The Passive House Concept _

An Energy, Environmental and Economic Optimum

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ABSTRACT **The heating requirements of a passive house are up to 15 kWh/(m²•a) of energy. Due to a good thermal and airtight envelope without thermal bridges, the building shows low transmission heat losses, while ventilation heat losses are reduced through a built-in system of controlled ventilation with heat recovery of the exhaust air. At their maximal load during peak heating season, heat losses do not exceed 10 W/m² and can be compensated with hot air heating. In such buildings, conventional heating systems are no longer required. Increasingly, heat pumps are used as heat generators.**

Such optimal results were made possible with considerable engineering knowledge and implementation experience, as the required rational concept can only be achieved by design optimisation, which must also be reflected in economic and environmental terms. Architectural and technological concepts to be included in the passive house design are presented. Using a model of a two-storey single-family house, five configurations are presented and evaluated with the parameters of energy efficiency (Q_{NH}/A_u), primary energy consumption ($PEC_{n.r.}$), CO_2 emissions (GWP_{100}), cost (*Cost*) and living environment (*LE*).

KEYWORDS passive house, low energy house, energy concept, primary energy, heating requirement

1 Introduction

The passive house concept was developed by Dr. Wolfgang Feist, who, in 1991, in Darmstadt, within the Cepheus project (Cost Efficient Passive Houses as European Standard), erected the first passive house. This prototype's successful performance led to the establishment of the passive house standard and passive houses have been part of the home market since 1998.

The passive house standard can be applied to buildings of all purposes, from passive single-family houses to multi dwelling buildings, office buildings, schools and kindergartens, sports halls, shops, churches, manufacturing plants, hotels, pools, etc. Similarly diverse are the building technologies used in the construction of a passive house. Today, passive houses are built on all continents in hot, temperate, and cold climate conditions. According to the Passivhaus Trust (2017) information, over 65,000 buildings have been built whose performance was certified to the passive house standard requirements. Both long-term experience with indoor living in passive houses as well as numerous studies show high user satisfaction (Keul, 2010). This is due not only to low heating costs and high environmental awareness, but mainly to the high indoor living comfort – the indoor air is fresh at all times and the air temperatures are uniform (Zbašnik-Senegačnik & Senegačnik, 2010).

The passive house's name does not stem from passive use of solar energy, but from the building not requiring a conventional space heating system (Feist, 1998a). A passive house is not a new construction technology. It is merely a very meticulously executed low-energy building, while its construction and function remain traditional. Neither does a passive house require additional design constrictions, as the higher standards are acquired solely through technical improvements of the building's envelope and of its heating and ventilation systems. All passive house demands can be met by installing innovative technical equipment for heating and ventilation, much in the same manner as the construction of a low-energy house.

Proper planning, followed by consistent implementation, is of key importance for achieving the passive house standard. The architectural design should include the optimal orientation, design, and functional arrangement of the building's premises. The thermal envelope with the pertaining joinery is very important for energy efficiency of the building and must be airtight and free of thermal bridges. The building must have mechanical ventilation. The heat demand of such a building is extremely low (Zbašnik-Senegačnik, 2009).

The cost of a passive house is 5 – 15 % higher than that of a conventional house (Galvin, 2014), with savings achieved in the medium and long term by consuming less fuel. Economic viability is difficult to assess accurately, since the future price of fuel and the discount rate are unknown (Galvin, 2010). Energy and environmental benefits are easier to assess because they are calculated directly on the basis of primary energy savings. The living comfort experienced by the users may be measured insofar as it refers to the temperature and humidity levels.

The study presents architectural and technological concepts of the passive house design. Presented below are five energy concept variants of single-family houses pertaining to different energy classes, including the evaluation of energy, environmental, and economy indicators. In an architectural model, all five-concept variants of single-family houses are evaluated with the parameters of energy efficiency (Q_{NH}/A_u), primary energy consumption ($PEC_{n.r.}$), CO_2 emissions (GWP_{100}), cost (*Cost*), and living environment (*LE*). The overall evaluation is carried out according to three methods of weighting: the objective weighting and the weighting from the national or user perspective.

2 The Definition and Concept of a Passive House

In comparison with conventional houses, constructed in accordance with valid regulations, passive houses do not demand additional building physics requirements. The building of passive houses, however, calls for strict observance of requirements regarding its components (Feist, 2015):

- thermal protection: the thermal transmittance coefficient U of all structural elements is below 0.15 W/(m²•K), with values below 0.10 W/(m²•K) recommended for free-standing single-family houses;
- thermal bridge free construction (linear thermal transmittance ψ £ 0.01 W/(m•K)
- high airtightness, monitored with a pressure test according to DIN EN 13829 – where the air exchange in both pressurised and depressurised states at 50 Pa pressure difference should be less than n_{50} = 0.6 h^{-1};
- glazing with U_w ≤ 0.8 W/(m²•K) with high total solar energy permeability (g ≥ 50 % according to DIN 67 507), allowing net heat gains even in winter periods;
- window frames with U_f ≤ 0.8 W/(m²•K) according to DIN EN 10077;
- the ventilation unit's consumption of electric energy ≤ 0.4 Wh/m³ of the transported air volume;
- minimal heat losses in the preparation and distribution of hot sanitary water;
- efficient use of electricity in the household (use of A and A+ energy class equipment and household appliances).

A building does not become a passive house by assembling the necessary passive house suitable components. The passive house standard is achieved through an integrative plan that links the individual components into a comprehensive whole.

Typical values of characteristics denoting a passive house are (Feist, 1998):

- specific annual energy consumption for space heating ≤ 15 kWh/(m^2•a)
- total primary energy consumption ≤ 120 kWh/(m^2•a)
- electricity consumption ≤ 18 kWh/(m^2•a)
- heat losses ≤ 10 W/m^2
- airtightness n_{50} < 0.6 h^{-1}

3 Architectural Optimization of Passive House Design

As the building's architectural design impacts on its energy efficiency, it is crucial that the design process of passive house takes into account the building's orientation, shape, and spatial hierarchy (Zbašnik-Senegačnik, 2009).

3.1 Orientation

The integration of solar energy into the building's energy balance and appropriate placement of a building into its surrounding landscape can strongly affect the building's energy efficiency. Favoured plots for passive house buildings are oriented to the south. During cold periods, a south orientation maximises solar energy use and contributes a share of up to 40 % of the building's space heating demand. Thus, the passive use of solar energy positively influences the building's heat balance. Larger glazed areas on south façades are advisable for solar gains. The efficiency of solar irradiation gains is reduced by shading the building with trees or other buildings. The distance between adjacent buildings should be dimensioned according to the low incidence angle of the winter sunlight (Fig. 3.1).

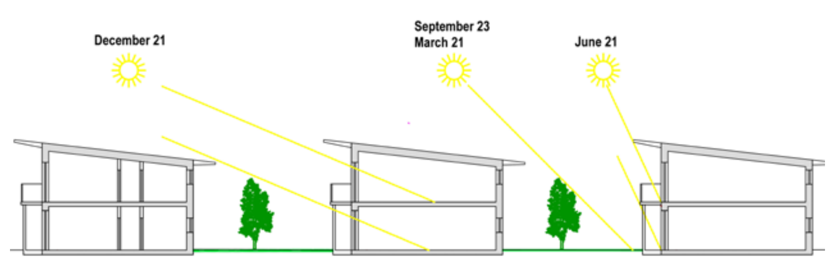

FIG. 3.1 The distance between adjacent buildings is determined by the low incidence angle of the winter sun.

3.2 The Building's Shape

Usually, most heat losses occur through a building's external envelope. Larger exterior envelope surfaces result in larger heat losses. In order to reduce these heat losses, it is imperative that the shape factor, i.e. the ratio between the surface area and volume, is carefully taken into account. Particularly favourable shape factors come with cubic, round, octagonal, and elliptical forms (Fig. 3.2). Typically, a freestanding single-family passive house will have a relatively high proportion of external surfaces relative to its volume (Fig. 3.3). Buildings in densely built clusters or large passive buildings have more favourable shape factors (Fig. 3.4).

FIG. 3.2 A round passive house floorplan resulting in a favourable shape factor

FIG. 3.3 Cubic shaped single-family passive houses with green flat roofs

FIG. 3.4 Compact shaped commercial building, Energy base

3.3 Functional Interior Space Design

Heat losses through walls increase with a growing temperature differential between the interior and exterior surface. To reduce a building's heat losses, rooms with lower temperature demands (i.e. staircase, storage, and other auxiliary spaces) should, ideally, be assigned to its north oriented spaces with the lowest exterior wall temperatures. Due to their larger temperature demand, living areas should be south oriented in order to gain heat from solar irradiation.

FIG. 3.5 A separate entrance into the unheated basement underneath the building (view from the terrace during construction)

FIG. 3.6 External staircase of a multi-unit residential passive house, excluded from the thermal envelope

Unheated areas should not be included within the thermal envelope. In buildings with basements, the whole floor above the basement should be thermally insulated, including the lower walls. The simplest solution is a separate basement entrance (Fig. 3.5). Especially in multifamily houses, where they account for a large part of the building's volume, staircases and halls may be excluded from the thermal envelope (Fig. 3.6).

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4 Technological Optimisation of Passive House Design

All construction technologies are applicable for the building of passive houses. Equal results can be achieved in both massive and lightweight construction types, as well as with different building materials. The choice is subject to the investor's personal preference and is, mostly, price dependent.

4.1 Massive Walls

In massive construction types, the load bearing construction is brick, brick filled with perlite, concrete, or aerated concrete brick, and in all cases is clad with an appropriately thick layer of thermal insulation on the outside (Fig. 4.1).

A

B

C

FIG. 4.1 A+B+C: A massive wall – brick with external mineral wool and XPS thermal insulation

The thickness of a massive wall depends on its load-bearing requirements, while the façade cladding, as in conventional buildings, may be ventilated or unventilated. The cladding, however, must be mechanically fastened with anchors in such a way as to avoid the formation of thermal bridges.

4.2 Lightweight Walls

There are two basic systems for timber frame passive house construction: the pillars and beams system, and the frame system. In either case, the empty spaces may be filled with mineral wool, sheep wool, linen, or thermal insulation of cellulose or wood flakes. Typically, passive houses have thicker exterior walls than conventional buildings. Thermally insulative materials are installed between the load bearing construction elements. On the outside of the walls, another layer of thermal insulation is added, serving simultaneously as a sublayer for the façade plaster. On the inside, before the vapour barrier, which simultaneously functions as an airtightness layer, the additional thermal insulation is added (Fig. 4.2).

FIG. 4.2 Passive house wall element, from left to right: Timber-frame with I-joists and cellulose thermal insulation (system Lumar IG); Panel construction system with wood fibre thermal insulation (system Marles hiše Maribor); Panel construction system with mineral wool thermal insulation (system Marles hiše Maribor) *(Image by The Producers Lumar IG and Marles hiše Maribor, 2017. Reprinted with permission)*

4.3 Thermal Insulation

Thermal insulation is the most important element of a wall. Its thickness of 25 – 40 cm depends on both the building material used and the wall structure. Any existing thermal insulation materials may be used in passive houses. In massive construction, the fastening of thermal insulation is carried out by gluing, anchoring, nailing, screwing, or installing with cants. In lightweight construction, some types of thermal insulation, i.e. cellulose and wood flakes, sheep wool, and hemp may be blown into the space between load bearing elements. The fastening of softer types of thermal insulation requires a substructure.

Thermal insulations differ in price and in their ecological components. The passive house concept is, by itself, environmentally friendly. The choice of building materials should consider that they are ecological, produced with a minimum of embodied energy, and that they have no negative impact on humankind and the environment during their total life cycle, the latter spanning from production, installation, and use, to demolition.

4.4 Joinery

The passive house development pointed to the crucial importance of high quality windows in meeting the requirements of the standard. With this in mind, triple glazed windows ($U_g \leq 0.8$ W/(m^2•K)) with a heat transfer U_w at most 0.8 W/(m^2•K) and with an improved frame insulativity ($U_f \leq 0.8$ W/(m^2•K)) (Fig. 4.3) (Feist, 1998b) were developed. Notwithstanding large glazed surfaces, such windows drastically reduce heat losses while simultaneously offering high solar irradiation gains. This contributes positively to the building's energy balance as, in south oriented windows, heat gains exceed heat losses even between December and February, the coldest period in our geographic location, thus resulting in a positive energy balance.

4.5 Prevention of Thermal Bridges

Thermal bridges are locally restricted surfaces on building elements with increased heat flow. They occur on the building's outer envelope as a consequence of improper and deficient design and implementation.

A building may lose copious amounts of heat through improperly protected parts of its façade.

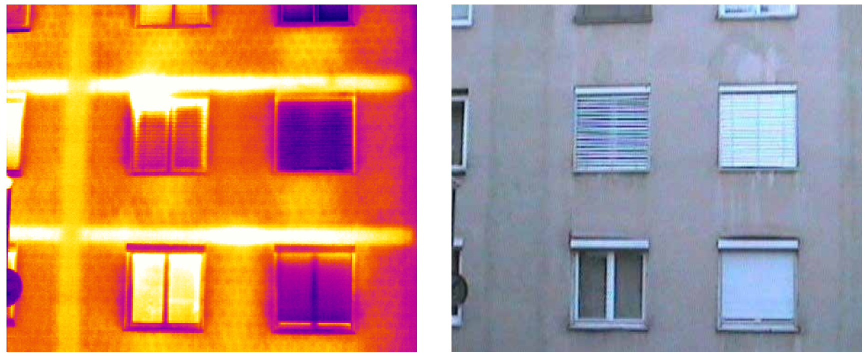


FIG. 4.3 Window frames fit for passive houses *(Source: Marles)*

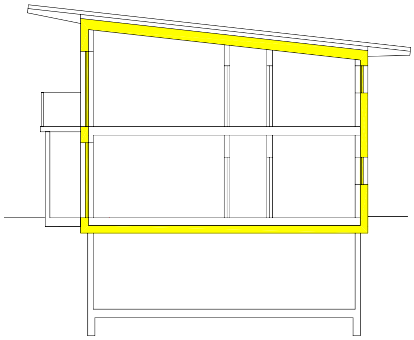
FIG. 4.4 A+B: Thermographic image of a façade – left in the infrared spectrum (7–15 mm) and right in the visible spectrum

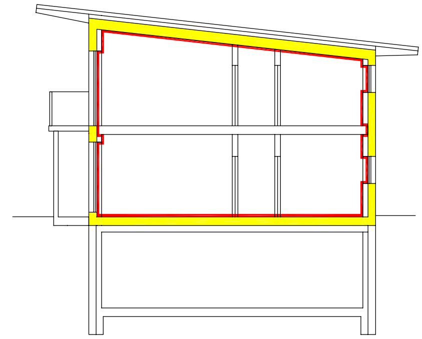
In passive houses, the so-called construction thermal bridges were found to be the most problematic (Feist, 2007). They occur at thermal envelope interruptions (Fig. 4.4). Mostly, they are caused by improperly designed details at openings, overhangs (braces, support beams), joints, ribs, and interrupted thermal insulation. Such mistakes should not happen in a passive house, as they are required to be thermal bridge free.

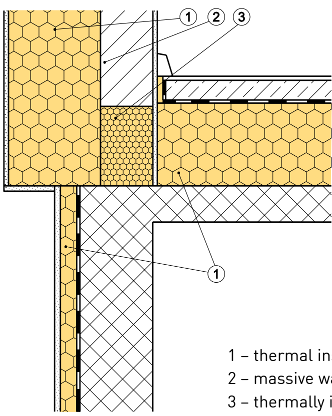
Any possible thermal bridge occurrences in a building should be checked using special two- and three-dimensional calculations. Generally, thermal bridges in a passive house must be avoided, or at least limited to the best of abilities, as even the heat losses from a small thermal bridge may seriously endanger the entire passive house concept. The basic principle of passive house construction is *thermal bridge free* implementation, following the basic rule that the thermally insulative layer must be designed as an uninterrupted envelope (Fig. 4.5).

In a building, thermal bridges occur at different locations: the building's thermal envelope may be interrupted on the plinth towards the foundation or the unheated basement, in the joining of the roof and exterior wall, on balconies and overhangs that are a part of the inner storey construction, or in the installation of windows and doors etc.

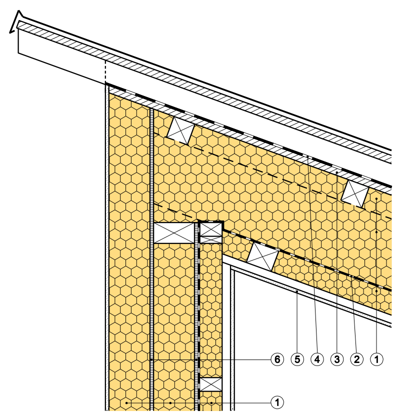
Thermal bridge free joints of constructional elements are achieved through carefully planned details, and careful construction (Fig. 4.8, Fig.4.9).







1 – thermal insulation
2 – massive wall
3 – thermally insulative plinth, λ = 0.12 W/(mK)



1 – thermal insulation
2 – vapour barrier
3 – boards
4 – secondary roofing
5 – plasterboards
6 – chipboard

FIG. 4.5 (top left) A building's thermal envelope must not be interrupted (yellow line).

FIG. 4.6 (top middle) Properly fixed window installation into the outer exterior wall plane, and the sealing process

FIG. 4.7 (top right) The airtightness layer in a passive house must continuously encompass the building's heated volume (red line).

FIG. 4.8 (bottom left) Connection detail of the thermal envelope's wall with an unheated basement

FIG. 4.9 (bottom right) Connection detail of the roof construction with a lightweight wall

Special attention should be paid to the window installation. In constructions with massive walls, windows are point fixed into the thermal insulation layer on the exterior wall, and all openings between the wall and windows are carefully sealed. The thermal insulation material must cover as much of the frame as possible to increase thermal protection (Fig. 4.6). Windows installed without such a protective frame cover may result in a 70 % increase of a building's linear heat transfer. The passive house's goal is to reduce linear heat transfer Ψ below 0.01 W/(m•K).

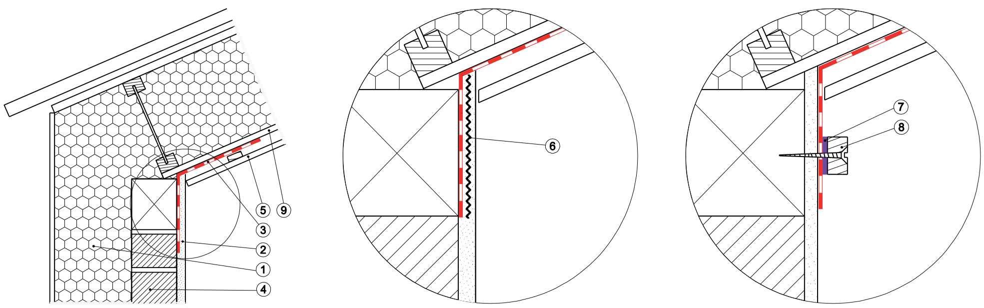
4.6 Airtightness

Airtightness refers to the intensity of the differential pressure-induced uncontrolled air flow through the building's construction, either into the building or out of the building. Uncontrolled air flow occurs through joints, cracks, or other leakages of the building's envelope.

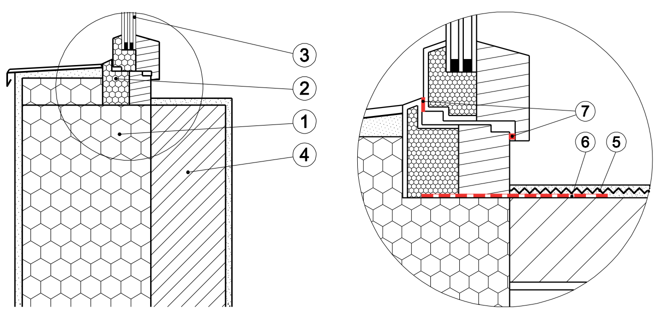
A

B

C



1 – thermal insulation
2 – plaster
3 – sealing tape
4 – masonry wall
5 – ceiling cladding
6 – plaster subsurface
7 – levelling strip
8 – screwed batten
9 – airtight board



1 – thermal insulation
2 – insulative frame
3 – insulative glazing
4 – masonry wall
5 – plaster subsurface
6 – sealing tape

FIG. 4.10 A+B+C: Measures to achieve airtightness

FIG. 4.11 Connection detail of a sloped roof and a masonry wall with plastered interior wall

FIG. 4.12 Airtight window installation into masonry wall

In order to achieve airtightness, all details of the joint datails of building elements must be carefully designed. The building's envelope airtightness, just as its thermal envelope, must be complete and continuous (Fig. 4.6).

Usually, the airtightness layer is located on the inside of the building's envelope and can be achieved using different materials. A massive masonry wall is airtight if the spaces between bricks are carefully filled and the inner plastering is executed continuously from the raw ground (before screed installation) up to the raw ceiling. In lightweight construction, vapour barriers may act as an airtight layer. Different foils or boards (OSB boards, plywood, DWD boards etc.) may be used, depending the producer's warranty. Special features in this respect are the joints between individual elements, where we must also ensure airtightness using different sealants, tapes, expansion tapes, sealing profiles etc. (Fig. 4.10).

The efficiency of the airtightness of the envelope is tested with the Blower Door Test. For passive houses, an upper limit value of $n_{50} \leq 0.6\ h^{-1}$ (Feist, 2005) is set.

Leakages may occur at joints, or seals, between individual elements of the airtightness layer (i.e. joints between foils or boards), at joints between individual elements (i.e. at joints of walls, at joints between the roof and walls, etc.) (Fig. 4.11), and at joinery installation (Fig. 4.12).

4.7 Ventilation

To reduce ventilation heat losses while simultaneously achieving optimal indoor air quality, a ventilation system with a minimum 75% efficient exhaust air heat recovery is mandatory for passive houses (Feist, 1997). This means that the warm exhaust air transfers its heat to the cold incoming air, thus additionally reducing ventilation heat losses. A bonus for allergy sufferers are filters that eliminate pollens and dust.

In passive houses, fresh air is taken from the building's environment through a safety mesh positioned either on the façade or on the roof, and transported through well-insulated ducts to the ventilation unit. Before entering the indoor space, dust particles are eliminated by filters. Fresh air is pre-warmed in the heat exchanger, with the warmth taken from the extract air as it is pumped out of the building. The pre-warmed fresh air leaves the heat exchanger through a duct system and flows into the so-called supply rooms (living room, dining room, bedrooms, and home office). Used air is extracted from wet and odorous spaces (kitchen, sanitary spaces, and possibly utility and auxiliary spaces) and transported through ducts to the ventilation unit. Here, it transfers its heat via the heat exchanger to the fresh intake air, to be extracted through well-insulated ducts into the environment (Fig. 4.13).

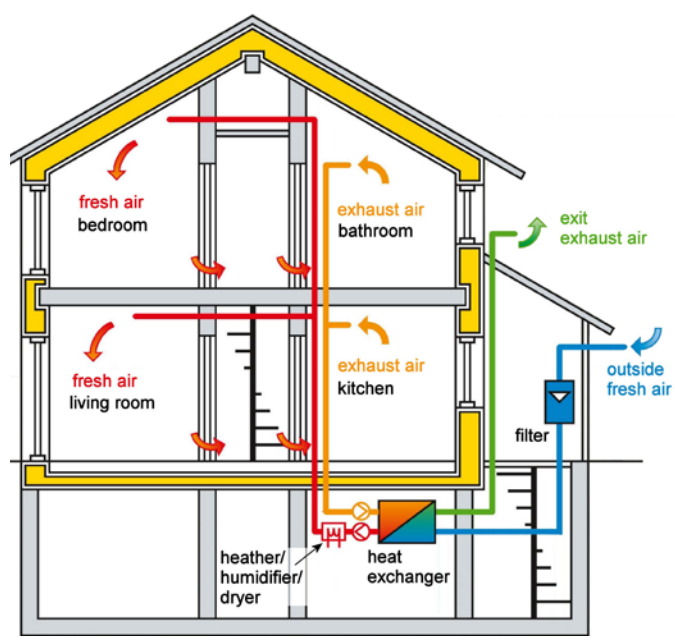


FIG. 4.13 Ventilation system performance in a passive house *(Source: Passive House Institut, in Zbašnik-Senegačnik, 2009, reprinted with permission)*

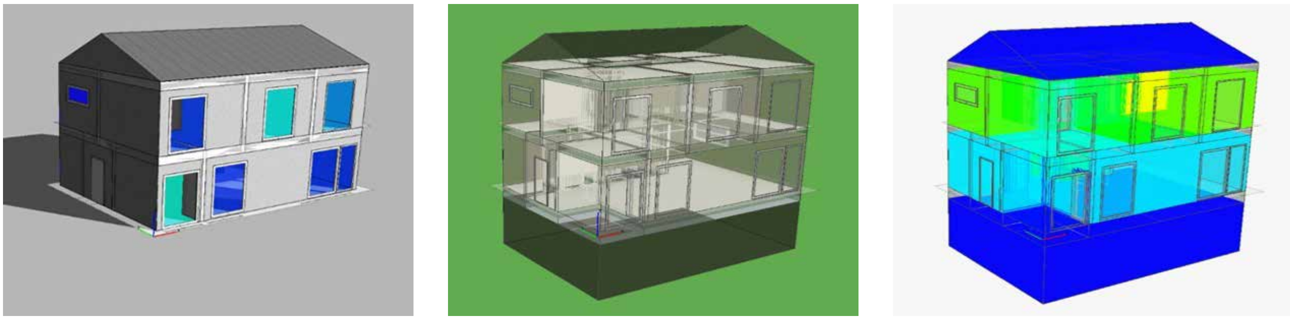
In modern ventilation units, heat exchangers may reach a very high efficiency, and almost completely recover the exhaust air heat (even above 90%). In this way, the greater part of the heat remains within the building while the indoor air is always fresh.

4.8 Heating

The reason for a passive house's minimal heat losses are a high quality and well-designed thermal envelope and a central ventilation system recovering the exhaust air heat. Heat demand, therefore, is low, and conventional heating systems are no longer required (Feist, 2009). Even at winter peaks, both transmission and ventilation specific heat losses can be less than 10 W/(m^2). For such low heat demand, warm-air heating is a suitable choice for space heating. Here, during winter, the air transported into the building is somewhat pre-warmed (Graf, 2000) by heat generators, heat pumps, or any other heat generators that may be used.

5 Comparison of Different Energy Efficiency Variations of Single-Family Houses

The decision to build an energy efficient house is based on certain criteria. Obviously, one of them is environmental concern. Energy efficient buildings are intrinsically environmentally friendly, as they reduce energy consumption in their operational stage. This, however, may be deceiving, as lower operational energy demand usually means higher embodied energy, that is, energy consumed in the production of building materials, energy used for the improvement of the building's thermal envelope, and energy used in the functioning of the equipment. Demand for space heating energy, therefore, cannot be the only criterion supporting the decision. Another high-ranking criterion is indoor living satisfaction – in a passive house, the air is always fresh and appropriately warm, and in winter, the surface temperature of walls and other elements is higher. Cost is another important factor in the form of initial investment in the construction stage, and in the form of rehabilitation cost in the operational stage. Even prestige may be a decision-making factor, although irrational and not easily quantifiable. The design of energy efficient houses considers a hierarchy of environmental, economic, and indoor living comfort indicators, which are, finally, unified into an assessment (Praznik & Zbašnik-Senegačnik, 2016).



A B C

FIG. 5.1 Presentation of the building's model (A), its energy interpretation (B), and graphic presentation of the result (C)

5.1 Presentation of the Single-Family House and its Energy Efficiency Variants

The valuation of five differing energy efficiency configurations is analysed on a two-storey single-family house model (shown in Fig. 5.1) with the following characteristics: conditioned surface A_u = 137 m^2, thermal envelope area A = 454 m^2, window's surface A_w = 30 m^2, shape factor f_o = 0.68 m^{-1}, average air exchange n_{50} = 0.4 h$^{-1.}$ The climate region has a temperature deficit HDD = 3200 K d a^{-1} (Ljubljana). The building is designed for four persons. The heat characteristics and heat transfer were calculated with a validated method based on methodology to international standards, and relevant to the respective building physics (Feist, 2015; SIST EN 13790, 2008).

Five configurations of the presented model, a timber frame single-family house (variants V1 through V5) were assessed, with different structures of the external envelope, space heating systems, and energy efficiency (from low energy to passive house):

Variant 1 (V1)
The building's heat demand is Q_{NH}/A_u = 50 kWh/(m^2•a); airtightness n_{50} = 1.0 h^{-1}; and mean thermal transmittance coefficient of the envelope U_m = 0.25 W/(m^2•K). Predominant in the thermal envelope is mineral wool, while window frames are PVC. The building uses natural ventilation. Due to higher space heating demand, an economically and environmentally more efficient system is chosen for heat generation – a pellet furnace with fitted solar panels for hot sanitary water preparation. The building uses radiators.

Variant 2 (V2)
This is a more energy efficient building design: Q_{NH}/A_u = 40 kWh/(m^2•a); airtightness n_{50} = 1,0 h^{-1}; mean thermal transmittance coefficient of the envelope U_m = 0.21 W/(m^2•K). Predominant in the thermal envelope is mineral wool, while window frames are PVC. The building uses natural ventilation. To maintain the investment value, a simple, yet, in the long term, both economically and environmentally less efficient heat generating system was chosen. The condensing gas furnace is fitted with solar panels for hot sanitary water preparation. The building uses radiators.

Variant 3 (V3)
This is a very low-energy house: Q_{NH}/A_u = 25 kWh/(m²•a); airtightness n_{50} = 0.8 h^{-1}; mean thermal transmittance coefficient of the envelope U_m = 0.20 W/(m²•K). Predominantly, the thermal envelope consists of mineral wool, and has wooden window frames. The building achieves higher energy efficiency using a central ventilation system with an 85% efficient exhaust air heat recovery. Heat for space heating and hot sanitary water preparation is generated with a heat pump that captures heat from a horizontal ground heat exchanger. Floor heating is installed for space heating.

Variant 4 (V4)
This variant is a passive house: Q_{NH}/A_u = 15 kWh/(m²•a); airtightness n_{50} = 0.6 h^{-1}; mean thermal transmittance coefficient of the envelope U_m = 0.16 W/(m²•K). In the building envelope, predominantly mineral wool is used, with wooden windows. The ventilation system achieves an even higher heat recovery (90%). Heat for space heating and hot sanitary water preparation is generated with a heat pump that captures heat from a horizontal ground heat exchanger. The space heating system is integrated into the ventilation system, thus reducing initial investment costs into HVAC.

Variant 5 (V5)
Variant 5 is built in the passive house standard with improvements in terms of energy efficiency and environmental friendliness, with the following values: Q_{NH}/A_u = 10 kWh/(m²•a); improved mean thermal transmittance coefficient of the envelope U_m = 0.14 W/(m²•K); airtightness n_{50} = 0.6 h^{-1}. To ensure higher values of environmental indicators, cellulose flakes were chosen for the envelope instead of mineral wool; windows are made of wood. The foundation slab is lined underneath with XPS.

For the comparison of above described building variants (V1 through V5), an operational cycle of 60 years is observed. This period consists of two 30-year cycles of building operation. After each cycle, some worn envelope elements require rehabilitation in the form of limited or small building repair. This 30 year cycled rehabilitation is estimated at 2% of the building's construction cost. In addition, a 15-year cycled rehabilitation period is observed for technical equipment for heat generation and space heating and ventilation. Solar panels, heat storage units for hot sanitary water and similar equipment require a 30-year cycle for replacement with new units.

The compared variants V1 through V5 have differing investment costs and, consequently, different financial burdens at every 15 year rehabilitation cycle. Differences also occur with respect to embodied primary energy and CO_2 emissions. The investment costs for the construction stage rely on the prefabricated house producer's calculations, and are supplemented with the authors' estimates with respect to HVAC investment costs. The estimated values of indicators showing the use of primary energy and CO_2 emissions during the construction stage were acquired from publicly accessible databases (Baubook, 2017). The authors' estimates of rehabilitation costs follow the same guidelines.

Even with identical hot sanitary water demand, the buildings' conceptually differing energy efficiency (Q_{HN}/A_u) results in different annual heat demand in the operational stage. Annual energy costs and respective primary energy use, as well as CO_2 emissions, were assessed for all configured heat generation systems. The cumulative cost, primary energy, and CO_2 emissions for the 60-year period of operation and interim building and equipment maintenance costs are shown in Fig. 5.2.

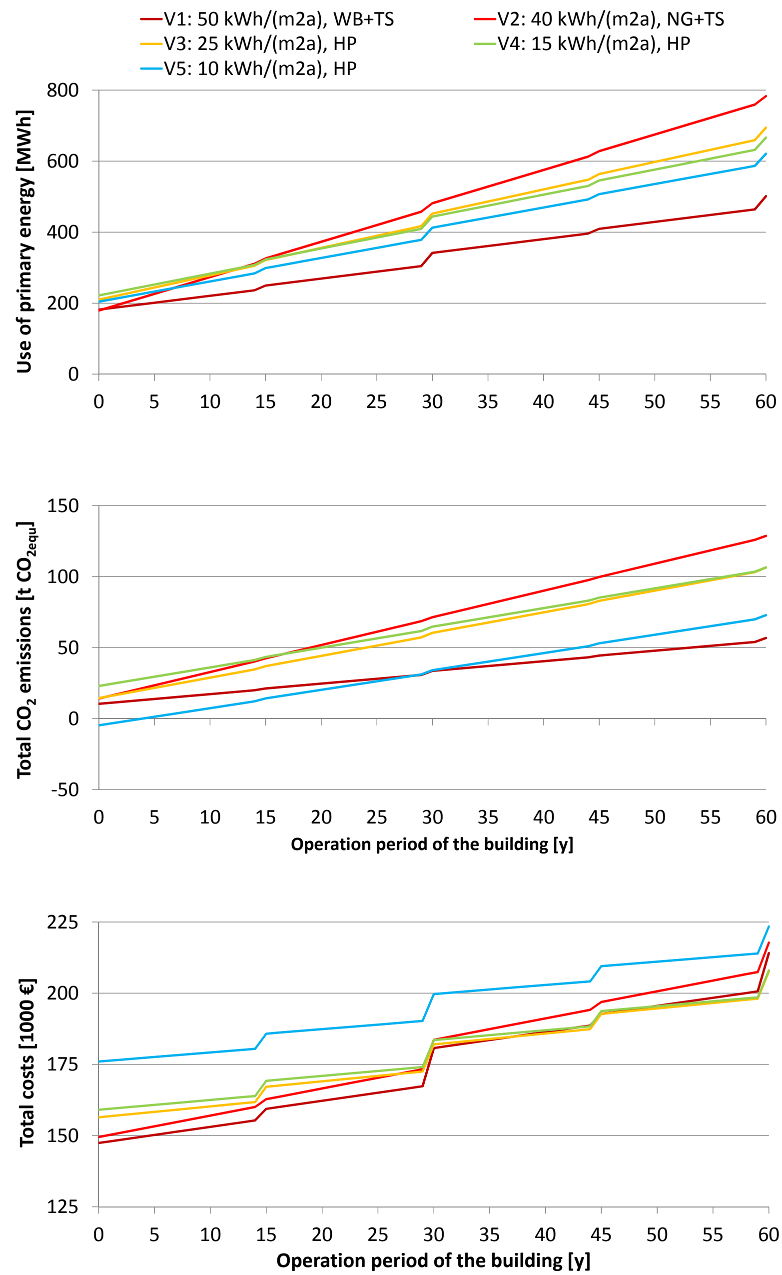


FIG. 5.2

Cumulative values of **energy indicators** of the building during its 60-year operation period

Cumulative values of **environmental indicators** of the building during its 60-year operation period

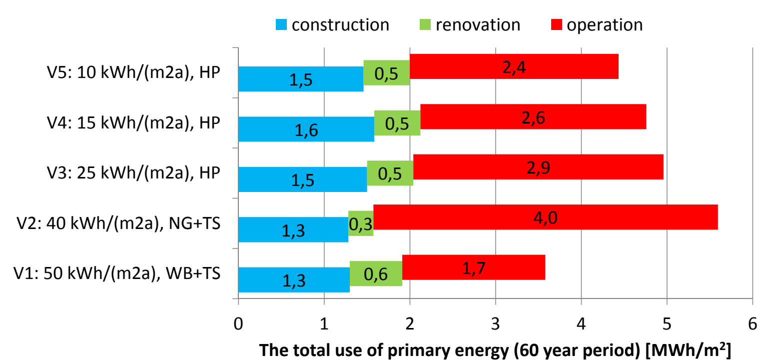
Cumulative values of **financial indicators** of the building during its 60-year operation period

The above diagram indicates why the five variants of new building configurations are a reasonable choice. V1 and V2 were chosen mostly to enable comparison between them, i.e. to show the impact of additional investment into small building envelope improvement, while simultaneously reducing the investment into heat generation systems. V3 and V4 indicate a comparison between very low-energy houses and passive houses, with possible optimisation of heat generator investment and additional investment into the building's envelope. V5 shows the impact of yet additional investment by installing natural building materials with a lesser environmental impact into a passive house.

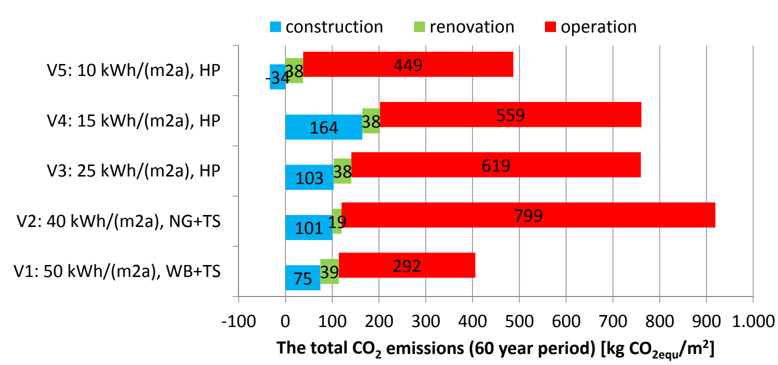
5.2 Valuation of Energy, Environment, and Economic Indicators in the Life Cycle of a Building

The result and findings of comparing all five building variants (V1 through V5) with respect to energy, environmental, and economic indicators are shown below (Fig. 5.3):

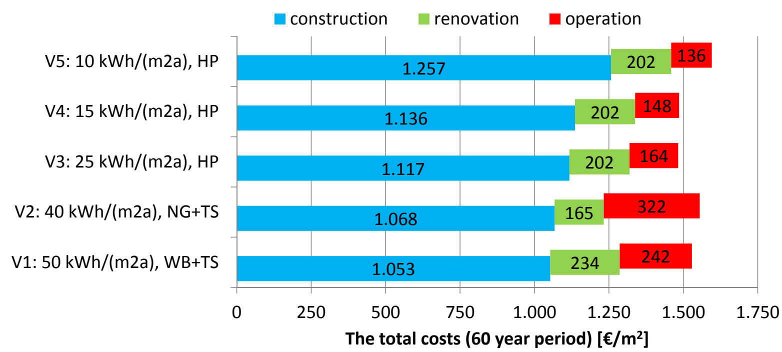
FIG. 5.3



Energy indicators of a building in 60 years of operation



Environment indicators of a building in 60 years of operation



Economic indicators of a building in 60 years of operation aption

– Irrespective of the extreme comparison divergence with regard to energy demand for space heating (Q_{HN}/A_u), the proportion of which, among the shown variants (V1 through V5), is a remarkable 1:5, the difference in the initial investment cost of a new building is relatively low. The difference in investment costs between V1 and V2 amounts to less than 2%. The difference in investment costs between V3 and V4, i.e. between building a very low-energy house and a passive house, also amounts to less than 2%. As shown, the difference in investment costs between the basic V1 and the very low-energy house V3 is 6%, and the investment cost difference between V1 and V4, which is a passive house, is 8%. The most energy efficient variant V5 requires a 19% increase of investment cost from the basic V1. As the investment cost difference between V4 and V5 amounts to approximately 11%, we may conclude that the better part of this differential is a consequence of choosing natural thermal insulation building materials, and not of energy efficiency improvement. Evidently, if accompanied with logical investment optimisation during the construction and installation stages, the leaps in energy efficiency have no meaningful impact on the height of investment cost.

– The rehabilitation investment cost, occurring four times in the observed period, amounts to approximately 15 – 20% of the initial investment cost. The rehabilitation costs are mostly dependent on measures connected with HVAC, as the service life of these components is much shorter than the service life of the building. The most costly rehabilitations of heat generating systems are a consequence of choosing technologies that result in less environmentally burdening indicators during their operation (V1).

– The cost of operational energy amounts to a 10 to 30% share of the initial investment cost. The highest share is attributed to the less energy efficient building, using a relatively lower cost demanding heat generation system (V2). In this case, the operational energy costs are double the rehabilitation costs. With an optimal combination of energy efficiency and heat generator systems cost, operational energy costs are lower than rehabilitation costs. We can conclude that in highly energy efficient buildings (V3 through V5), the majority share of the costs within the 60-year period is caused by »avoiding« costs related to energy consumption.

- Notwithstanding the different values and proportions of building, operation, and rehabilitation costs, the final sum total is nearly identical across all five described variants (V1 through V5). V2 differs from V1 by only 2%. The low-energy house and the passive house (V3 and V4, respectively) show an identical final result, 3% lower than the total cost of V1. V5 exceeds V1 by 4%. We may conclude that, irrespective of energy efficiency and heat generation system, the total cost is similar, as the group shows a deviation of less than 5% from the average value. This conclusion, consequently, indirectly confirms the fact that priority in modern building design should be given to the reduction of the buildings' impact on energy consumption and environment. With similar total cost, we should strive for the best values of the buildings' environmental and energy indicators.

- As the economic indicator was predominantly influenced by the initial investment cost, we may conclude that all consequent energy and environment indicators are predominantly influenced by the operational stage and its respective energy consumption.

- In terms of embodied primary energy, the demand of the more energy efficient buildings (V3 through V5) exceeds the basic V1 by 15 to 20%. In the rehabilitation stage, the embodied primary energy demand amounts to an average of one third of the initial investment cost. Relatively lower rehabilitation impacts are typical for solutions with simpler HVAC systems. Due to an appropriately chosen heat generation system, larger proportions of embodied primary energy in the rehabilitation stage result in decidedly lower annual operational primary energy consumption, thus leading to a favourable end result.

- With a complex heat generation system (V1), rehabilitation requires more embodied primary energy. The investment cost sum total in V1, however, is the lowest in the group due to lower primary energy consumption in the operational stage, irrespective of the fact that the building was designed with the lowest energy efficiency. In V2, the sum of primary energy consumption in 60 years is the highest in the group and is larger than the result for V1 by 50 %. In more energy efficient buildings, the primary energy consumption in the operational stage is decreasing, while still exceeding the sum of primary energy consumption in both initial and rehabilitation inputs.

- With regard to these results, it can be concluded that the balance between a building's energy efficiency and its heat generation systems is a key factor in the design of an energy efficient new building. On the contrary, with respect to primary energy consumption, a less energy efficient building- can be optimised by introducing more environmentally acceptable heat generation systems.

- The importance of an appropriate choice of building technology is also clearly shown from the viewpoint of primary energy use. While increasing the thermally protective envelope in a building, eventual additional inputs of primary energy can be reduced by choosing different building materials, both for construction and thermal protection. This is clearly shown in variant V5, where, if compared to the previous variant V4, no primary energy increase in the construction stage was noted. On the contrary, there was a 10% reduction.

- The CO_2 emission environmental indicator shows a continuation of the trend noted in primary energy examination. Its values, however, strongly reflect the impact of energy consumption and transformation in the operational stage. Between 75% and 85% of total CO_2 emissions occur in the operational stage. A larger share of the latter is expected to stem from the environmentally more burdensome heat generation systems. The smaller proportion reflects the use of more CO_2 neutral heat generation systems.

- The construction stage is also important in terms of energy consumption. Increasing a building's energy efficiency may result in the reduction of the environmental indicator value, if, where appropriate, CO_2 neutral systems of construction and heat protection are used. A clear example thereof is, again, the result for V5 in comparison with V4. In all solutions, the rehabilitation stage accounts for 20% to 50% of all CO_2 emissions as compared to the indicators' value in the buildings' construction stage.

5.3 Buildings' Valuation Using Five Key Indicators

The design, i.e. configuration, of a building affects its energy efficiency, primary energy consumption, the amount of CO_2 emissions, the cost, and the level of indoor living comfort. For their assessment, five key indicators were used:

- the Q_{NH}/A_u indicator (annual heat demand for space heating): the lower its value, the higher the building's energy efficiency

- the $PEC_{n.r.}$ indicator (amount of non-renewable primary energy used per unit area of the structural component and operation): a lower $PEC_{n.r.}$ value shows lower environmental impact

- the GWP_{100} indicator (CO_2 emissions during the production of building materials and heat generation for the building's operation): a lower GWP_{100} value denotes higher environmental efficiency

- the *Cost* indicator (costs of construction and costs of energents for heat generation in the operational stage of the building): lower costs imply higher economic efficiency

- the *LE* indicator (living environment): better indoor living conditions reflect a proper building's design with respect to the inhabitant's requirements

The assessment is based on the respective indicator values, the latter having been acquired both objectively and subjectively.

The Q_{NH}/A_u indicator

This indicator's value was assigned by calculating the building's energy balance using conventional methods (Feist, 2015; SIST EN 13790). A quick approximation of this value is also possible with the following equation (Eq. 5.1) (Praznik, Butala, & Zbašnik-Senegačnik, 2013):

$$Q_{NH}/_{A_u} \approx (78{,}3\times H'_T \times f_d + 64{,}2\times n_v) - \eta_G \times \left(4{,}9\times {q_i}/_{A_u} + 78{,}7\times {ASF}/_{A_u} - 2{,}3\right)$$

Included is a smaller number of parameters, which affect the building's energy balance: its shape and intended use, thermal envelope characteristics, and the type of ventilation.

Indicators $PEC_{n.r.}$, GWP_{100} and *Cost*

Both $PEC_{n.r.}$ and GWP_{100} are connected with materials and components installed in the building. Data for primary energy consumption and CO_2 emissions are at the designer's disposal in publicly accessible databases (i.e. Baubook, 2017). The investment cost data for building materials and HVAC machinery are available from sellers. The operation stage is limited to 60 years. The consumption of primary energy, the CO_2 emissions, and the energy costs are calculated using the estimated electricity of fuels for heat generation (Gustavsson & Joelsson, 2010). Also assessed are the rehabilitation costs for the building envelope and heating and ventilation machinery within the 60-year period, as are, consequently, the primary energy, CO_2 emissions, and cost demand.

Indicator *LE*

This indicator's value is assessed with respect to three areas affecting living comfort:

- thermal comfort is a consequence of the building's thermal envelope. A value of 0% is assigned to thermal envelopes of the highest energy efficiency, and 35% to the envelope with the lowest thermal protection and with temperature asymmetries;

- thermal comfort as a consequence of the heating system operation: 0% is assigned to the system with minimal negative impact on living comfort, and 35% to the system which only essentially fulfils its operation requirements;

- providing air quality with the ventilation system: a 0% value is assigned to the ventilation system with minimal negative impact, and 30% to systems with barely acceptable impact on living comfort.

The complex valuation of different design variants may be achieved in three different ways (Fig. 5.4):

– objective weighting of indicators – in the overall estimate, all indicators are assigned equal weights;

– weighting according to state criteria – both Q_{NH}/A_u and GWP_{100} are assigned double weights;

– weighting according to the user's criteria – both *Cost* and *LE* indicators are assigned double weights.

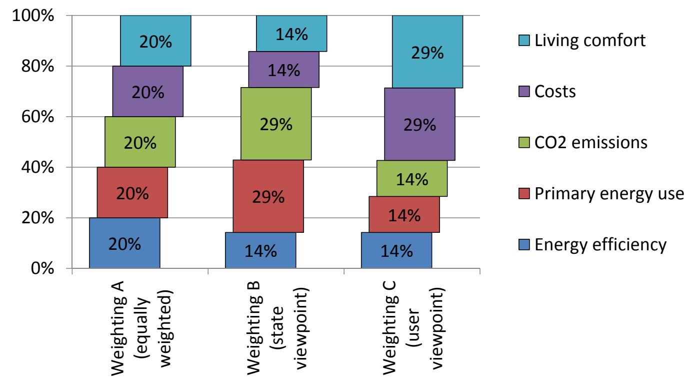


FIG. 5.4 Five key indicators with differently assigned weights – assignation of equal weights and assignation of weighting for both the state and the user point of view

5.4 Valuation of Buildings with the Five Indicators Method

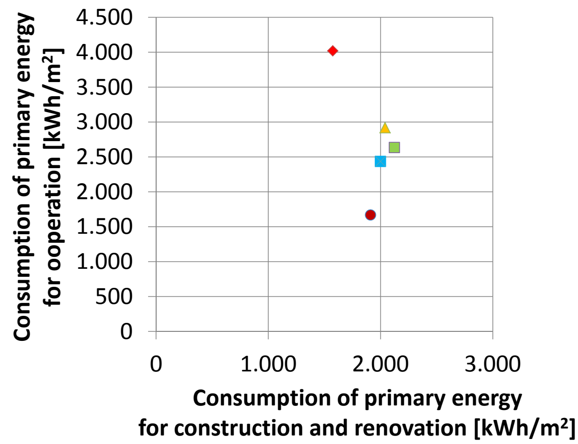
The five building variants with differing energy efficiency (V1 through V5) were evaluated using the five indicators method.

In Fig. 5.5, the data used for value assignment to $PEC_{n.r.}$, GWP_{100} and cost indicators (Fig. 5.3) is shown from the initial cost, rehabilitation cost, and cost of operation point of view.

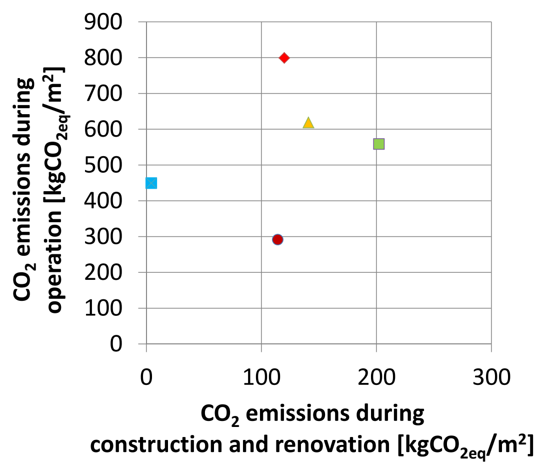
All five indicators are assigned values for every variant V1 through V5. The highest value of 100% for indicators Q_{NH}/A_u, $PEC_{n.r.}$, GWP_{100}, and *Cost* is assigned to the variant with the best cumulative result. The indicator values for other variants are proportionally reduced according to the deviation of their result from the maximum result reached in the comparison group of variants V1 through V5. The *LE* indicator (living environment) is assigned values with regard to three estimated areas. For negative impact on indoor living comfort as a consequence of the building's thermal envelope, values between 0% and 35% are assigned (i.e. 0% should be assigned to the variant with the best performing thermal envelope and 35% to the variant with the barely acceptable thermal protection). Similarly, the negative impacts of the heating system on the temperature comfort are estimated. The third part of the estimation reflects the negative impact of ventilation and the resulting effect of the indoor air quality on the indoor living comfort (a value of 0% is assigned for ventilation with the least impact and 30% for ventilation with acceptable living comfort impact). All assigned indicator values for all variants (V1 through V5) are shown in Fig. 5.6.

FIG. 5.5 Values of primary energy use (A), CO2 emissions (B) and costs (C) for all five variants V1 through V5 in a 60 years period

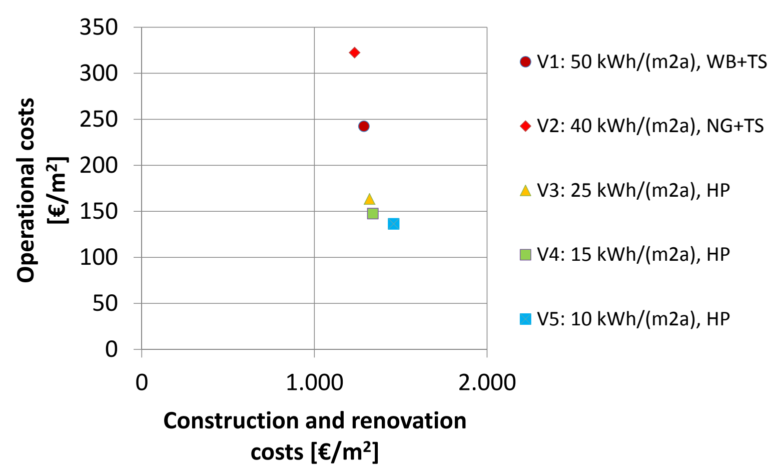
A



B



C



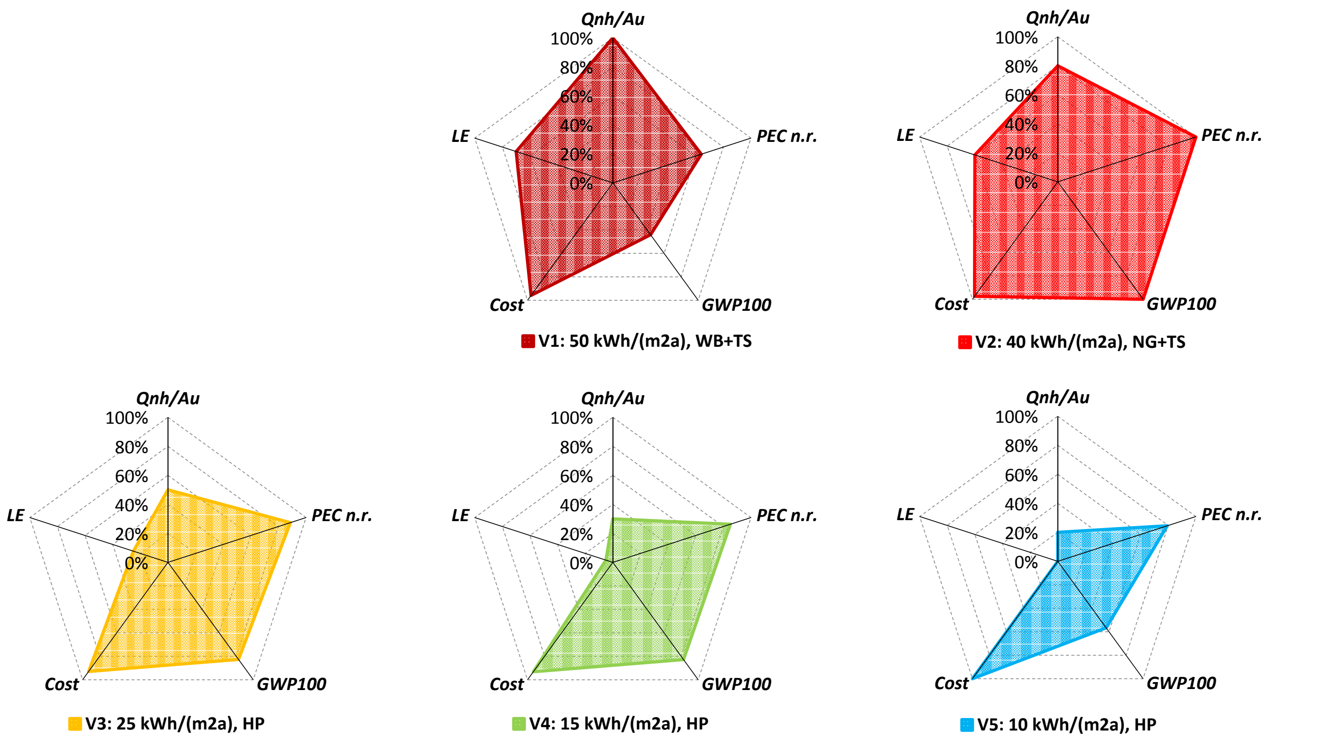


FIG. 5.6 Values of five key indicators for the five variants of building design

The complex valuation is executed using three methods as shown in Fig. 5.7 the objective weighting, and with weight assignment according to the state or users' point of view. The results confirm our premise that an appropriately optimised new building design concept, shown here with the two passive house variants (V4 and V5), achieves the best, i.e. minimal, total assessment score, valid for the objective as well as for both subjective assessment methods. In variant V5, the results vary between 58% and 61%, and in variant V4 between 66% and 73 %. The complex valuation of the design concept for a very low-energy building (variant V3) comes in third place with regard to all three assessment methods, with an estimate between 77% and 80%. The worst complex valuation result of 100% was reached by the less energy efficient design concept (variant V2), where heat is predominantly generated using fossil fuel. This result is shared over all three-weight assignment methods. Also confirmed by the complex valuation is the fact that even the least energy efficient concept of a new building (variant V1) may be improved with appropriately corrected heat generation, based solely on using renewable sources of energy. After the implementation of such measures, variant V1 was reassessed and achieved a result between 76% and 93%.

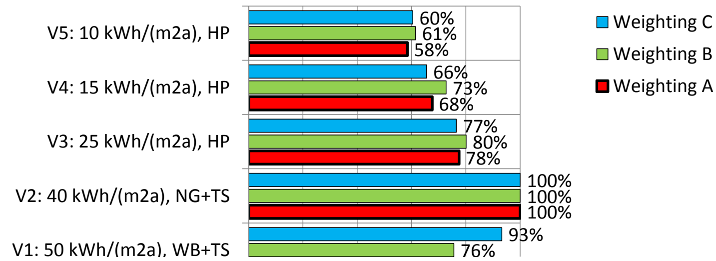


FIG. 5.7 Comparison of the indicator valuation for variants of a new building using differing weight assignment

6 Conclusions

In recent years, increasing attention has been paid to the energy efficiency of buildings. The legislation prescribes a maximum permitted energy use for heating, and in most EU countries, the heating demand is below 50 kWh/(m²•a). With further improvements to the building envelope and the installation of ventilation system, the energy consumption is reduced accordingly until the passive house standard is achieved, with energy consumption up to 15 kWh/(m²•a). Improvements and optimisation of passive houses allow the energy consumption to drop even below 10 kWh/(m²•a). By increasing the energy efficiency of buildings, the living comfort is improved and the space heating demand is reduced but, as a consequence, the negative impacts on the environment and the cost of construction, or investment amount, are increased.

Selecting the energy class of the planned house is a multi-faceted decision and is based on various criteria. Five variants of energy efficient buildings have been displayed using a single-family house model. The variants with the following energy consumption values for heating have been evaluated: V1 up to 50 kWh/(m²•a), V2 up to 40 kWh/(m²•a), V3 up to 25 kWh/(m²•a), the passive house variant V4 up to 15 kWh/(m²•a), and the improved passive house V5 up to 10 kWh/(m²•a). The evaluation with the energy efficiency (Q_{NH}/A_u), primary energy consumption ($PEC_{n.r.}$), CO_2 emissions (GWP_{100}), cost (*Cost*), and living environment (*LE*) indicators was carried out.

The evaluation was performed according to three methods of weighting, depending on the perspective of the evaluator. In objective weighting, all five indicators are equally weighted. From the national perspective, the Q_{NH}/A_u and GWP_{100} indicators have double weight, and from the perspective of the users of the building, the *Cost* and *LE* indicators are given double the weight. The results confirm the assumption that the properly optimised concept of the most energy-efficient new building, represented by the two passive house variants V4 and V5, whose energy consumption for heating is up to 15 kWh/(m²•a) or up to 10 kWh/(m²•a), respectively, would obtain the best evaluation results under all three weighting methods.

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