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# Energy efficiency and economic analysis of the thermomodernization of forest lodges in the Świętokrzyski National Park

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**Abstract.** This paper analyses energy efficiency of thermomodernization project on the example of three forest lodges located in the Świętokrzyski National Park. Currently, one of the basic requirements posed for the buildings subjected to modernization is to reduce carbon dioxide emissions even above 80% in comparison with the original values. In order to fulfil such criteria, it is necessary to apply alternative solutions based on renewable energy sources. Due to limited budget, low cubic capacity and location of the buildings, solar collectors with storage tanks and biomass boilers provide a rational option. For such a case, the emissions of basic pollutants such as $CO_2$, $SO_x$, $NO_x$ or particulates is obtained. The study also gives the results of calculations of payback time (SPBT) for the investment for exemplary forest lodge.

## 1 Introduction

Emissions of harmful substances into the air, associated with various activities and manufacturing processes, are currently under tight state control all over the world [1]. According to [2], anthropogenic activities are responsible for 78% greenhouse gases emissions in the EU countries. Construction industry, broadly understood, is one of the economy sectors which generates considerable pollution [3]. Therefore, different tasks are undertaken to increase energy efficiency by reducing energy consumption for heating, ventilation, and domestic hot water production. Also, it is aimed to reduce energy losses in local heating plants and local energy sources that power them. Conventional energy sources could be replaced, completely or partially, with the renewable ones. Some activities are intended to control lighting intensity and maintain it at the required level, and to make improvements in the equipment efficiency and in control of the power supply [4].

Better efficiency of end-use energy can be obtained by the development of new innovative technologies [5]. As regards existing buildings, to achieve that outcome, it is necessary to perform energy audits, and also collect inventory data on heat and cooling sources, and sanitary installations with respect to technical and construction aspects [6].

It is therefore time-consuming to perform an energy audit, and the auditors need to be professionals with expertise and experience in the theme. In [7], a simplified methodology was developed to determine the energy efficiency in buildings with small cubic capacity (single-family houses), and to analyse the return on thermal upgrading investment.

The tool employed to perform engineering diagnostics and heat loss balance is a thermal imaging camera [8, 9]. Study [10] shows how to correctly assess and interpret the results of thermography measurements for facilities located in open areas. To that end, the authors developed a method that involves the determination of the equivalent ambient temperature. That allows computing the substitute radiative ambient temperature. This value is further used to determine local heat losses through radiation in accordance with recommendations in the European standard [11].

Contactless measurement of the temperature field and qualitative thermographic analysis combined with visual examination also provides an effective tool to reveal moisture anomalies in the building envelope elements [12].

Study [13] presented a review of the existing thermography methods for diagnostics of construction faults, which contribute to increased thermal energy consumption.

In addition to reduction in the end-use energy consumption, one of major requirements for buildings intended for thermal upgrading is a reduction in carbon dioxide emissions and particulate matter emissions into the atmosphere [3]. Depending on the source of funding, it is required that after thermal upgrading the quantities mentioned above should decrease even by as much as 80% compared with the existing data [14]. It is possible to meet that requirement when alternative solutions are used, including renewable energy sources. Some solutions of that kind, however, require heavy investments, which represents a considerable limitation, especially for institutions financed from the state budget.

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This paper presents an analysis of energy efficiency and environmental effect of thermal upgrading. The project involved three forest lodges located in the Świętokrzyski National Park (central Poland). The paper also discusses economic issues related to the selection of the optimal improvements.

## 2 Characteristics of the buildings

This study provides the analysis of the results of the energy and environmental audits carried out for three settlements located in the Świętokrzyskie Mountains (legal status as of 1 Dec. 2010). The settlements mostly provide residential facilities for foresters employed by the Świętokrzyski National Park. Some of the area of the buildings is used as office space.

Table 1 shows basic data on the buildings of concern. Two of them were constructed in the 1950s. Lodge 1 is a timber building, whereas two other buildings, namely Lodges 2 and 3, are traditional masonry constructions.

**Table 1.** General data on the buildings.

| Description | Forest Lodge 1 | Forest Lodge 2 | Forest Lodge 3 |
|---|---|---|---|
| Structure | timber | masonry | masonry |
| Year of construction | 1926 | 1958 | 1960 |
| Cubic capacity, $m^3$ | 459.7 | 830.3 | 571.7 |
| Heated volume of the building, $m^3$ | 459.7 | 830.3 | 571.7 |
| Floor space, $m^2$ | 179.9 | 261.8 | 194.5 |
| Usable floor area of the residential part, $m^2$ | 129.1 | 216.0 | 148.7 |
| Form factor, $m^{-1}$ | 0.98 | 0.43 | 0.57 |
| Building users, number | 4.00 | 4.00 | 3.00 |
| Ventilation | natural | | |

It was decided that the settlements needed major refurbishment because of the age of the buildings, the condition of the building envelope elements and that of window and door joinery. The refurbishment was extended to include thermal upgrading. Table 2 lists heat transfer coefficients for the building envelope elements before thermomodernisation and after thermal upgrading.

Because of the buildings location in the vicinity of deciduous trees, the area layout needed to be altered in such a way as to prevent further biological degradation of the walls that is observable in Figure 1. Biological corrosion was found on the surfaces of interior timber ceilings.

**Table 2.** Heat transfer coefficients of the building envelope elements with thermal upgrading, *U* W/$m^2$K

| | | Before thermomodernization | After thermomodernization |
|---|---|---|---|
| No. | **Forest Lodge 1** | | |
| 1 | Exterior walls | 0.77, 0.80 | 0.24, 0.25 |
| 2 | Windows | 2.20, 2.20 | 1.10, 2.20 |
| 3 | Doors/traffic doors | 2.60, 2.60 | 2.00, 2.00 |
| 4 | Floors on the ground | 1.28 | 0.28 |
| 5 | Ceilings over the passage | 1.32 | 0.29 |
| | **Forest Lodge 2** | | |
| 1 | Exterior walls | 0.73, 0.51 | 0.24, 0.21 |
| 2 | Roof/flat roof | 1.35, 2.36 | 0.19, 0.47 |
| 3 | Doors/traffic doors | 2.60 | 2.20 |
| 4 | Interior ceilings | 0.61 | 0.22 |
| | **Forest Lodge 3** | | |
| 1 | Exterior walls | 0.73, 0.81, 0.51 | 0.24, 0.25, 0.21 |
| 2 | Roof/flat roof | 0.60 | 0.21 |
| 3 | Windows | 2.20 | 1.10 |
| 4 | Doors/traffic doors | 2.60 | 2.20 |
| 5 | Interior ceilings | 0.49 | 0.22 |

**Fig. 1.** A view of the western façade of Forest Lodge 2 after partial thermal upgrading (roof replacement), the photograph by Piotr Szafraniec, Świętokrzyski National Park.

Additionally, computations concerning thermal and moisture conditions, carried out acc. [15], demonstrated that the exterior wall in Forest Lodge 2 ($U$ = 0.733 W/$m^2$K, $R_c$ = 1.365 W/($m^2$K)) was incorrectly designed with regard to avoiding mould growth. The effective value of the temperature coefficient of the building envelope element, $f_{Rsi}$ = 0.712, was determined on the basis of the heat transfer coefficient $U$ and the total thermal resistance of the element $R_c$. Steam condensation is observed in the months of the space heating season from November till March. February turned out to be a critical month as the temperature coefficient was $f_{Rsi.max}$ = 0.732.

To avoid the accumulation of moisture, the building envelope element should be designed in such a way so that the condition $f_{Rsi} > f_{Rsi.max}$ could be satisfied. Figure 2 shows pressure distribution in the element of concern. It can be seen that in the second and third layers of the wall, the saturation pressure $P_{n.sat}$ takes on the values lower than steam partial pressure $P_n$, which results in precipitation.

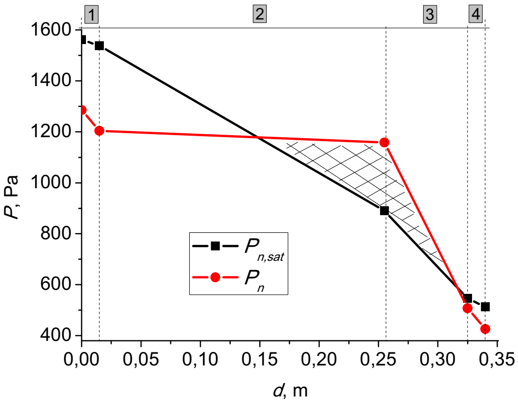

**Fig. 2.** Graph of moisture condensation in the critical month in the exterior wall shown in Figure 1; 1-4 – the envelope components in succession: cement-lime plaster, hollow masonry unit, cement-bonded particle board, cement-lime plaster.

In all three buildings, the heat source for central heating installations is a ~25 kW boiler fired by solid fuel, mainly wood. Because of good condition of the boilers, replacements are not planned. In all buildings, domestic hot water, is delivered due to gravitation to the 100 dm$^3$ tank via the boiler. In the audit, it was planned to modernise DHW installation and to set up solar collectors.

## 3 Analysis of the optimum thermal upgrading option

To have a part of the loan, taken out for thermal upgrading, written off, it was necessary to show that the planned works would result in at least 25% reduction in thermal energy demand, and also lower emissions of greenhouse gases. Having a limited budget for thermomodernization, to meet the conditions above, it was decided to upgrade the building envelope elements with the highest heat transfer coefficient $U$ and to modernise the domestic hot water system. In all settlements, flat solar collectors, relying on renewable energy sources, with the area of 6m$^2$, 300 dm$^3$ DHW tank, 18 dm$^3$ diaphragm expansion vessel and other minor pieces of hydraulic equipment, together with thermal insulation. were installed. It was assumed that solar collectors should provide approx. 70% of DHW demand. The remaining portion should be obtained by biomass combustion in the existing boiler.

Figure 3 shows Forest Lodge 2 after thermal upgrading with solar collectors installed on the south side of the building. The building envelope elements were appropriately designed to avoid mould growth.

Table 3 lists selected improvements included in the optimum thermal upgrading option, ranked in the ascending order of the value of return on the investment expressed as Simple Pay-Back Time (SPBT) for an exemplary settlement, namely Forest Lodge 2.

**Fig. 3.** A view of the eastern and southern façades of Forest Lodge 2 after thermal upgrading (solar collectors installed), the photograph by Piotr Szafraniec, Świętokrzyski National Park.

**Table 3.** Improvements included in the optimum thermal upgrading option and Simple Pay-Back Time (SPBT) for Forest Lodge 2.

| Item | Improvement/ modernisation | Planned costs of works, EUR | SPBT, years |
|---|---|---|---|
| 1 | Ceiling above the cellar | 2832.15 | 10.93 |
| 2 | Domestic hot water installation | 3698.22 | 15.05 |
| 3 | Roof | 8216.79 | 22.01 |
| 4 | Exterior wall 1 | 5465.39 | 44.72 |
| 5 | Exterior doors 1 | 507.23 | 52.13 |
| 6 | Exterior doors 2 | 507.23 | 52.13 |
| 7 | Exterior wall 2 | 1296.45 | 73.67 |
| 8 | Foundation wall | 881.72 | 148.02 |

High SPBT values should be given some attention. It turned out that thermal upgrading of old deteriorated buildings could not be performed without a major retrofit. That generates high unit costs that can significantly affect the pay-back time of the investment outlays. If the audit were conducted strictly in accordance with the legal regulations [16], the works not directly related to improvements in thermal conditions, or those not considered economically viable (e.g. modernization of the foundation wall in Forest Lodge 2), should not be classified as thermal upgrading. In reality, it is difficult to clearly distinguish between thermal upgrading and retrofit.

Additionally, thermal energy demand was established by means of computations [17]. For central heating system, especially in old buildings, it is difficult to unambiguously determine the demand value without earlier monitoring of the internal environment parameters [18]. The rooms are most often underheated, the design internal temperature values are not reached during the heating period, and moisture accumulations are found on the envelope elements (see Figs. 1 and 2).

It should be added that the optimum thermal upgrading option that was selected was the one that could generate the greatest energy costs savings. The costs were calculated to meet the annual energy demand for heating and hot domestic water production. The savings, expressed as percentage values for individual settlements, are presented in Table 4.

As a result of thermal upgrading work, energy performance of the buildings will be also considerably altered. Major computational parameters are presented in Table 5.

**Table 4.** Savings that result from the choice of the optimum thermal upgrading option.

| Settlement | Annual savings in thermal energy demand, % | Annual savings in energy costs, % |
|---|---|---|
| Forest Lodge 1 | 35.23 | 33.18 |
| Forest Lodge 2 | 32.19 | 31.70 |
| Forest Lodge 3 | 37.66 | 36.31 |

**Table 5.** Energy performance of the buildings.

| | | before thermomodernization | | | after thermomodernization | | |
|---|---|---|---|---|---|---|---|
| No. | **Forest lodge** | 1 | 2 | 3 | 1 | 2 | 3 |
| 1 | Design thermal output of the heating system, kW | 26.88 | 23.41 | 23.17 | 18.02 | 16.66 | 17.20 |
| 2 | Design thermal power for DHW production, kW | 2.03 | 1.63 | 2.03 | 2.03 | 2.03 | 2.03 |
| 3 | Annual heat demand for the building space heating (disregarding the heating system efficiency and space heating seasonal variation), GJ/year | 363.83 | 290.25 | 202.56 | 262.83 | 206.31 | 158.88 |
| 4 | Computation of energy consumption for DHW production, GJ/rok | 65.69 | 72.26 | 65.69 | 16.80 | 12.60 | 14.40 |
| 5 | Design non-renewable primary energy demand (PE), kWh/m$^2$a | | | | 61.7 (145.07)* | 64.6 (146.98)* | 46.7 (185.63)* |

* PE for a reference building after upgrading acc. [19]

## 4 Environmental effect

The measurable effect of the thermal upgrading of concern is a reduction in emissions of harmful substances into the atmosphere. Table 6 lists specific emission factors for different pollutants, pertinent to different fuel types [20].

The computations of yearly amounts of harmful substances emitted into the atmosphere, including the most important ones, i.e. carbon emissions, together with the environmental effect for exemplary Forest Lodge 2 are shown in Figure 4.

**Table 6.** Specific emission factors for different pollutants.

| Fuel type | Unit | SO2 | NOX | CO | CO2 | Particulates | Soot | Benzo(a)pyrene (BaP) |
|---|---|---|---|---|---|---|---|---|
| Solar collectors | kg/Mg | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Electric energy | kg/kWh | 0.91 | 0.0023 | 0.00069 | 1 | 0.0015 | $27\cdot10^{-7}$ | $54\cdot10^{-9}$ |
| Biomass | kg/Mg | 0.69 | 19.97 | 1.17 | 0 | 0.69 | 0 | 0 |

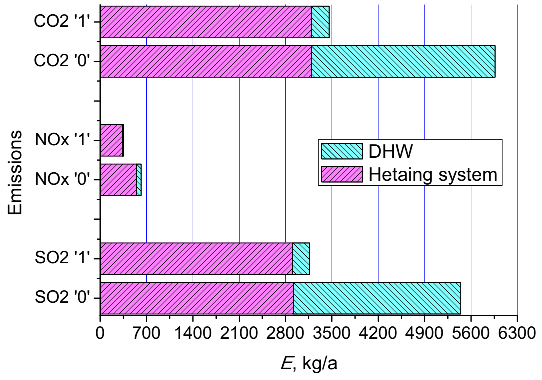

**Fig. 4.** Environmental effect of thermal upgrading for exemplary Forest Lodge 2; ‘0’ – before, ‘1’ – after thermomodernization.

Multiplying the computed emissivities by the so-called toxicity index $K$, equivalent emissions for individual substances before ($E_{r0}$) and after ($E_{r1}$) thermal upgrading are calculated. The environmental effect for equivalent emissions was determined from the dependence: $E = E_{r0} - E_{r1}$. The results are presented in Table 7.

**Table 7.** Equivalent emissions for the optimal thermal upgrading option in Forest Lodge 2.

| Pollutants emitted | Toxicity index K | Emissions | | Equivalent emissions | |
|---|---|---|---|---|---|
| | | Before | After | Before, $E_{r0}$ | After, $E_{r1}$ |
| | | upgrading, kg/year | | upgrading, kg/year | |
| $SO_2$ | 1.00 | 5448.57 | 3158.91 | 5448.57 | 3158.91 |
| $NO_X$ | 0.75 | 618.55 | 353.71 | 463.91 | 265.28 |
| Particulates | 0.75 | 29.84 | 17.13 | 22.38 | 12.85 |
| Soot | 3.75 | 0.02 | 0.01 | 0.06 | 0.04 |
| BaP | 30000.0 | 0.00 | 0.00 | 9.66 | 5.60 |
| Total equivalent emissions | | | | 5944.58 | 3442.68 |
| Environmental effect for equivalent emissions, kg/year | | | | 2501.90 | |
| Environmental effect for equivalent emissions, % | | | | 42.09 | |

## 5 Conclusions

The study presents the analysis of the energy efficiency of a thermal upgrading project that covered three forest lodges located in the Świętokrzyski National Park (Poland), and constructed in the years 1958, 1960 and 1926. In the study, attention was paid to high values of SPBT of the investment, which was shown in Table 3. For instance, thermal upgrading of the exterior walls in one of the lodges will recoup in as long as 45 years. High SPBT values are related to large outlays on repairs and ancillary works. Additionally, static indicators of economic efficiency are usually overestimated and they do not account for the whole period of the project operation. They are intended to provide initial assessment of the investment profitability.

It was shown that in all cases thermal upgrading results in the reduction in the annual thermal energy demand by at least 30%. Moreover, annual energy costs will be higher than also 30%.

Additionally, computational demand for non-renewable primary energy in lodges 1, 2 and 3 is 47, 62 and 65 kWh/m$^2$a, respectively.

The energy audit demonstrated that the environmental effect produced by thermal upgrading is a reduction in greenhouse gasses emissions. The total equivalent emissions are 2501 kg/year, which amounts to 42.09 %.

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