Thermal envelope quality versus nZEB parameters and long-term economics: the Eco-Silver House case in Ljubljana

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ABSTRACT

In 2014 the first multi storey residential building planned and constructed to meet the Passivhaus Institute (Darmstadt) criteria was put in operation in Ljubljana, the capital of Slovenia. This massive-structure building is part of the FP7 EE-Highrise project, aiming to demonstrate nearly zero energy building (nZEB) technologies, an integrated design concept, and advanced systems for sustainable construction. The aim was to test and assess the technological and economic feasibility of innovative energy solutions on a large-scale real project (www.ee-highrise.eu). The construction phases had to be meticulously prepared in order to reach the goals and meet the targets defined during the integrated planning process and selection of most viable design options. This included among other special on-site training and coaching of construction workers, preparation of how-to written protocols, and performing various non-destructive tests and measurements within the established quality assurance scheme.

As two of the most important objectives were to reach the passive house standard according to the PHPP methodology and to possibly comply with the national nZEB boundary values while securing a high level of thermal comfort special attention was put also on the airtightness and avoidance of thermal bridges on the thermal envelope, both in planning and implementation phase. The air exchange rate (n50) strongly influences the energy use and affects the efficiency of ventilation system with heat recovery, conditioning of occupied spaces and overall performance of smart control units in each apartment. A high level of airtightness and absence of thermal bridges are two of the vital preconditions for reaching the nZEB standard after having had other parameters successfully fine-tuned.

Through a step-by step process of repetitive Blower door tests in consecutive construction and installation phases all weak point were identified, solutions for sealing proposed and implemented, corrective measures tested and the final state approved. The same approach was used for identification and remedy of thermal bridges using infrared thermography. The goal was not just to achieve remarkable energy indicators on paper, but on the actual building. The paper describes the main principles and implementation of the above mentioned approach.

Another point of consideration was the long-term economics of selected solutions, i.e. an analytical study of the influence of various building quality parameters (like air exchange rate and thermal bridges). The question was how is the energy use according to different scenarios reflected in the long-term costs. An LCC analysis based on parametric sensitivity studies about the influence of individual thermal envelope features was conducted to find out which of them is the most significant. The aim was twofold, namely to see what is the impact level of the quality of specific work procedures and, indirectly, skills of workers on operational costs, and to see if common guidance for future similar projects can be extracted from the results. The paper explains selected findings and point out the main lessons learnt to be considered on the way towards nZEB standards and sustainable buildings.

KEYWORDS

Integrated design, quality control, airtightness, nZEB, costs.

1 INTRODUCTION

The Eco-Silver House (ESH) is a multi-residential high-rise building with 128 flats located in the city centre of Ljubljana, Slovenia (Figure 1). It is part of the FP7 EE-Highrise demonstration project, aiming to demonstrate new nearly zero energy building (nZEB) technologies, an integrated design concept and systems for sustainable nZEB construction in order to test and assess the technological and economic feasibility of innovative energy solutions within a real high-rise multi-residential building project (www.ee-highrise.eu). The ESH was designed as two rays forming a shape of an inverted letter »L«. The net total area covers a surface of 23.455 m^2 over 17 floors (12.870 m^2 net treated floor area). The building is a private investment built for the market and its concept aims to correspond to the specific needs of potential buyers looking for an intelligently controlled and eco-oriented building in a passive standard (according to the Passivhaus Institute criteria).

Figure 1: Eco-Silver House – the design concept and the completed building
(Design: Akropola; Photo: Milan Tomažin).

During the design and construction phase the focus of the demonstration project was on implementation of integrated energy design and quality assurance (QA) protocols. The scope of the on-going post-occupancy research is monitoring of the energy performance indicators, comfort parameters and users' satisfaction as well as assessment of sustainable building indicators.

Among other actions substantial efforts were put on avoidance of thermal bridges and securing a high level of airtightness, which both positively contribute to energy indicators of the building, to operational efficiency and proper functioning of certain mechanical equipment, and of course to easier control of indoor comfort parameters.

2 THE MAIN ECO-SILVER HOUSE FEATURES

The energy concept of the building allows cost-independent performance of individual apartment units where excellent insulation of thermal envelope and dynamic shading as well as the possibility of intelligent control of indoor conditions ensure that each apartment can function like an independent passive unit. The U values of the building envelope are 0,17 W/(m^2K) for walls and 0,14 W/(m^2K) for the flat roof, while the U value of a triple glazed (U_g = 0,58 W/(m^2K)) window of standard dimensions is 0,83 W/(m^2K). The airtightness level

(n_{50}) of building sectors measured with Blower door test is between 0,45 h^{-1} and 0,59 h^{-1}, i.e. bellow the design value of 0,6 h^{-1}.

The building is connected to the energy efficient municipal district heating, with wood biomass co-burning and cogeneration. In addition to the main district heat station each apartment has its own heat substation for space heating and domestic hot water preparation, while electricity is used for operation of mechanical ventilation with heat recovery with a system efficiency of 0,85 and for an air to air inverter heat pump for preheating or precooling of the inlet air. The heat is emitted via radiators and in larger apartments also partly via floor heating. Cooling needs are negligible in the standard usage profile. A multi-split air conditioning system can be installed in larger flats on request and depending on the particular usage pattern.

The fundamental principles of sustainable design of the building are reflected in the demonstration project through comprehensive planning of energy efficiency features with respect to passive house standard criteria and national nZEB criteria. The important features include utilisation of renewable energy sources, very good thermal insulation, high-performance air-conditioning system with heat recovery, dynamic sun protection, intelligent control and management of electric and mechanical devices, machinery and tools, and a significant share of ecological materials. Building owners use rainwater stored in a roof tank (60 m^3 of storage covers a 10-day sanitary water demand and brings 500 m^3 of fresh water savings), a micro solar power plant (34 kWp) on the roof, green roof, and e-mobility with car sharing (Figure 2). The building was completed in 2014, and in 2015 it entered the post-occupancy monitoring period.

Figure 2: Eco-Silver House – PV power plant on the flat roof and the intelligent control unit in each apartment (Photo: Borut Slabe).

3 NATIONAL nZEB CRITERIA

Slovenia implemented minimum requirements for energy-efficient buildings in the 2010 Building Codes based on the recast EPBD. In the 2008 Regulation (PURES 2008) an intensive reduction of transmission losses through the building envelope as well as new requirements on the obligatory 25% use of renewable energy sources in the final energy use were introduced. The 2010 Building Codes (PURES 2010) built on the 2008 version and placed the focus also on the calculation of primary energy and CO_2 indicators, set additional minimum requirements for the primary energy for heating, limited the heating and cooling needs, both in terms of useful and primary energy, and added many new minimum requirements for energy systems.

From January 2015 more severe minimum requirements for maximum energy needs for heating have entered into force according to the long term perspective integrated in the rules of the PURES 2010 Building Code. Minimum requirements are expressed using performance-based requirements, energy-related requirements, and detailed technical requirements for building components and systems. By the end of 2015 the Building Codes are planned to be revised with respect to the outcome of the national cost optimal study and amended and upgraded with further details accompanying the national definition of nZEB.

The climate in Slovenia is very diverse, which results from many intertwined factors. This is visible from the distribution of degree-days on the map in Figure 3. It is determined among other by the geographic location, type of terrain, orientation of mountain ridges and proximity to the sea. There are three predominant types of climate in certain areas but their effects are intertwined: the eastern Slovenia has a temperate continental climate, the central part a sub-Alpine (Alpine in the mountains) one and west of the Dinaric-Alpine barrier there is a sub-Mediterranean climate. Over 90% of inhabitants live in the regions with more than 2800 degree days.

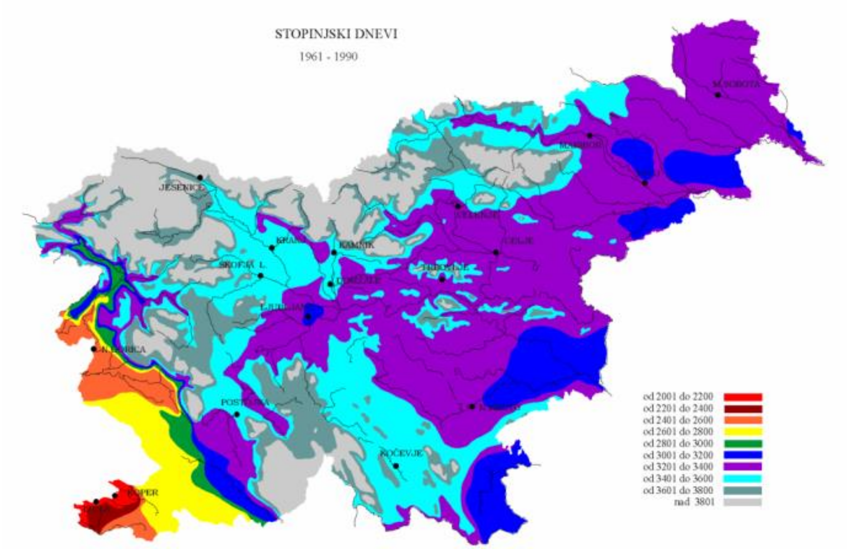

Figure 3: Spatial distribution of degree-days in Slovenia *(Mekinda - Majaron, 2002)*.

The national definition of nZEB *(Ministry of Infrastructure, 2014)* was formulated based on the cost-optimal study of minimum energy efficiency requirements *(Šijanec Zavrl et al, 2014)* with consideration of building tradition, availability of technologies for nZEB and with respect to the Slovenian climate.

Table 1: Minimum requirements for nearly zero energy buildings (nZEB) in Slovenia

Building Type	**Minimum requirements for nZEB Primary Energy Q_P (kWh/(m^{2}a)) and Share of Renewable Energy (%)**		
	New building Max. Q_P kWh/(m^{2}a)	**Major renovation Max. Q_P kWh/(m^{2}a)**	**Min. share of renewable energy %**
Single family house	75	95	50
Apartment building	80	90	50
Non-residential building [a]	55	65	50

a. Appliances and equipment not included.

The National definition of nZEB is based on a cost optimal study for reference buildings where the primary energy as a core nZEB performance indicator is complemented with the criterion of achievable target of 50% share of renewables in the final energy use, selected with consideration to the nZEB acceptable technologies and available renewable energy sources. In future the use of RES will be increased due to growing share of RES in district heating systems that are subject to comply with 2020 energy efficiency targets set in the Energy Act. In addition to that, the nearly zero or very low amount of energy required is achieved by further limitation of energy need for heating to a maximum value between 25 kWh/(m^{2}K) and 15 kWh/(m^{2}K), with respect to the shape factor and climate on the location. Although not directly prescribed the very high energy performance of nZEB will be demonstrated with nZEB building ranked in class A1, A2 or B2 based on the building heating needs.

The nZEB definition provided minimum requirements for primary energy (for all energy use according to Directive EPBD Annex I, including lighting in residential building and excluding appliances and other energy use but EPBD-related) for new buildings as well as for major renovation, for single family houses, apartment buildings and for non-residential/office buildings (Table 1). An nZEB action plan with the national definition of nZEB was accepted by the government in April 2015.

4 ENERGY INDICATORS ACHIEVED

The Eco-Silver House, as built, fulfils the commonly accepted passive house standard characteristics with a PHPP annual heating demand of 14 kWh/(m^{2}a) and a total primary energy use for building operating systems including electrical household appliances of 106 kWh/(m^{2}a). According to the national energy performance certificate ESH is ranked in energy performance class A1 with a standard annual heat demand of 8 kWh/(m^{2}a).

Figure 4 shows the total delivered energy amounting to 51 kWh/(m^{2}a) and the primary energy to 71 kWh/(m^{2}a). The latter number is reduced to 55 kWh/(m^{2}a) when exported energy from the PV power plant is considered. These are values calculated using the prescribed national method and national primary energy conversion factors for various energy carriers. The ESH presents a new standard of the energy-efficient apartment building in the Slovenian construction sector, meeting the 2015 definition of nZEB, which set the maximum allowed primary energy for apartment buildings to 80 kWh/(m^{2}a). The graphs below show also a comparison of the ESH indicators with the "state-of-the-art" ones, which would be reached using a standard approach according to current regulation.

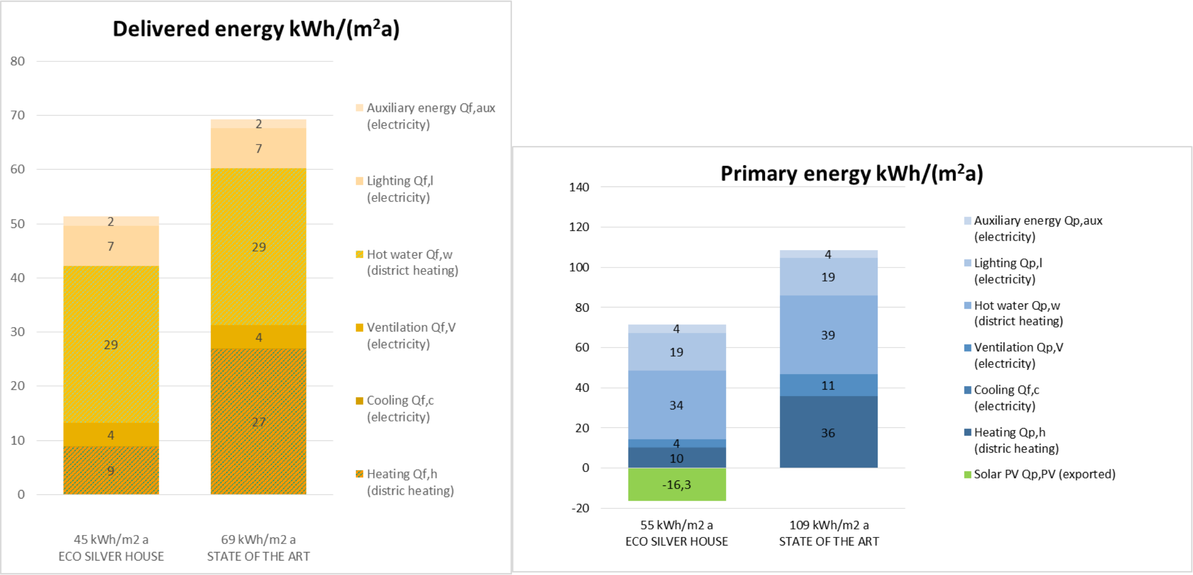

Figure 4: Delivered and primary energy for the ESH demonstration building and a (reference) state of the art new building in Slovenia.

5 QUALITY CONTROL AT THE CONSTRUCTION SITE – AN EXAMPLE FOR AIRTIGHTNESS AND (CONVECTIVE) THERMAL BRIDGES

Already before the start of the actual construction work it was clear that due to special demands and high targets of this project special attention will have to be put upon the quality of individual work tasks. The design process therefore included numerous sessions where the details of individual stages were discussed and defined. One of the key segments was to ensure provision of adequate knowledge and upgraded skills to construction workers to enable them to meet the set targets. Quality assurance and quality control had to be integrated in all phases from design to the finalization of the building (Figure 5).

Figure 5: ESH (FP7 EE-Highrise) QA steps from paper to the construction site.

To ensure the optimal results the demonstration project accommodated pilot trainings for on-site workers, where various approaches were tested. The QA process for nZEB during the construction phase covered: training of on-site working teams; video streaming of best practice applications of nZEB technologies; special coordination meetings of on-site workers, contractor, designers, investor and QA team; selected quality control on site (Figure 6). During the construction phase the weak points of the installation of nZEB technologies were identified (i.e. continuity of the thermal envelope, sealing of penetrations, installation of air-tightness layers within the building volume, installation of windows according to the RAL guideline). The QA was based on the plan-do-check-act principle where bottlenecks in nZEB-related skills were identified and missing experience integrated within corrective actions.

The integration of the FP7 demonstration EE-Highrise project and the understanding of relatively rigid performance and feedback of the construction sector studied in detailed in the Build Up Skills Slovenia project provided added value for both – reaching nZEB targets in demonstration as well as smooth provision of better skilled workforce.

The benefits of implementation of QA are reflected not only in the technical aspects but also in improved processes and better skilled workforce as well as in profound understanding of barriers specific to various occupations and workers’ profile. The theoretical background of nZEB planning was integrated into construction process by defining of various protocols, where comprehensive knowledge and skills in the whole production chain (investor, designer, contractor, quality control, technology provider etc.) are essential for a success of such demonstration project.

The importance and benefits of consecutive quality testing were expressed through constant improvements of the results. The workers implementing newly acquired knowledge were made aware of needed improvements of certain techniques and proper use of specific materials in real time, so it was to a large extent a learning-by-doing process.

Figure 6: Preparation and execution of Blower door tests.

The gradual but steady improvement of airtightness levels was visible through repeated Blower door tests, where findings of each session served workers as a guidance on how to remedy the performance (example in Table 2 and Figure 7).

Table 2: Air exchange rate (n_{50}) from Blower door tests done during the initial external quality control at demonstration phase, during internal control by the building contractor and during the final external quality control at the building completion

INITIAL EXTERNAL

Airtightness zone – apartment or sector description	Apartment or sector code	Area (m^2)	Date	n_{50} (h^{-1})
3-bedroom	C-1-1	69.59	21.11.2013	1,04
2-bedroom	C-1-2	57,82	21.11.2013	0,88
3-bedroom	C-1-3	81,40	21.11.2013	1,92
4-bedroom	C-1-4	98,90	21.11.2013	1,36
Sector C-1	C-1-1, 2, 3, 4	401,00	12.5.2014	0,77
Sector C-1	C-1-1, 2, 3, 4	401	24.7.2014	0,58

INTERNAL

Sector description	Sector code	Area (m^2)	Date	n_{50} (h^{-1})
C-1-1, 2, 3, 4	C-1	401	12.5.2014	0,77
C-2-1, 2, 3, 4	C-2	401	30.4.2013	0,65
C-3-1, 2, 3, 4	C-3	401	21.11.2013	0,68
C-7-1, 2	C-7	278	21.11.2013	0,88
C-8-1, 2	C-8	229	21.11.2013	1,92
C-9-1	C-9	165	21.11.2013	0,86

FINAL EXTERNAL

Flats in sector	Sector code	Area (m^2)	Date	n_{50} (h^{-1})
C-1-1, 2, 3, 4	C-1	401	24.7.2014	0,58
C-2-1, 2, 3, 4	C-2	401	21.7.2014	0,58
C-3-1, 2, 3, 4	C-3	401	23.7.2014	0,59
C-4-1, 2, 3, 4	C-4	401	23.7.2014	0,59
C-5-1, 2, 3	C-5	350	24.7.2014	0,56
C-6-1, 2, 3	C-6	347	24.7.2014	0,57
C-7-1, 2	C-7	278	24.7.2014	0,60
C-8-1, 2	C-8	229	23.7.2014	0,60
C-9-1	C-9	165	23.7.2014	0,56

Figure 7: Airtightness sectors C-1 (apartments C-1-1, C-1-2, C-1-3, C-1-4), B-1, A-1 covering three staircases of the 1st floor of the residential part.

6 BUILDING ENVELOPE QUALITY AND ITS FINANCIAL ASPECTS

A high-end project in performance terms featuring also demonstration elements as described above has a specific financial framework, but need not be high-end in costs as well. This is especially true when looking at the long-term impact of implemented energy efficiency solutions affecting operational costs. A number of particular ESH features and solutions were checked for their impact, but there are also other, non-measurable elements to be recognised such as indoor comfort, well-being and satisfaction of the dwellers. On the other hand the work force involved in the construction acquired new knowledge and skills, which makes them competent for implementation of further nZEB (or similar) works and highly competitive on the construction market.

Here we present only one example of different scenarios, the one related to the manner of installation of windows. Installation according to the RAL guideline was prescribed and implemented, which is indeed more costly than the standard procedure. But, this upgrade strongly influences the airtightness of the thermal envelope and consequently the energy demand for heating. It also supports proper functioning of certain mechanical systems.

We analysed three airtightness scenarios with corresponding investments:

- The business as usual approach considered no special attention given to installation of windows, and an airtightness of n_{50} = 3,00 h^{-1} (a conservative value based on long-term experience from the national building stock).
- The basic integrated design approach considered on-site training without Blower door tests and use of moderate class sealing materials and techniques. According to the results of preliminary Blower door tests (see the excerpt in Table 2 above) an assumption was made for an average building envelope airtightness of n_{50} = 1,50 h^{-1}.
- The advanced integrated design approach considered on-site training with consecutive Blower door tests performed at selected project milestones (pilot apartment, confirmation of adequate sealing, internal control by the building contractor, and final external quality control) and use of state-of-the-art sealing materials and techniques, which as a result brought the airtightness level down to n_{50} = 0,55 h^{-1}.

The surplus costs for RAL installation depend in practice also on the scope of the operation and on particular investor-contractor arrangements. The total installation length in ESH was 5.782 m, and the surplus cost for moderate class sealing materials and techniques was estimated to 6 EUR per meter, and to 15 EUR per meter for the state-of-the-art sealing performance.

The comparison of results based on data from Table 3 is shown in the spider chart below (Figure 8), which compares parameters such as payback period, CO_2 emissions, primary energy for heating and DHW.

Table 3: Input data and results for evaluated scenarios.

Window installation (total perimeter) length	5782 m
State-of-the-art cost surplus (compared to business as usual) per unit length n_{50}=0,55 h^{-1}	15 €/m
Moderate class cost surplus (compared to business as usual) per unit length n_{50}=1,50 h^{-1}	6 €/m
Training costs	22.500 €
Blower door plus internal QA	15.000 €

Scenario	**Airtightness n_{50} (h-1)**	**Primary Energy for Heating and DHW per TFA (kWh/(10*m^2a))**	**Annual CO_2 emissions per TFA (kg/(10*m^2a))**	**Payback period in years**
Business as usual (n_{50}=3,00 h^{-1})	3,00	5,1 kWh/(m^2a)	1,7 kg/(m^2a)	0,0
Basic ID approach (n_{50}=1,50 h^{-1})	1,50	4,0 kWh/(m^2a)	1,3 kg/(m^2a)	5,0
Advanced ID approach (n_{50} = 0,55 $h^{-1)}$	0,55	3,5 kWh/(m^2a)	1,1 kg/(m^2a)	8,3

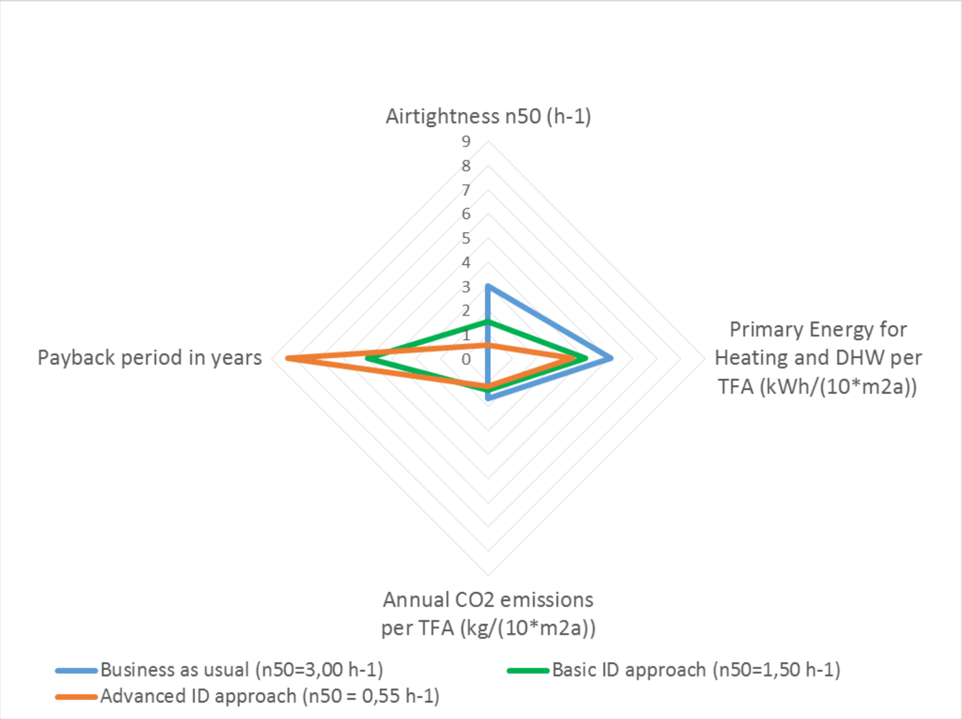

Figure 8: The comparison of parameters for different scenarios.

7 CONCLUSIONS

The Eco-Silver House/FP7 EE-Highrise project clearly showed the necessity of an integrated design approach including a QA scheme when rigorous targets are set for energy indicators. The key problem of nZEB lies not in availability of products and technologies, but in knowledge, competences and skills of planners and contractors, accompanied by understanding and at least basic technical knowledge of the investor. The situation can be more critical when smaller markets are in question where specialisation of the construction sector is less developed also for economic reasons.

The demonstration part of the project also showed that such actions cannot be satisfyingly implemented without clearly defined quality assurance protocols prepared in advance. Training of workers and monitoring of construction stages with guidance on remedy procedures in case of inadequate results are vital parts of nZEB construction.

The state-of-the-art procedures (i.e. protocols, training, monitoring, repeated work tasks) described in the paper did consequently affect the construction price, but not to an extent which would bring the initial decision in question. The activities proved to be sensible both from the aspect of energy indicators and cost parameters. For example, the presented installation of windows according to RAL guidelines with all due materials and procedures contributed to reaching very favourable energy indicators including complying with the national nZEB requirements, while the payback period for these additional efforts including QA-related costs remains notably short and points out the cost-effectiveness of the approach.

It has to be stressed that airtightness and particularly installation of windows was just one of many segments and their impacts considered within the project, and that the interaction of various interventions was studied in advance, too, in order to achieve well-balanced results related to energy, economy, and indoor comfort.

8 ACKNOWLEDGEMENTS

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