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# Integrated assessment of energy supply system of an energy-efficient house

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ABSTRACT

The paper presents an integrated assessment model of an energy supply system for an energy-efficient building (ESSINTEGRA). This assessment comprises a comprehensive analysis of the building energy demand and energy supply systems as well as determining a rational solution on the basis of the selected assessment criteria: energy efficiency, environmental impact, economic, comfort and technical functionality. ESSINTEGRA is applied for a case study of a single family house. Six different alternatives of the house envelope parameters and 15 combinations of the technological solutions of the building energy supply systems (BESS) are explored as design options. Applying the model has allowed to determine the rational solution for the energy-efficient single family houses in Northern European climate (zone 5). When the combination of the wood boiler with a solar collector system is used, the primary energy demand of 10.1 kWh/m$^2$, $CO_2$ gas emissions of 0.24 kg$CO_2$/m$^2$ and the renewable energy fraction of 97.4 % can be obtained.

When the decision making method is applied, the reliability of the rational solution amounts to 99.5%. The sensitivity analysis has shown that the variation of the criteria significances has no influence on the reliability of the rational solution.



## 1. Introduction

In order to create the required indoor climate, buildings use 40% of the total EU energy and generate 1/3 of the greenhouse gases [1]. According to the Energy Performance of Buildings Directive 2010/31/EU, all Member States shall ensure the cost-optimal levels of the energy performance of buildings, increase the portion of renewable energy in the total share of consumed energy and make all new buildings to be "nearly zero-energy buildings" (nZEB) by 2020 [2]. Therefore, the recent reviews [3–7] and studies [8–11] pay great attention to the simulation-based building performance optimization, in order to obtain efficiently the high energy performance buildings.

The coupled use of simulation tools and the optimization methods is the current research trend and the issue of the development of building information modelling (BIM) at the integrated design stage. The simulation-based building performance optimization includes a big amount of input data, multi-objective issues, large uncertainties and restrictions of model. Meanwhile, the main reasons of the restricted use of optimization in practise are the following: decision making time, required high level knowledge and skills, lack of convenient tools, and uncertainty [3,5]. The complex evaluation of the building energy demand and its energy supply system is essential in the optimization process.

The design of the high energy performance buildings using simulation-based building performance optimization approach was studied by Magnier and Haghighat [12], Fesanghary et al. [13], Hamdy et al. [10,11], Bichiou and Krarti [14], Diakaki et al. [15,16], Tuhus-Dubrow and Krarti [17], and other researchers. These researches used appropriate optimization algorithms (evolutionary, genetic, particle swarm, sequential search) and simulation software according to the application area. The findings indicated that evolutionary algorithms were more efficient for the global

*Abbreviations:* ESSINTEGRA, an integrated assessment model of an energy supply system for an energy-efficient building; nZEB, nearly zero-energy buildings; BIM, building information modelling; WASPAS, weighted aggregated sum product assessment; AHP, analytical hierarchy process; BESS, building energy supply system; DHW, domestic hot water preparation; V1...V6, variants of the energy demand for the house; D1...D15, combinations of BESS technologies; WB, wood boiler; PB, pellet boiler; GB, condensing gas boiler; $HP_{air-water}$, air–water heat pump; $HP_{ground-water}$, ground–water heat pump; SC, solar collectors; PV, photovoltaic modules; v.s., ventilation system.

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**Nomenclature**

| | |
|---|---|
| $X_{in}$ $\{E_{i,del,in}\}$ | Delivered energy, kWh/m$^2$a |
| $X_{out}$ | Building energy demand, kWh/m$^2$a |
| $A$ | A reverse coupling matrix |
| $Q_{H,nd}$ | Energy need for space heating, kWh/m$^2$a |
| $Q_{W,nd}$ | Energy need for domestic hot water, kWh/m$^2$a |
| $Q_{C,nd}$ | Energy need for cooling, kWh/m$^2$a |
| $E_V$ | Energy use for ventilation, kWh/m$^2$a |
| $E_L$ | Energy use for lighting, kWh/m$^2$a |
| $E_{AP}$ | Energy use for appliances, kWh/m$^2$a |
| $W_{HW}$ | Auxiliary energy of heating and domestic hot water systems without generation, kWh/m$^2$a |
| $\varepsilon_{em}$ | Seasonal energy efficiency of emission subsystem |
| $\varepsilon_c$ | Seasonal energy efficiency of control subsystem |
| $\varepsilon_{dis}$ | Seasonal energy efficiency of distribution subsystem |
| $\varepsilon_s$ | Seasonal energy efficiency of storage subsystem |
| $\varepsilon_{gen}$ | Seasonal energy efficiency of generation–transformation subsystem |
| $\varepsilon_{SC}$ | Seasonal energy efficiency of solar collectors |
| $\varepsilon_{PV}$ | Seasonal energy efficiency of photovoltaic modules |

search of the optimal solution [5]. Meanwhile, the genetic algorithms solve the issues of the design, operation and management of the building and energy supply relatively easily, when the search space is large, discontinuous and there is no need to find the global optimum [5]. Therefore, the evolutionary, genetic algorithms and the particle swarm optimization methods generate better results than other methods and are mostly used for the optimization of complex hybrid energy supply systems and their combinations [18–23]. In these studies the mostly used design variables of energy supply systems are the following: minimum capacity, minimum cost, and the loss of the power supply probability, the reliability of the systems, installation and control. However, in order to find a reliable optimal solution using a minimum number of optimization runs, a repeatability of the certain algorithm has to be investigated [24].

Methods of the sequential search are efficient, when the discontinuity of the objective function is insignificant, otherwise the search can be terminated quickly at the local minimum. These methods are mostly used to find the cost-optimal levels and to identify the optimal design for zero energy buildings [14,17,25].

The parametric simulation methods, known as numerical optimization, are used to improve the energy performance of the buildings [26,27]. However, these methods are time-consuming and result in partial improvement due to the complex and nonlinear interactions of input variables on the simulated results [5].

The multi-criteria decision making methods are applied in the projects of planning and integration of the renewable energy technologies, where the issues of the centralised and decentralised energy supply have been solved [28–34].

The results of the newest findings of the building energy performance optimization show that the existing complex optimization algorithms with continuous variables do not always obtain the best (optimal) solution [3]. Also, due to the complexity of the existing optimisation approaches, only small groups of the designers use building performance optimisation in practise. Some reviews [4,5,7] indicate that designers often use the dynamic simulation software to analyse the energy performance of the buildings. Therefore, in order to promote the use of the simulation-based building optimization, the main task is to simplify the optimization process performed in the early-design stage. Considering the application of the above mentioned optimization methods, recent researches [8,35] can be considered as systematic and simplified frameworks in order to achieve cost-optimal and zero-energy building solutions.

This paper introduces new model of the integrated assessment of the building and its energy supply systems (ESSINTEGRA). This model combines energy modelling tools, modified combined matrix of building energy flows, multi-criteria decision making method and sensitivity analysis. In order to ensure the reliability of the rational solution, the application of Weighted Aggregated Sum Product Assessment (WASPAS) [36] and sensitivity analysis for ESSINTEGRA model enable to reduce the search space of alternative solutions, to interconnect the evaluation of the quantitative and qualitative rates, to combine different objectives, and to increase the accuracy of the grade of alternatives.

The main goal of this study is to create a new integrated assessment model in order to find the rational energy supply system for the energy-efficient house. The rational energy supply system refers to the best solution that combines seeking the minimal consumption of primary energy, extremely low influence on the environment, standard thermal comfort and air quality level, minimum global costs during the lifetime of the system, and sufficient level of automatization and ease of maintenance. In order to implement the objective of this study, the following tasks have been set out:

1. to create an integrated assessment model of an energy-efficient building energy supply system (BESS), in order to determine a rational solution in terms of energy, ecological, economic, comfort and technical functionality criteria (see Section 2); 2. to perform energy demand simulation for the different variants of the energy-efficient single family house, using different passive energy efficiency measures (see Section 3); 3. to perform simulation of the selected BESSs, comprised of different energy generation (transformation) technologies and to provide the systemic analysis for each BESS combination (see Section 3); 4. to apply the created ESSINTEGRA model to determine a rational solution in terms of energy, ecological, economic, comfort and functionality (see Section 4); 5. to assess the reliability of a rational solution in terms of variation in significance values of criteria and to determine the most influential criterion over the final solution (see Section 4).

## 2. Methodology

In this section a newly-created integrated assessment model of building energy supply system (ESSINTEGRA) is presented.

### *2.1. Originality, advantages and assessment limitations of ESSINTEGRA*

In order to find the rational energy supply system for the energy-efficient house at the early design stage, a wide variety of possible design alternatives have to be taken into consideration and many criteria have to be involved in the process. Therefore, the methodology provides the algorithm of the integrated assessment model of energy supply system for energy-efficient building (ESSINTEGRA). The main originality of the proposed model consists of combining dynamic simulation tools, modified matrix of building energy flows, multi-criteria decision making method, and sensitivity analysis and presenting the evaluation of the best alternative according to the optimality of the selected five criteria.

However, the algorithm of the model is based on a sequential search approach. The modelling and assessment processes are decoupled into several sub processes [37]: simulation of building indoor climate and energy demand modelling, energy supply systems modelling, multi-criteria evaluation and sensitivity analysis. In case of the coupling simulation and optimization approaches,