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A life-cycle cost analysis of the passive house "POLITEHNICA" from Bucharest

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ABSTRACT

The objective of this article is to create a mathematical model based on the analysis of the life-cycle cost of a passive house, including its technical design variations. In this study, we analyzed 14 types of houses derived from the design of the passive house POLITEHNICA; every house was differentiated by the type of renewable solution used (EAHX, GHP, solar collectors, PV panels) or by the insulation thickness, and it was compared with H12, a standard house with classical HVAC systems and a thermal insulation of 100 mm. The houses were compared according to criteria of economic performance throughout their life cycle. It was found that the additional investment in an energy efficient house can be recovered in 16–26 years, 9–16 years and 16–28 years if the replaced HVAC system is classical gas fuelled, electric or district distribution. A sensitivity analysis is performed which revealed the influence of the price of electricity and PV panels. The classification system made the decision-making process easier for a possible investment in a solution. This classification system showed that the first three recommended solutions for investment are the houses H14, H17 and H20.

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1. Introduction

Energy efficient houses began to be widely publicized after the oil crisis of the 1970s that led to an alarming increase in energy prices. This led to the development of concepts related to super-insulation, air tightness of the building, passive design and also the implementation of high efficiency heat recovery. The passive solar design for buildings was promoted by G.F. Keck with the "House of Tomorrow" (1933) and by MIT University with "Solar House 1" (1939) and later, the houses of the 1970s such as "Philips Experimental House" (Germany, 1975), "DTH Zero-Energy House" (Denmark, 1975), "Lo-Cal House" (USA, 1976), "The Saskatchewan Conservation House" (Canada, 1977), "Leger House" (USA, 1977) brought to the forefront issues such as super-insulation "super-glazing" air tightness, heat recovery ventilation.

In the 1990s, in Germany a series of energy-efficient buildings were built, beginning with the building "Kranichstein" from Darmstadt as a result of the concept of "passive house" issued by W. Feist and Bo Adamson. Passivhaus Institut, founded in 1992 by W. Feist has three basic requirements for the certification of a passive house: space heat demand (or, heating load) $\leq 15\,\mathrm{kWh/m^2/y}$ ($\leq 10\,\mathrm{W/m^2}$), pressure test $n_{50} \leq 0.6\,\mathrm{h^{-1}}$, and primary energy demand (for all energy services) $\leq 120\,\mathrm{kWh/m^2/y}$ [1]. In addition to the basic requirements, some other rules of design are established, including: Average ventilation volume flow with ACH = $0.30\,\mathrm{h^{-1}}$ at least, indoor design temperature of 20 °C, Heat recovery efficiency of at least 75%, use of the ground-sourced heat exchanger, demand for domestic hot water (DHW) to be partially or fully covered by solar collectors [1].

There is a point up to which intense thermal insulation ensures the maximum efficiency of the investment, which, if exceeded, leads to over-investment. In this situation one can calculate whether adding additional electrical panels to the passive house can be a more effective investment than over-insulation beyond the optimal point [2].

In 1992, Fraunhofer Institute of Solar Energy Systems (Germany) completed an "autosufficient house', a building Off-Grid which produces the entire electricity it needs by means of PV panels [3]. In 1994, Rolph Disch built in Freiburg (Germany) the building "Heliotrope" with PV panels capable of producing 4–6 times

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Nomenclature

AIRR	adjusted internal rate of return [–];
C	cost [Euro];
c_e	unit cost of electric energy [Euro/kWh];
$C_e(i)$	total cost of the energy in the year i [Euro];
DPBT	discounted payback time [years];
E, E_{el}, E_i, $_{i=P,S,PHI,PV\_HVAC,PV\_Storage,N,Grid\_balance}$	total energy, electric energy, energy: primary, secondary, PassivHaus Institut recommended, PV delivered to HVAC system, PV delivered to storage tank, total delivered by PV, electric network (grid), grid electric balance [kWh/m^2/y];
f_{grid}	index of bi-directional interaction building-network;
$f_{P\text{-}S}$	factor of transformation from primary to secondary energy [–];
FV	future value [Euro];
f_s	factor of variation of the escalation of the prices from sensitivity analysis;
I_0	initial investment [Euro];
INT( )	integer function;
Inv	investment [Euro];
LCC	LCC$_{basa\ case}$, LCC$_{alternative}$—Life-Cycle Cost: standard, basic project, alternative project [Euro];
NS	net saving [Euro];
PV, PVxi	photovoltaic panels; photovoltaic panels multiplied by i factor of level of production.
PV_i, $_{i=Invest,Struct,Ins,NonReimburs,Energy,Subsid,Repl,OM\&R,Pers,Taxes,Envir,Residual,Decommis}$	Present value: investment, basic structure, insulation, non-reimburse funds of investment, energy, subsidies, replacements, Operation Maintenance and Repair, Personnel, Taxes, Environmental taxes, Residual cost, Decommissioning cost;
Q_i, $_{i=H,C,walls,fen,solar,vent\&leak,int,ground,DHW,P,S,SC,EAHX,GHP}$	thermal load: heating, cooling, walls, fenestrations, solar radiation, ventilation and air leakage, ground, Domestic Hot Water, primary, secondary, solar collector, EAHX heat exchanger,
r_a, r_i, r_{rd}, r_{re}, $r_{re,s}$	rate of actualization, rate of inflation, real rate of discount (interest), real rate of escalation (of prices), real rate of escalation (of prices) of the sensitivity analysis;
ROOT( )	root function;
SIR	saving-to-investment ratio [–];

more energy than necessary; this was among the first "Plus-Energy" buildings [4]. This new opportunity of increasing the energy efficiency as well as the economic efficiency of the investment by adding PV panels and by making the bidirectional connection to the electric network led to the need to develop the concepts of Plus Energy Building and Net-Zero Energy Building [5,6].

These types of buildings are taken in consideration in the study of this paper. In one year a Net-Zero Energy Building produces the same amount of energy it consumes [7], while a Plus-Energy House produces more energy than it consumes, thus offering the opportunity to earn an income. Throughout the year for these buildings there is a monthly balance network monitored by a Net-Metering System and the factors taken into account are the weighting factors of import–export of electricity from the exchanges with the network [8,9]. The surplus energy exported to the grid is paid by the network operator [10–12].

Starting from the targets imposed by international organizations and international treaties that promote environmental sustainability, the development of the residential sector is considering the use of renewable resources and the reduction of emissions of greenhouse gases. Thus, mention must be made of the Kyoto Protocol which obliged the signatory industrialized countries to reduce the emissions of greenhouse gases by 5.2% in 2010 as compared to the year of 1990 [13]; for the period 2013–2020 the protocol of Doha (2012) is agreed upon, to be fully adopted in 2015 [14].

In Europe, buildings consume 40% of the total primary energy and they emit 40% of all CO_2 emissions [15]. This percentage is high and there are technical and legal resources to be significantly reduced. An EU directive issued in 2006 and approved in 2007 considered the following three goals: for the period 2006–2020 to reduce the primary energy consumption by 20%, renewables to reach a percentage of 20% and also for the period 1990–2020 CO_2 to be reduced by 20% [16]. The widespread application of the passive house concept will significantly contribute to the achievement of the objectives set at the European level. The European Climate Change Programme (ECCCP 2006) [17] identified the objectives and strategies for cost effective solutions, standards and energy efficiency measures for buildings. At the institutional level several incentives are given to investors in clean energy, including mechanisms that partially or totally cover the investment by non-reimbursable funds, green cards that over-pay the unit of clean energy produced, connection to public facilities, etc. Programs funded with support for energy efficient buildings catalyze the implementation of the European objectives [18]. The European Union Directive on the energy performance of buildings EPBD2010 [19] insists on increasing energy efficiency, by implementing passive heating and cooling systems and it uses the term "Nearly-Zero Energy" [20,21] for buildings that use renewable energy sources in a significant proportion. There are also requirements to achieve an optimum balance between investment cost and energy cost savings, a balance should lead to a reduction of the cost over the estimated economic life cycle, an aspect fully treated in the Supplementing Directive No. 244/2012 [22–24]. The use of alternative energy is indicated as a way of bringing the building's performance at an optimal cost level. Kurnitski et al. [25] and Hamdy et al. [26] exposed several calculation methodologies for buildings based on solutions of optimal cost.

Among the requirements of a passive house, three aspects are of interest in this study and they are related to criteria of cost and energy efficiency: thermal insulation, renewable energy equipment and energy cost throughout the building's life cycle. The investment in a project such as a passive house does not mean only meeting a quality standard, but also meeting the criteria of sustainability (low energy and as well as energy from renewable resources, cost efficiency, concern for the impact on the community, environmentally friendly, beneficial ecological status, and even the use of recycled construction materials). The assessment of a house only by means of the quality–cost concept is not the most relevant because it is reduced only to the present time evaluation. The concept of cost throughout the life cycle of the building brings major contributions to the evaluation of a project by considering the present cost, the duration of use, the cost of operation, the interest rate, the escalation of the energy market price, the escalation of price for various systems and the inflation, in order to update the value of the building. Thus, it is necessary to underline the advantages of investing in an energy efficient house involving the cost over a period of the life cycle. The analysis of the life-cycle cost (LCC) is particularly suitable for the assessment of building design alternatives that satisfy a required level of performance and can be

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