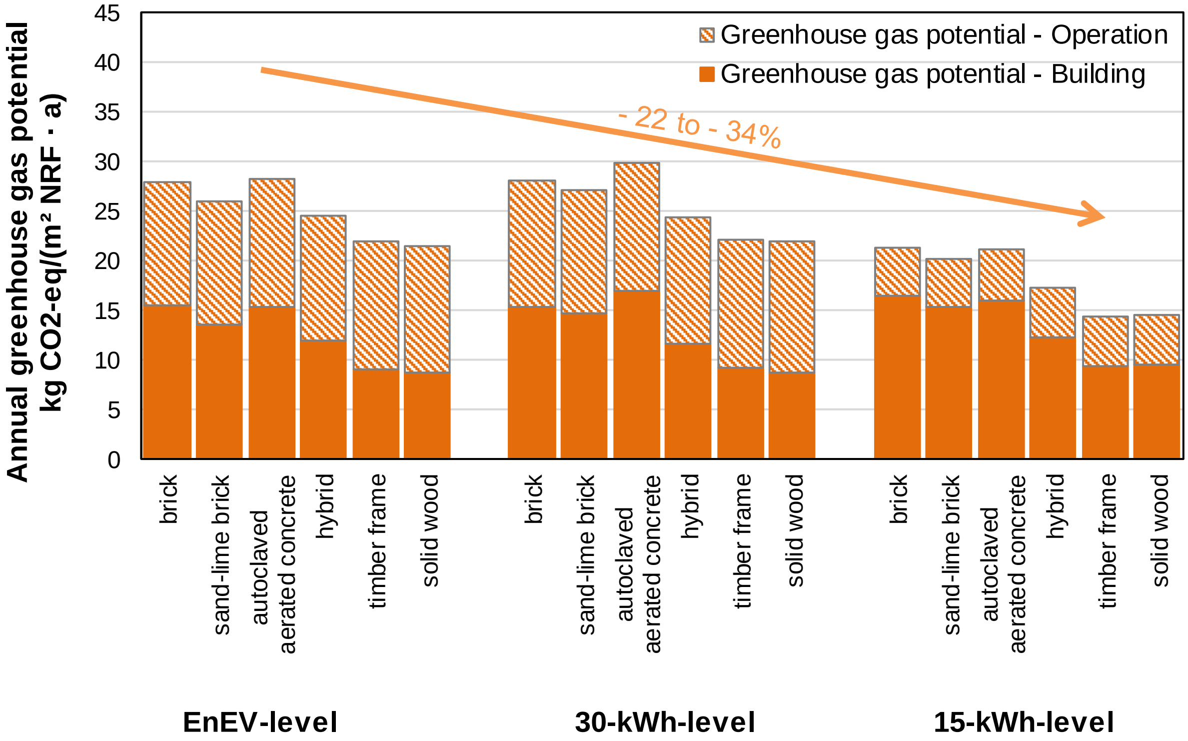

Image 5: Greenhouse gas potentials of the different construction methods and energy levels using gas-fired condensing heating with solar thermal energy as an example

6.3. Sensitivities

- **Variations of the period under consideration**

Apart from the one-time costs for resources and the primary energy consumption for the production and construction, the service life of the primary construction and its components is decisive for the overall balance of a building. High-quality construction, flexible layout plans and high-quality planning result in the longest possible service life of the basic construction of a building. Thus, the relative primary energy consumption (grey energy) of the building over its lifetime is decreased as the energy for its construction is distributed over a longer period of time. A sensitivity analysis with a variation of the service life and the observation period of 30, 50 and 80 years was carried out to investigate this. When the observation period was prolonged from 30 to 50 years, the savings potential for the total primary energy consumption of the building was calculated as 27% on average depending on the construction and heating technology method used. By prolonging the period from 50 to 80 years it is possible to achieve an additional savings potential of 10% on average (image 6).

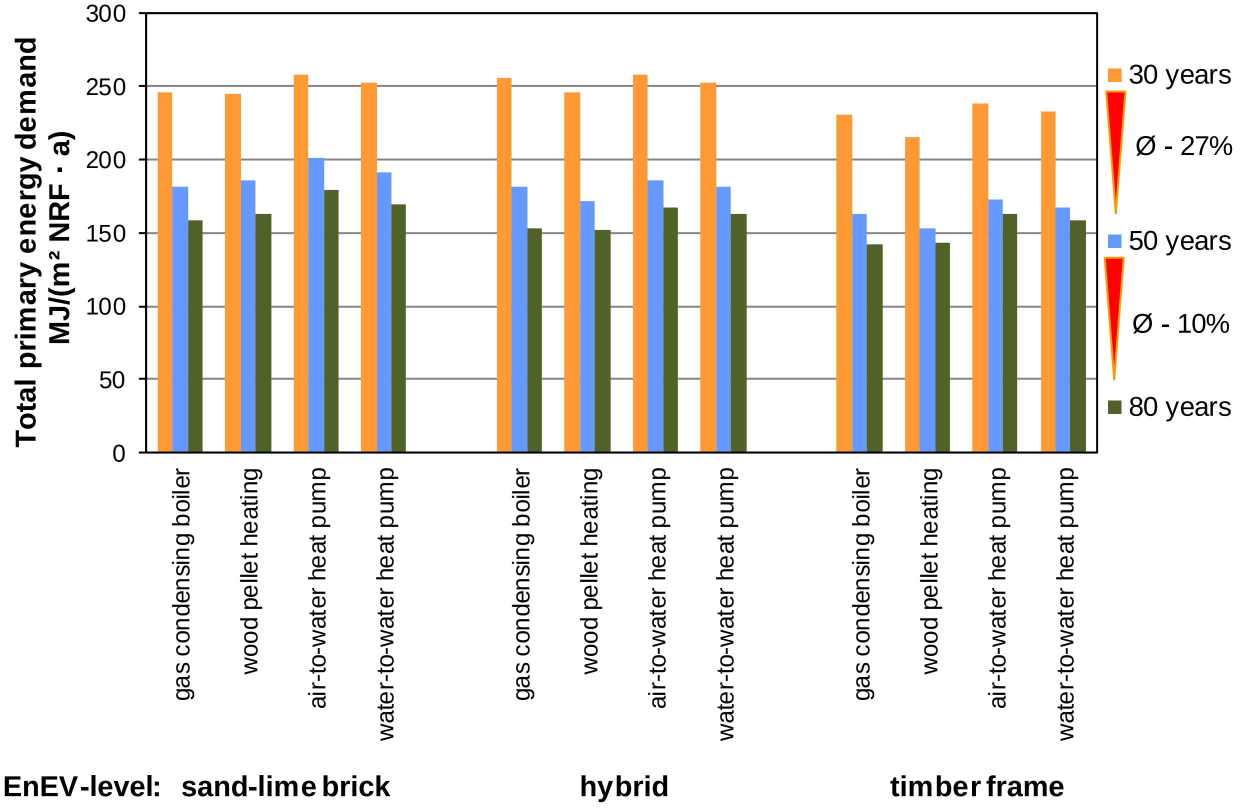

Image 6: Comparison of the total primary energy consumption values of the different construction methods and heating technologies over the usage periods of 30, 50 and 80 years

- **Cellar**

Additionally, it was examined how adding a cellar influences the life cycle assessment.
With a cellar, the building absolutely requires more energy during its construction. However, there is thus also more usable floor space so that relatively speaking the result is a lower environmental impact. If there is no cellar, it is important to consider that possibly retrofitted supplementary living space such as sheds have to be included in the ecological assessment. Therefore, it should be taken into consideration already in the planning phase how much usable floor space is going to be required over the total service life and therefore also whether a cellar is required or not.

- **Insulating material varieties**

In order to be able to assess the potential for optimization of the life cycle assessment of the insulating material, three sensitivities for the construction methods sand-lime brick and timber frame were carried out, examining only the construction, maintenance and demolition of the building of a 15 kWh level without operation. For both construction methods a standard variety of insulation was compared to one only consisting of synthetic insulating material and one consisting of renewable raw material (plus granulated foam glass for the base plate).

The environmental impact of the different varieties of insulation are within the same range, however, the variety made of renewable raw material causes, apart from the parameter overfertilization, the lowest environmental impact potential. Compared to the other two, this insulating variety based purely on synthetic insulating material only has advantages in terms of the overfertilization potential.

- **Room temperature**

For another sensitivity analysis, the target room temperature was raised from 20°C to 22°C. The following table gives an overview of the resulting increase of heat energy requirement per increased Kelvin room temperature:

Energy level of the building	Increase of the heat energy requirement per Kelvin increase of the room temperature, %	Increase of the heat energy requirement per Kelvin increase of the room temperature, kWh/(m²·a)
EnEV-level	12	7
30-kWh-level	12	5
15-kWh-level	16	3

7. Quality aspects

With the help of the thermal-dynamic simulation it is also possible to make statements about the ***thermal comfort in the summer***. Shading and night ventilation to reduce overheating of the building in the summer were integrated in the simulation. The result was that solid buildings show significantly lower overheating during the summer months due to a high effective thermal mass (temperature buffering) (image 7). The limit temperature for summer overheating is 26°C. The hybrid design in comparison also has a very low overheating potential. If the insulation level and thus the efficiency standard of the building increases, the number of overheating hours by surface area of above 26°C can be drastically minimised and the threshold value according to DIN 4108-2 of 1200 Kh/a can be undershot for all construction methods. In addition to thermally solid components serving as heat buffers, external sun protection with a solar reduction factor of up to 0.3 (such as roller shutters) and cooling by outside air, which can be achieved by an increased air exchange rate, are also required.

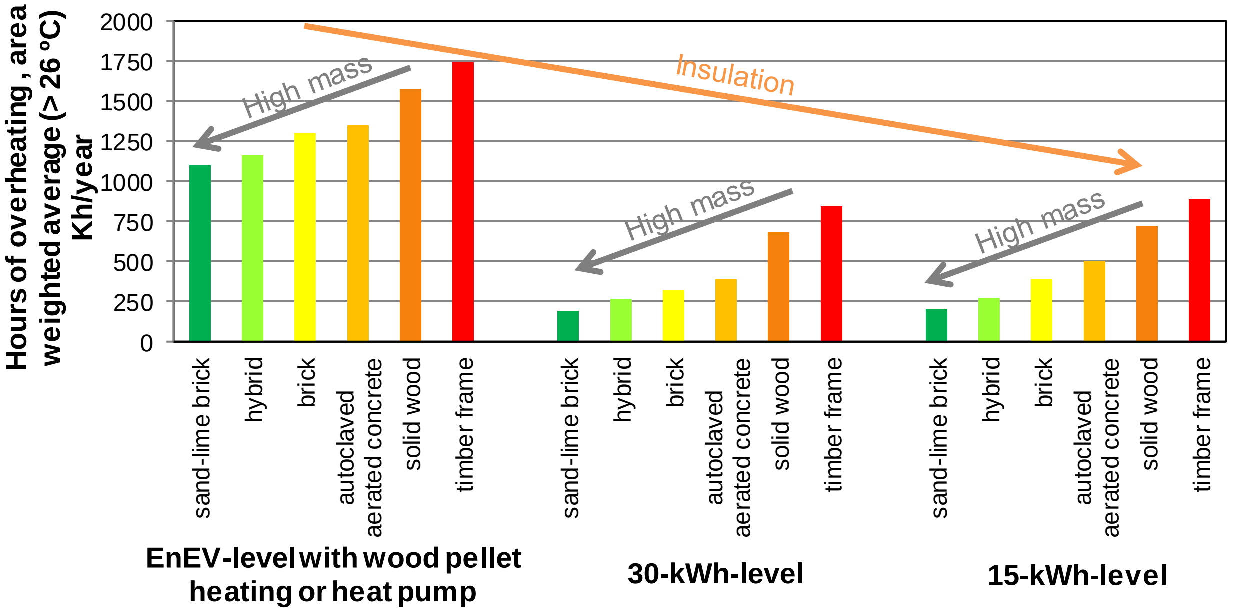

Image 7: Overheating hours by surface area of the different construction methods and energy levels

Inside the house, sound exceeding certain threshold values can be considered a disturbance. By choosing heavy construction of walls and ceilings (brick, sand-lime brick, autoclaved aerated concrete, hybrid), the propagation of airborne noise can generally be limited, so that in the area of ***acoustics*** a sound insulation exceeding the minimum requirements can be achieved. However, for lightweight construction (wood frame or solid timber construction) additional measures are often necessary which cause additional material costs. For example, to reduce noise the false ceiling between the ground floor and the upper floor can be equipped with an additional weight-bearing layer of concrete, clay or gravel.

All construction methods meet the legal requirements for ***fire resistance***. Stone constructions meet the fire resistance requirements of F 90 (90 minutes) and wooden constructions usually have a fire resistance of F 30 (30 minutes).

However, all construction methods have in common that a ***long service life*** of the building can only be achieved by high-quality and flawless realisation. Therefore, durable products should be used and adequate weather protection – also during the construction phase – and a high level of airtightness of the building should be aimed at.

Furthermore, the products used should be as environmentally friendly and as harmless to health as possible. It has to be considered that wood products can be treated with varnish and glues made of formaldehyde-based materials, or that wood rich in resins can emit hydrocarbons. However, when mineral substances are used, care should also be taken to ensure that they do not emit fumes in order to keep ***harmful substances in the room air*** to a minimum. Certified building products marked with the ecolabel "Blue Angel" (Blauer Engel) can be used.

8. Economics

Finally, a **life cycle cost analysis** was carried out considering the costs of construction, repair, utilities, maintenance, demolition and disposal using the present value method or based on the methodology of the DGNB[7] (German Sustainable Building Council), the NaWoh[8] (German Rating System for Sustainable Housing Constructions) and the BNK[9] (German Rating System for Small Residential Buildings) certification systems. The aim is to thus achieve comparability of buildings with different production and follow-up costs over an observation period of 50 years. The framework conditions for the calculation were defined as follows: present value interest rate 1%, increase in construction costs 1%, increase in energy prices 4%. Four different construction methods at EnEV energy level and a wood pellet heating system were examined.
The sand-lime brick construction method shows increased costs over the observation period of 50 years, which is exclusively due to the calculated one-time exchange of the exterior insulation and finishing system after 40 years (image 8). This effect does not occur if the EIFS has a longer service life.

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[7] "Deutsche Gesellschaft für Nachhaltiges Bauen" (DGNB) ("German Sustainable Building Council") in the version of the profiles of 2015

[8] "Bewertungssystem Nachhaltiger Wohnungsbau" (NaWoh) ("German Rating System for Sustainable Housing Constructions") of 2011

[9] "Bewertungssystem Nachhaltiger Kleinwohnhausbau" (BNK) ("German Rating System for Small Residential Buildings") of 2016

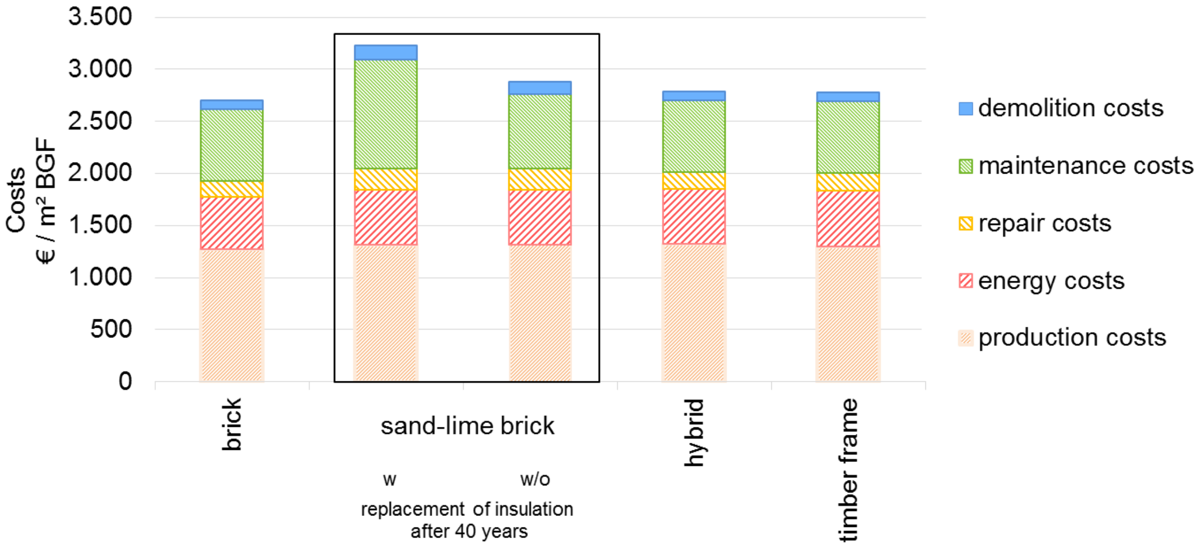

Image 8: Investment amounts for selected construction methods over a service life of 50 years

9. Summary

Due to their high thermally effective mass, ***heavy solid structures*** achieve a high heat buffering effect, they can thus reduce the heat energy requirement by around 10% and thus significantly reduce overheating of the building in the summer. A high level of sound insulation and good fire resistance properties can also be easily achieved.

The advantages of the lighter ***wood construction methods*** are mainly the energy savings for the production and construction of the building (grey energy) as well as lower emissions in terms of greenhouse gas emissions, acidification, eutrophication and causing of photochemical smog.

Therefore, each of the construction methods has both strengths and weaknesses, so that neither solid nor lightweight constructions can be exclusively favoured. The results show a promising potential of the ***hybrid construction method***, which combines many advantages of both variants. For example, during the production process, the energy consumption and thus the impact on the environment and also the heat energy requirement during operation can be reduced.

It was generally confirmed that an increase in ***energy efficiency*** entails a reduction of the environmental impact during the life cycle of the building, which is why this should be aimed for. The additional expenditure required to achieve the increased production efficiency is typically more than compensated for by savings during the service life in terms of primary energy consumption and greenhouse gas potential. It can also increase the comfort of living, especially due to low overheating of the building in summer.

Furthermore, it showed that with high energy efficiency the **choice of heating technology** plays a minor role. In the case of wood-fired heating systems, however, above all the higher dust emissions, which were not the subject of the investigations in this study, should be considered.

Ultimately, it should be noted that the relative primary energy requirement can be reduced and the life cycle assessment of the building improved, above all by a ***long service life***. Therefore, attention should be paid to high quality construction and thorough planning of the building (e. g. with variable floor plans) for a service life of 50 years and more.