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A multi-stage optimization method for cost-optimal and nearly-zero-energy building solutions in line with the EPBD-recast 2010

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ABSTRACT

Finding cost-optimal solutions towards nearly-zero-energy buildings (nZEBs) in accordance with European energy performance of buildings directive (EPBD-recast 2010) is a challenging task. It requires exploring a huge number of possible combinations of energy-saving measures (ESMs) and energy-supply systems including renewable energy sources (RESs), under a comparative framework methodology. The current study introduces efficient, transparent, and time-saving simulation-based optimization method for such explorations. The method is applied to find the cost-optimal and nZEB energy performance levels for a study case of a single-family house in Finland. Different options of building-envelope parameters, heat-recovery units, and heating/cooling systems as well as various sizes of thermal and photovoltaic solar systems are explored as design options via three-stage optimization. The resulted economic and environmental trade-offs show that primary energy consumption ≥93 and ≤103 kWh/m^{2}a is a cost-optimal energy performance level. It is economically feasible to achieve nZEB with 70 kWh/m^{2}a. However, incentives (e.g., energy credits) are required to reach lower-environmental-impact houses. Investing in low-operating-cost environmentally friendly heating system (e.g. ground source heat pump) is a key element for optimal solutions. The optimal implementation of ESMs and RES depends significantly on the installed heating/cooling system and the escalation rate of the energy price.

1. Introduction

Buildings are responsible for 40% of energy consumption and 36% of the EU's CO_2 emissions. Energy performance of buildings is a key element to achieve the EU climate and energy objectives, namely a 20% reduction of the greenhouse gases emissions and 20% of primary energy savings by 2020. Improving the energy performance of buildings is a cost-effective way of fighting against climate change and improving energy security [1–3]. From the economic point-of-view, the best environmental solutions cannot be guaranteed by regulations which depend mainly on building envelope requirements [4–7]. The analysis of energy efficiency and cost optimality should consider the energy sources and building systems. Seeking for cost-optimal high-energy-performance buildings, the EPBD-recast 2010 [8] requests the Member States to avoid establishing rules whereby a measure on the building envelope is always applied first and only then a measure on a building system is allowed. According to the EPBD recast, the minimum energy performance requirements should be set with a view of achieving cost optimal levels for buildings, building units and building elements. Higher energy performance buildings, like nZEBs, should also be economically feasible. Finding cost-optimal minimum energy performance requirements and nZEB solutions is an arduous task. The task requires exploring a huge number of design solutions (combinations of energy saving measures and energy supply systems) under a comparative framework methodology. The EPBD recast required the EU Commission to establish a comprehensive methodology by 30th June 2011.The methodology is demonstrated by the Buildings Performance Institute Europe (BPIE) [9] and the European Council for an Energy-Efficient Economy (ECEEE) [10]. The current study introduces a multi-stage optimization method for exploring wide spaces of building and system integrated solutions, transparently and efficiently. The method is designed to reduce the exploration and analysis efforts needed to find optimal solutions for the new EU-buildings in line with the EPBD framework methodology. The method uses simulation-based optimization approach hence it should be suitable for most of new buildings in Europe where the heating is the major demand for thermal comfort.

1.1. The EPBD recast comparative framework methodology

The EPBD recast comparative framework methodology was established for calculating cost-optimal levels of minimum energy performance requirements for buildings and building elements

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Nomenclature

AHU	air handling unit
COP_{cu}	coefficient of performance of the cooling unit
dEle	difference between electricity demand and production [kWh/m^{2}a]
dLCC	difference in life-cycle costs between any solution and the reference design [€/m^2]
dPV	difference in present value between any solution and the reference design [kWh/m^{2}a]
dQ_{DHW}	domestic hot water energy saving by the solar thermal collector [kWh/m^{2}a]
DH_{27}	degree hours over 27 °C indoor temperature [°C h]
DH	district heating
DHW	domestic hot water
DHW_{ele}	the electrical portion of domestic hot water [kWh/m^{2}a]
E_{hv}	the electricity consumption of the HVAC systems (fans and pumps) [kWh/m^{2}a]
E_{la}	the electricity consumption of lighting and appliances [kWh/m^{2}a]
Ele	electricity consumption [kWh/m^{2}a]
EH	electrical heating
EPBD	energy performance of buildings directive
ESMs	energy saving measures
GSHP	ground source heat pump
IC	investment cost [€/m^2]
LCA	life-cycle assessment
NSGA_II	elitist non-dominated sorting genetic algorithm
nZEBs	nearly zero energy buildings
OB	oil boiler
OC	operating cost of energy [€/m^2]
PEC	primary energy consumption [kWh/m^{2}a]
PV	photovoltaic
PV_e	the useful electricity produced by photovoltaic system [kWh/m^{2}a]
PW	present worth
Q_c	space cooling energy demands [kWh/m^{2}a]
Q_h	space-heating energy demands [kWh/m^{2}a]
RC	replacement cost [€/m^2]
RES	renewable energy sources
SH	space heating [kWh/m^{2}a]
SH_{ele}	the electrical portion of space heating [kWh/m^{2}a]
SHGC	solar heat gain coefficient
SWSC	short wave shading coefficient
S-factor	solar gain factor
T-value	solar transmittance
U-value	heat-transfer coefficient [W/m^2 K]
η_{SHS}	efficiency of the space-heating system [%]
η_{DHWS}	efficiency of the domestic hot water system [%]
η_{dist}	distribution efficiency of the heating system [%]

[9,10]. The methodology requires comparing the global costs (additional investments, replacement costs, energy costs, etc.) and the delivered primary energy of combinations of compatible energy efficiency and energy supply measures (packages of measures). The packages should range from those in compliance with the current regulations to combinations that realize nZEBs. The packages should also include various options for renewable energy sources (RES) generation. Fig. 1 shows a predicted cost-optimal curve that will be found when assessing all combinations of commonly used and advanced measures. The lowest part of the curve represents the economic optimum for the combinations of measures. The minimum energy performance requirements are represented by the

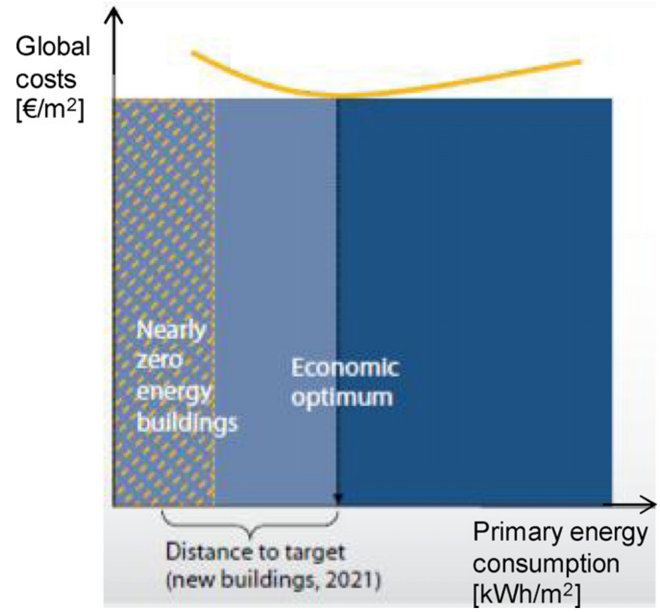

Fig. 1. Cost optimal curve and distance to 2021 target [9].

economic optimum point that delivers the lowest cost for the end-user and/or for the company or society. The part of the curve to the right of the economic optimum represents solutions that underperform in both aspects (environmental and financial). The left part of the curve, starting from the economic optimum point, represents the cost-optimal energy-performance levels for low and nearly-zero-energy buildings. The figure shows also the distance to the EU-2021 target (nZEB) for new buildings.

1.2. The aim of the current study

One of the main challenges of the EBPD-2010 calculation methodology is to ensure that, on the one hand, all measures with a possible impact on the primary or final energy use of a building are considered, whilst, on the other hand, the calculation exercise remains manageable and proportionate [11]. Applying few options for several variants could offer millions of design solutions. In order to limit the number of solutions, the guideline of the EBPD draft [11] proposes to address a matrix of energy efficiency packages, which rules out mutually exclusive technologies. For instance, a heat pump for space heating (SH) does not have to be assessed in combination with a high efficiency boiler for space heating as the options are mutually exclusive and do not complement each other. The possible energy efficiency measures and measures based on RES (and packages/variants thereof) can be presented in a matrix and unfeasible combinations eliminated.

The elimination approach cannot guarantee global cost-optimal solutions because it explores only some of the available combinations of design options. Furthermore, considerable effort and experience are needed to make correct eliminations. To establish a comprehensive overview, all compatible combinations of commonly used and advanced measures should be considered. Stochastic methods are promising, and can be used to investigate a huge number of combinations. However, they should be employed under a suitable scheme. The aim of this study is to introduce a suitable optimization scheme/method which provides efficient, transparent, and time-saving exploration.

- Efficient exploration is performed by using a combination of a modified elitist multi-objective non-nominated sorting genetic algorithm and detailed simulation programs.