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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^2a]
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^2a]
dQ_{DHW}	domestic hot water energy saving by the solar thermal collector [kWh/m^2a]
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^2a]
E_{hv}	the electricity consumption of the HVAC systems (fans and pumps) [kWh/m^2a]
E_{la}	the electricity consumption of lighting and appliances [kWh/m^2a]
Ele	electricity consumption [kWh/m^2a]
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^2a]
PV	photovoltaic
PV_e	the useful electricity produced by photovoltaic system [kWh/m^2a]
PW	present worth
Q_c	space cooling energy demands [kWh/m^2a]
Q_h	space-heating energy demands [kWh/m^2a]
RC	replacement cost [€/m^2]
RES	renewable energy sources
SH	space heating [kWh/m^2a]
SH_{ele}	the electrical portion of space heating [kWh/m^2a]
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

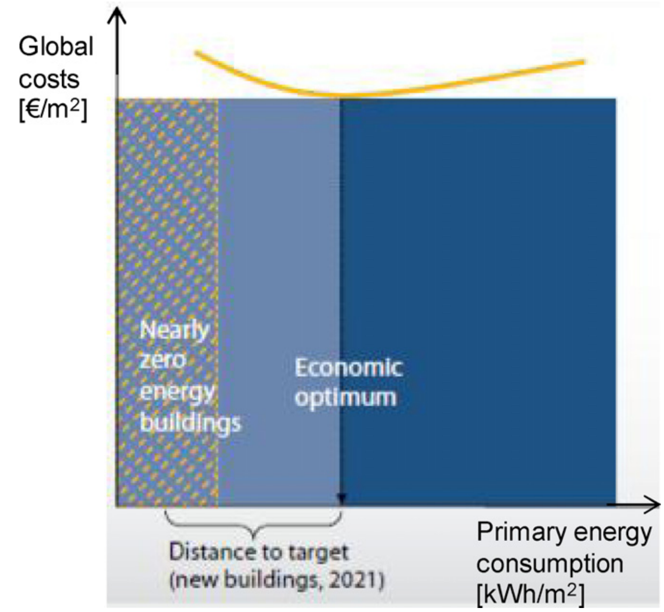

Fig. 1. Cost optimal curve and distance to 2021 target [9].

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.

- Transparent exploration is presented via three optimization stages showing the effect of the design-variable combinations on the objective and constraint functions.
- Time-saving exploration is achieved via speeding up the exploration by avoiding the unfeasible design-variable combinations and using pre-simulated results instead of running time-consuming simulation (when possible).

1.3. Relevant studies

The EBPD recast-2010 is still a quite new directive. Therefore, it has not been widely complied with. The economic environment scope of the EBPD recast is based on the European Standard EN 15459 [12]. BS ISO 15686-5 [13] is the first international standard for property life-cycle costing. The EN 15459 and ISO 15686-5 were complied with in [14] and [15], respectively. Many of building studies, e.g., [14–18] investigate the economic and environment point-of-views. However, the majority address a limited number of design solutions. For instance, Georges et al. [14] investigated a single-family dwelling in Belgium, addressing combinations of sixteen heating systems and five building designs. Marszal and Heiselberg [15] found the minimum life-cycle cost for a multi-storey residential net-zero-energy building in Denmark, addressing three levels of energy demand and three alternatives of energy supply systems. In Finland, the first house designed for minimal energy consumption was built in the early 1990s, and its energy consumption was monitored for three years. On the basis of this monitoring, VTT (Technical Research Centre of Finland) estimated that additional investment in energy efficiency pays itself back in 5–6 years and yields a return of 15–20% [19]. VTT's energy renovation technologies project [20] studied the profitability of energy renovation measures (structural improvements, heat supply systems, ventilation systems, lighting, electrical appliances, solar shading and cooling) for three types of buildings. The project applied the simple payback time method for its calculation. Pylsy and Kalema [21] made a life-cycle cost sensitivity analysis, addressing four building insulation levels, four building tightness levels, three ventilation-heat recovery types, and nine heating systems to find cost-effective concepts for low-energy houses. The analysis found that the improvement of the thermal insulation of the building envelope is the most effective way to reduce the space-heating energy need. However, the lowest building insulation level is selected as a cost-optimal solution when ground-source heat pump (GSHP) is selected for heating. Hasan et al. [22] combined simulation and optimization to minimize the life-cycle cost (LCC) of a single-family detached house. The study investigated a wide range of wall, roof, and floor insulation levels, two types of windows, and two types of ventilation-heat recovery units. However, no heating alternatives were addressed. Alanne et al. [23] considered the selection of a residential energy-supply system as a multi-criteria decision-making problem involving both financial and environmental issues. The study analyzed the competitiveness of micro-CHP as 1 of 10 alternative heating systems for a Finnish single-family house. The analysis showed that the micro-CHP is a reasonable alternative to traditional systems, particularly from the environmental point of view. Alanne et al. [24] searched for optimized strategies for the integration of a stirling engine-based micro-cogeneration system in residential buildings by comparing the performance of various system configurations and operational strategies with that of a reference system, i.e., hydronic heating and a low temperature gas boiler in standard and passive house constructions located in different climates. Saari et al. [25] studied eight different energy-saving design concepts and three heating modes for a typical new Finnish detached house. The study showed that the payback time of the heating system depends on the real interest rate and the building construction.

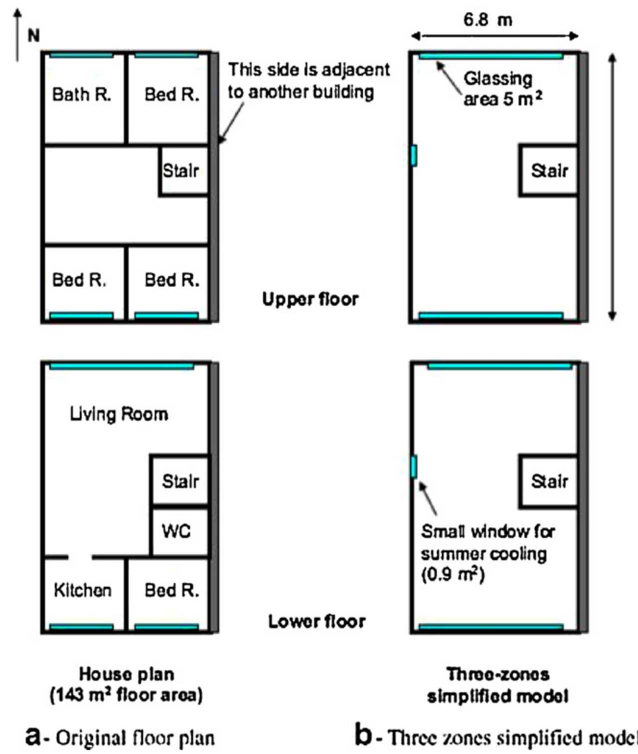

Fig. 2. Plan of the two-storey house studied (143 sq m).

The above Finnish studies focused mainly on the heating energy. This is not consistent with the EBPD recast 2010, which focuses on the total energy consumption (including the energy consumption of heating, cooling, lighting, appliances, and auxiliary equipment) and its financial and environmental impacts. Generally, the reviewed studies either are inconsistent with the EPBD-recast 2010 or cannot guarantee global cost-optimal solutions because they investigate a limited number of design solutions. As mentioned above, the current study introduces efficient, transparent, and time-saving exploration for wide solution spaces. The introduced method is applied to find the cost-optimal and nZEB energy performance levels for a single-family house in Finland in line with the EPBD recast.

2. Methodology

2.1. Defining the building and its conceptual design

Energy efficiency of houses can strongly influence overall energy use in the building sector. In Finland, residential buildings comprise 85% of the building stock and occupy 64% of the building area [25]. A single-family house is chosen as a residential building case study (Fig. 2) because about 70% of the Finnish population live in houses [26]. The house, in Helsinki (60° N, 25° E), consists of two storeys. The floor area of the house is 143 sq m. The internal height of each storey is 2.5 m. The glassing area represents about 15% of the floor area. The two storeys are connected by a staircase and have operable windows for natural cooling in summer. To avoid summer overheating risk, different types of shading and a mechanical cooling unit are offered as design options. Building tightness and insulation levels could also control the risk. All the building envelope and system options are described in Section 2.3. According to the Finnish Building code D5-2012 [27], the construction type of the house is Medium-heavy I. The house has interior effective thermal capacity of about 21 kWh/K. The house is ventilated by one air-handling unit (AHU), which supplies fresh air to the bedrooms and living room and draws the exhaust air from the bathrooms and

Table 1
Insulation thickness (design variables no. 1, 2 and 3).

Insulation of. . .	Material	Range of insulation thickness (m)	No. options using a uniform step (0.02 m)	U-value of the construction (W/m^2 K)	Investment cost (€/m^3)
External wall	Mineral wool	From 0.185 to 0.48	16	From 0.17 to 0.07	62.72
Roof	Blow-in wool	From 0.41 to 0.55	8	From 0.09 to 0.07	36.2
Floor	Polyure-thane	From 0.2 to 0.44	13	From 0.17 to 0.080	111.4

Costs are taken from [7], [36] and updated to 2011 ones by using 3.8% inflation rate [37] considering the rise in the material costs.

Table 2
Building tightness levels (design variable no. 4).

Levels	Specification n_{50} (1/h)	Price for labour cost (€/m^2)
1	2	0
2	1	11
3	0.5	22

Costs are taken from [7] and updated to 2011 ones by using 2.1% inflation rate [37] considering the rise in the labour costs.

the kitchen. The AHU heating coil keeps the supply air temperature at 18 °C when the incoming outdoor air temperature is lower than this temperature. The average exhaust-air flow from the whole house is equal to 0.65 air change per hour [1/h], which is higher than the minimum requirements (0.5 1/h) of the Finnish Building code D2-2012 [28]. The internal gains due to people, lighting, and electric appliances are 10.3, 7.8, and 17.8 kWh/m^{2}a, respectively. The values are in accordance with the D5-2012 [27]. The dynamic changes of domestic hot water, lighting, and appliance energy are considered by using profiles based on the typical Finnish life style [29]. The domestic hot water tank has the size of 300 l. The supply-water temperature to the space heating is controlled as a function of the outdoor air temperature. The electrical-energy consumptions of the auxiliary equipment (fans and pumps) are calculated, assuming 0.625 kW/(m^3/s) specific fan power and 15 kPa nominal pumping pressure head. The fans and pumps have efficiencies of 60% and 50%, respectively. Both consume about 7.5 kWh/m^{2}a of electricity. The dynamic thermal performance of the house and systems are simulated by IDA ICE [30] and IDA ESBO [31]. The simulation uses reference year weather data (Vantaa_TRY2012) which is developed recently for energy calculation purposes in Finland [32].

2.2. Defining the building reference design

In line with the EPBD comparative framework, the economical and environmental viability of the design solutions is assessed relative to a reference design. The reference design is with U-values 0.17, 0.09, 0.17, and 1 W/m^2 K for external walls, roof, ground floor, and window, respectively. The values are based on the National Building Code of Finland, C3-2010 [33]. The house has a building tightness (n_{50}) of 2 l/h, where n_{50} is the number of air changes per hour equivalent to an air-leakage rate with a 50 Pa pressure difference between indoor and outdoor. The window type has a solar heat gain coefficient (SHGC) and a solar transmittance (T-value) of 46 and 34%, respectively. To achieve acceptable level of summer overheating, the windows are shaded by blinds, with horizontal laths, between the inner panes. According to the market share of heating systems [34], 42% of the small houses in Finland

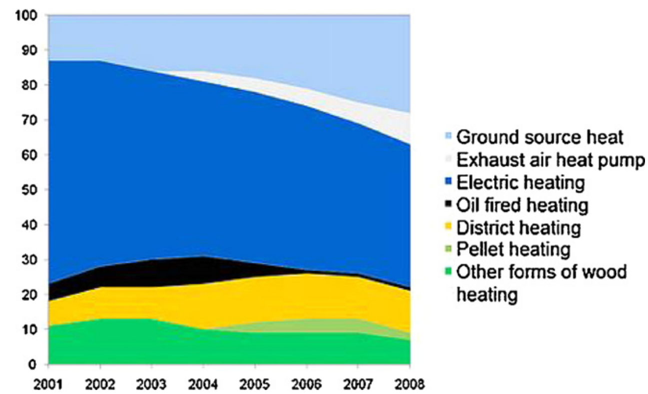

Fig. 3. The market share of heating systems in new single-family houses in Finland [34].

are heated by electricity (Fig. 3). Because of the mild climate in summer, most of the Finnish houses do not have mechanical cooling. In the current study, the reference design is served by electrical radiators for space heating; electrical boiler for domestic hot water; and mechanical ventilation unit with 60% heat recovery efficiency. Neither mechanical cooling nor on-site renewable systems are implemented. The calculation by the IDA ICE [30] building simulation program indicates that the required space-heating energy for the reference case is 46 kWh/m^{2}a. The annual domestic hot water demand is 32 kWh/m^{2}a. The total electricity demand of the house is 126.5 kWh/m^{2}a, including fans, pumps, appliances, lighting, and heating demands.

2.3. Defining the design variables

The design variables are selected to cover packages of measures ranging from compliance with the requirements of the current national building code C3-2010 [33] to combinations that realize nZEBs (e.g., passive house U-values [35], photovoltaic, and solar thermal collectors). The variables include a number of external wall, roof, and floor insulation thicknesses (Table 1), three building tightness levels (Table 2), three window types (Table 3), four shading options (Table 4), three heat recovery units (Table 5), two cooling options (Table 6), four heating systems (Table 7), and different sizes of on-site solar systems (Table 8). The costs of the ESMs (insulation, building tightness, window type, and heat recovery unit) are from previous studies [7,36]. The costs are updated here by using building-cost indices and inflation rate from [37]. The technical properties of window and shading options are taken

Table 3
Window types (design variable no. 5).

Type	U-value (W/m^2 K)	T-value	SHGC	Cost (€/m^2)	Description
1	1	0.34	0.46	228.4	Triple Laminated glass Wood aluminum frame (Argon gas)
2	0.85	0.29	0.42	267.4	Triple Laminated glass Wood aluminum Frame (Argon gas)
3	1.1	0.28	0.38	234	Quadruple Laminated Wood aluminum frame(Argon gas)

Costs are taken from [7] and updated to 2011 ones by using 3.8% inflation rate [37] considering the rise in the material costs. Technical description [38].

Table 4
Shading options (design variable no. 6).

Type	*S*-factor	SWSC	Description	Cost (€/m^2)
1	0.14	0.09	External blind, horizontal laths	200
2	0.33	0.12	Blind between the outer panes, horizontal laths	60
3	0.53	0.14	Blind between the inner panes, horizontal laths	50
4	0.65	0.16	Internal blind, horizontal laths	25

Costs are based on the Finnish market 2011 prices. Technical description: IDA ICE [30].
The windows shading decreases SHGC by (1–*S* factor)*100% and *T*-value by (1 − SWSC) × 100%.

Table 5
Heat recovery unit (design variable no. 7).

Type	Annual efficiency (%)	Description	Cost (€/m^2)
1	60	Cross-flow heat exchanger	3533
2	70	Counter-flow heat exchanger	3835
3	80	Regenerative heat exchanger	4138

Costs are taken from [7] and updated to 2011 ones by using 2% inflation rate considering the rise in the system costs.

from [30,38], respectively. The installation costs of the heating and cooling systems are assumed based on the Finnish market prices [39–44]. The mechanical cooling option (Table 6) with a set-point of 25 °C is implemented for building designs which cannot provide comfort conditions [45] in summer by shading (Table 4) and/or natural ventilation via window opening. The energy prices are taken from [46,47].

Since solar energy is one of the most favorable RESs in Europe [48], the current study offers solar thermal and photovoltaic systems to reduce the DHW and electricity demands. An economic feasibility study of a net-zero-energy house in the cold climate of Montreal [49] concluded that flat-plate solar collectors are the best financial option regardless of how many collectors are installed. Flat panels are the most durable type of collectors, and they also have the best performance for systems designed for temperatures within 100 degrees. Based on this conclusion, the current study investigates only the flat plat collector as a cost-effective solar thermal option. The installation cost of a solar thermal kit includes the costs of a flat plate collector, a storage tank with heat exchangers, a circulating pump, piping and insulation. The 1000 € cost of a regular storage tank (300 l), to be installed on a non-solar thermal system, is deducted from the total cost. The price of a photovoltaic module and inverter are based on the average prices in Europe (2.37 and 0.53 €/W, respectively) [50]. By adding the installation cost, the total cost reaches 6 €/W.

2.4. Defining the objective functions

In order to find the cost optimal curve (Fig. 1), a multi-objective optimization problem is defined with two objective functions:

$$\text{Min}\left\{f_1(\bar{x}), f_2(\bar{x})\right\} \quad \bar{x} = [x_1, x_2, \ldots\ldots x_m]$$

where
f_1: primary energy consumption PEC.

Table 6
Cooling options (design variable no. 8).

Options	Specifications	COP_{CU}	Cost (€/unit)
1	No cooling	–	0
2	Small unit 2.5 kW cooling capacity with rotary piston compressor, refrigerant R407C Eco	3.2	850

Costs are based on the Finnish market 2011 prices [44].

Table 7
Primary heating systems (design variable no. 9).

System	Investment cost (€)	Service cost (€/a)	Subscrip-tion fee (€/a)	Energy price (c/kWh)	η_{SHS} (%)	η_{DHWS} (%)	η_{dist} (%)	Energy factor (*F*)
Direct electricity with electrical radiators (EH)	50 kW_p + 2700	30	83	13.5 10.9[a]	100	88	94	1.7
Oil boiler with water radiators (OB)	286 kW_p + 7143	135	83	6.12	81	81	87	1
District heating with water radiators (DH)	50.5 kW_p + 9050	40	404[b]	6.5	94	94	87	0.7
GSHP with floor heating (GSHP)	592.5 kW_p + 12155	145	83	13.5 10.9[a]	300	250	84	1.7

Energy prices are based on the Statistics Finland [46] and Helsingin Energia [47].
Costs are taken from [39–42] and updated to 2011 ones by using 2% inflation rate.
[a] The price of day electricity (13.5 c/kW) on weekdays, from Monday to Friday, 7 am–8 pm. The price of night-time electricity (10.9 c/kW) at other times [41].
[b] Beside the 83 € annual fee of electrical connection, 321 € is added for district heating connection.

Table 8
On-site RES supplementary systems (design variables no. 10 and 11).

Options	Solar system	Total cost (€)	Size (sq m)
1	Flat plate solar thermal system	380 $A_{collector}$ + 3200	From 0 to 30 m^2
2	Multicrystalline silicon Photovoltaic (PV) system	6 €/W	From 0 to 70 m^2

Costs are based on the Finnish market 2011 prices [43,50].

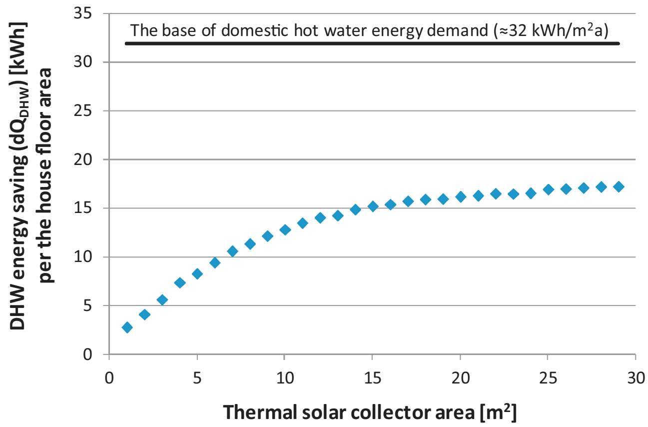

Fig. 4. The annual domestic hot-water energy saving (dQ_{DHW}) using different areas of flat-plate solar thermal collector.

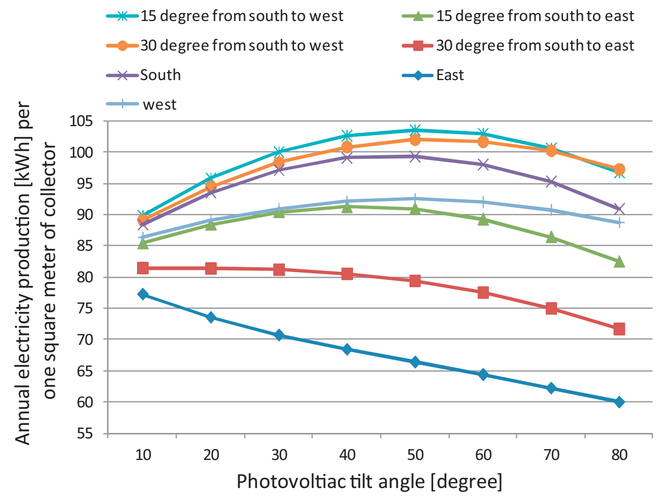

Fig. 5. Annual electricity production [KWh] per one square meter of PV.

f_2: difference in life-cycle cost between any design option and the reference design dLCC.

$\bar{x}$: combination of the design-variables $(x_1, x_2, \ldots x_m)$.

m: number of the design variables.

2.4.1. *Primary energy consumption (PEC, first objective function)*

In order to achieve environmental solutions, the PEC is minimized as a first objective function. Primary energy is the favorable metric, according to the latest EPBD recast [8]. The PEC considers the energy use of the building (heating, cooling, ventilation, lighting, pumps and fans, other technical service systems, DHW, cooking, appliances, lighting) and the energy-saving by RES generations. The PEC is calculated by using non-renewable primary energy factors F according to the energy source (Table 7)

$$\mathrm{PEC} = F\,\mathrm{SH_{delivered}} + F\,\mathrm{DHW_{delivered}} + F\,\mathrm{Ele_{delivered}} \tag{1}$$

$$\mathrm{SH_{delivered}} = \frac{(Q_h/\eta_{dist})}{\eta_{SHS}}$$

$$\mathrm{DHW_{delivered}} = \frac{(Q_{DHW} - dQ_{DHW})}{\eta_{DHWS}}$$

$$\mathrm{dEle}(t) = \frac{Q_c(t)}{\mathrm{COP_{Cu}}} + \mathrm{SH_{ele}}(t) + \mathrm{DHW_{ele}}(t) + \mathrm{E_{hv}}(t) + \mathrm{E_{la}}(t) - \frac{\mathrm{PV_e}(t)}{\eta_{inverter}}$$

$$\mathrm{Ele_{delivered}} = \sum_{t=1}^{t=8761} \max\left\{\mathrm{dEle}(t), 0\right\}$$

Eq. (1) divides the energy demands (Q_h, Q_{DHW}, Q_c) by the annual efficiencies to calculate the delivered ones. According to the heating system applications (space heating and the domestic hot water applications), two efficiencies (η_{SHS}, and η_{DHWS}) are considered as being consistent with the Finnish regulation [27]. Based on the installed space-heating (electrical radiator, water radiator, or floor heating), the distribution efficiency (η_{dist}) is assumed 94%, 84%, or 87%, respectively (Table 7). When mechanical cooling is needed, it will take place for a short period. Therefore, the $\mathrm{COP_{cu}}$ of the nominal operating condition (25 °C outdoor air temperature) is used in presenting the annual performance. The implementation of a flat-plate solar thermal collector reduces the domestic hot water demand Q_{DHW} by dQ_{DHW}. The DHW energy saving (dQ_{DHW}) is simulated by IDA ESBO [31] and checked by TRNSYS (Type 1b) for different sizes of solar collector (Fig. 4). The solar thermal collector is orientated to south and tilted by 45°. These angles are selected to achieve maximum DHW energy saving. This is in accordance with [27], which indicates that the best orientation in Finland is south, southeast or southwest, and the optimal tilt angle is in between 30 and 70 degrees.

The hourly photovoltaic (PV) electricity production is simulated also by IDA ESBO [31] and checked by TRNSYS (type 194). Parametric analysis (Fig. 5) shows that the maximum electricity production from one square meter PV module can be achieved by 50° tilt angle and 15° azimuth angle (from south to east). Because of the house orientation, the optimal azimuth is not allowed. Therefore, the PV collector is oriented to south. To achieve the best performance from south orientation, the PV is sloped by 45 degrees. The annual electricity production is only 4% less than the maximum that could be achieved by the optimal azimuth and tilt angles.

Fig. 6 shows the annual useful electricity generated by different photovoltaic panel sizes. The useful electricity generation is the production which matches hourly the total house electricity use, including lighting, appliances, fans, pumps, and heating. Fig. 6 presents three cases without flat-plate solar thermal collector installation. Case 1 shows the electrical demand and useful production if the reference house is heated by electrical radiators, and an electrical boiler is used to deliver domestic hot water (DHW). In this case the house electrical annual demand is 126.5 kWh/m^{2}a. Case 2 assumes that the house and the DHW are heated by a GSHP. Case 3 shows that no electricity is used for heating, oil boiler or district heating (DH) to cover all heating demands.

2.4.2. *The difference in life-cycle cost (dLCC, second objective function)*

The life-cycle cost (LCC) is one of the commonly used tools to assess the financial viability of projects, and it has been widely used in energy-efficient building research [15,21–23,49,51–57]. LCC finds the assessment of long-term costs, as it takes into account discounted cash flows and covers the entire lifetime of the investment. From the private perspective, the LCC is the sum of the present value of investment and operating costs for building and service systems, including those related to maintenance and replacement, including taxes, over a specified calculation period. Since the current investigation aims to compare different designs in the specified solution space, the absolute value of the LCC is not calculated, but the difference (dLCC_i) between the LCC for any design (LCC_i) and that for the reference one (LCC_r). dLCC is the second objective function

$$\mathrm{dLCC}_i = \mathrm{LCC}_i - \mathrm{LCC}_r \tag{2}$$

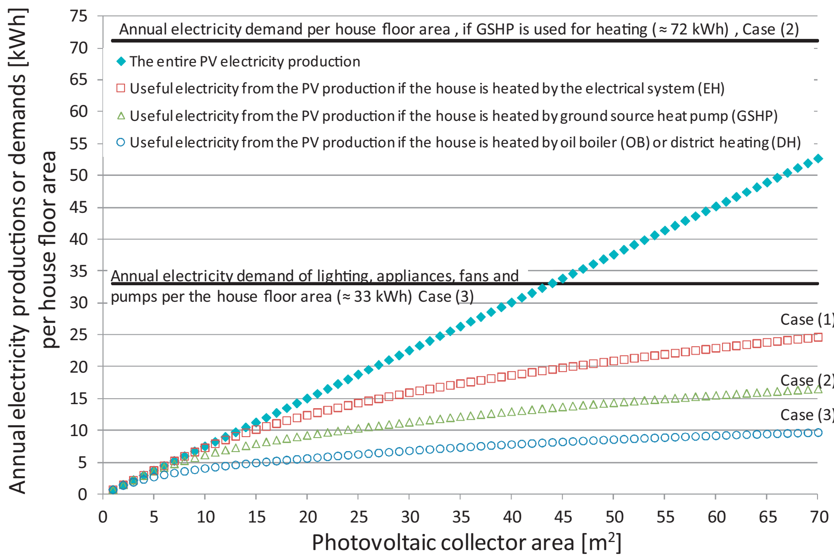

Fig. 6. Electricity demand and useful PV-electricity production where different heating systems are implemented for house with the reference envelope (Section 2.3).

$$\mathrm{LCC} = \sum_{j=1}^{11} \mathrm{IC}_j + \sum_{j=5}^{11} \mathrm{RC}_j + \mathrm{MC} + \mathrm{OC} + \mathrm{C}$$

where IC is the investment costs of the eleven investigated design variables (Tables 1–8), RC is the replacement cost of the replaced building elements and systems (e.g., window, shading, heat recovery unit, etc.), MC is the maintenance costs of the heating systems (Table 7), IC,RC, and MC are described in Section 3.2, OC is the operating cost of energy (Section 3.2), and C is a constant for other costs such as construction and design cost, i denotes indexes for the design solution, j is an index for the design parameter (e.g., building insulation, window type etc.).

In this way, there is no need to include cost data for all components of the building but only the differences produced by the variation of specified parameters between the reference design and any other investigated design. According to the Directive 2010/31/EU [8], the life-cycle cost analysis is performed for a 30-year calculation period. Longer calculation periods are not recommended, as beyond a 30-year timeframe, assumptions on interest rates and forecasts for energy prices become very uncertain [9]. It is worthwhile to mention that no disposal costs are taken into consideration for components with lifetimes longer than the calculation period.

In line with the draft's cost-optimal regulation [58], 3% real interest rate (r) and 2% energy price escalation rate (e) are used to demonstrate the introduced optimization method (Sections 3.1–3.3). Sensitivity analysis with different r and e is performed to present the influence of the economic assumptions on the cost-optimal combination of building elements and heating/cooling system (Section 3.3).

2.4.2.1. Investment, maintenance and replacement cost calculation. The investment cost (IC) is the summation of the investment cost of wall, roof, and floor insulation, cost of window, shading cost, additional labour cost of improving the building tightness, the investment cost of the ventilation heat recovery unit, the installation cost of the heating system, the cost of cooling system (if used), and the installation cost of solar systems. The replacement cost (RC) is calculated for the building elements and systems which have a lifespan shorter than the calculation period (30 years): windows, shading elements, heat recovery unit, cooling unit, solar thermal collector, and the inverter of the photovoltaic system. The replacement costs are discounted, assuming the replacement will take place in the middle of the calculation period.

$$\mathrm{RC}_k = \mathrm{IC}_k \times (1+r)^{-n/2} \tag{3}$$

where k is the subscript of the replaced building element, r is the real interest rate and n is the lifespan

No maintenance costs are assumed for the replaced elements. Maintenance costs (MC) are assumed for the heating systems (Table 7), including the replacement costs of some system parts.

2.4.2.2. Energy operating cost calculation. Operating costs include the annual fees of the electrical and the district heating (where used) connections and the annual heating/electrical energy costs. The annual connection fees (Table 6) are discounted by a discount factor (a), calculated from [59], considering the real interest rate (r) and the calculation period (n) into account

$$a = \frac{1-(1+r)^{-n}}{r} \tag{4}$$

Different energy prices P (Table 7) are used to calculate the energy cost. The calculation of the electrical energy cost is based on the daytime/night time rates, including taxes. The daytime rate is applied on Mondays–Fridays between 07:00 and 20:00. The night time rate is applied outside these times. The energy costs are discounted

$$\mathrm{OC} = a_e\,\mathrm{P}\;\mathrm{SH}_{\mathrm{delivered}} + a_e\,\mathrm{P}\;\mathrm{DHW}_{\mathrm{delivered}} + a_e\mathrm{P}\;\mathrm{Ele}_{\mathrm{delivered}} \tag{5}$$

$$a_e = \frac{1-(1+r_e)^{-n}}{r_e}$$

$$r_e = \frac{r-e}{1+e}$$

where

a_e: discount factor (a) takes into account the escalation rate of the energy price as well.

r_e: real interest rate (r) including the effect of the escalation rate of the energy price.

The current study assumes there is no change in the building energy demand over the calculation period.

In Finland, the energy consumption per dwelling has been rather steady over the years (from 1995 to 2007) when normalized for outdoor temperature [60]. Concerning the electric energy demand of European residential users, various studies have been carried out [61–63]. The ODYSEE Project [63] showed that the electric demand per dwelling did not vary significantly in the decade between 1996 and 2005 since, even though household appliance consumption declined, electric appliance penetration and use increased.

2.5. Using a multi-stage optimization method

In order to find the optimal trade-off between the defined objective functions (PEC and dLCC), multi-stage optimization method is proposed to explore more than 3×10^9 $(16 \times 8 \times 13 \times 3 \times 3 \times 4 \times 3 \times 2 \times 4 \times 31 \times 71)$ combinations of the design-variable options. Considering the impact of the design variables on the objective functions, the exploration is performed in three stages:

- Stage 1 aims to find the optimal combinations (packages) of the design variables which influence the thermal performance (heating, cooling, comfort) of the house i.e., building envelope parameters (Tables 1–4) and heat recovery unit (Table 5).
- Stage 2 assesses the economical and environmental viability of implementing the offered primary heating/cooling systems (Tables 6 and 7) to the optimal combinations found in Stage 1.
- Stage 3 investigates improving the economical and/or environmental viability of the optimal combinations of building-envelope parameters and HVAC systems assessed in Stage 2. Stage 3 addresses the RESs (Table 8) as supplementary systems for heating and/or electricity production.

The stages provide the decision maker a trade-off relation between the environmental and financial viability of the studied building. The decision maker can choose the cost-optimal and nZEB solutions according to his or her preferences

3. The optimization stages: results and discussions

3.1. Optimal combinations of building envelope and heat recovery design options (Stage-1)

The aim of the stage is to find representative energy-efficient building designs, disregarding the heating, cooling, and energy-supply systems. In order to achieve this, the space-heating energy demand of the house and the present worth (PW) of the influencing measures (insulation, building tightness, window type and shading option, and heat recovery type) are minimized, while a penalty function is applied when the summer-comfort criterion ($\mathrm{DH}_{27} \geq 150\,^{\circ}\mathrm{C\,h}$) is violated. Thermal demand is minimized because it is the major demand in residential buildings, particularly in the cold-climate EU countries [64]. The PW presents the initial and replacement costs of the addressed measures

$$\mathrm{PW} = \sum_{i=1}^{5} \mathrm{IC}_i + \sum_{i=1}^{5} \mathrm{RC}_i \tag{6}$$

The investment costs (IC) are shown in Tables 1–5. The replacement costs (RC) are calculated by Eq. (3). According to the Finnish building code D3 [45], degree-hours (DH_{27}) are used to measure the summer overheating risk

$$\mathrm{DH}_{27} = \sum_{i=1}^{i=8760} dT_{27} \Delta t \tag{7}$$

$$dT_{27} = (T_i - 27) \quad T_i - 27 > 0$$

$$dT_{27} = 0 \text{ when } T_i - 27 \leq 0$$

where T_i is the mean air temperature [°C] at the warmest zone (upper floor) and Δt is a one-hour time-period [h].

Since it is computationally expensive to explore (simulate, assess, then compare) all the available combinations of the building-envelope parameters (Tables 1–4) and the heat-recovery units (Table 5), automatic simulation-based optimization method is used. The simulation time is reduced by using a simplified three-zone model (Fig. 2b) for a multi-zones predefined house (Fig. 2a). The simplification's details are described in a previous work [7]. To save time, a modified multi-objective genetic algorithm *PR_GA* is used to speed up the exploration. The algorithm is a combination of deterministic and a controlled elitist GA (a variant of NSGA-II [65]) from MATLAB toolboxes (2008b). The modified algorithm is able to address discrete and continuous variables, avoid repetition, keep all the iterations in archive and use them in non-dominated sorting processes. The algorithm was developed [66] and used successfully in previous building and HVAC studies [7,67,68]. The idea of the algorithm is that instead of initiating the GA optimization with random population, the algorithm performs a preparation phase PR attempting to find diverse solutions close to optimums and provides them to the GA as seeds. By this, the algorithm reduces the random behavior of the GA and converges to the Pareto-optimal sets faster than simple GAs would. The preparation concept can be adopted in different ways (e.g., parametric analysis) as shown in [69].

In the current optimization stage, the *PR_GA* is employed with a manual preparation phase (PR). The GA optimization started with an initial population (20 individuals), including 10 random and 10 manually chosen diverse building-envelope and heat-recovery combinations: the reference design, the cheapest and the most expensive combinations, and seven intermediate low-energy combinations. The intermediate low-energy combinations have lower space-heating demands than the cheapest solution and lower investments than the most expensive one. The intermediate combinations are chosen manually with incremental *U*-values in between the lower and upper bounds (Table 1). The intermediate combinations have the same building tightness and shading option as the reference design.

Aiming to achieve high quality results, GA performed 40 generations, considering all the design variables as discrete. The *U*-value's boundaries of wall, roof, and floor constructions are divided by a constant step ($0.02\,\mathrm{W/m^2\,K}$) to 16, 8, 13 options, respectively. The total building-envelope and heat-recovery combinations $(16 \times 8 \times 13 \times 3 \times 3 \times 4 \times 3 = 179712)$ are explored effectively by only 800 simulation runs. Lower number of simulations was applicable. However, accurate results were desired.

All the simulations are shown in Fig. 7. The optimal ones are classified into two groups. Group 1 satisfies the summer overheating criterion (Eq. (7)), while Group 2 does not. Groups 1 and 2 consist of 19 and 13 solutions, respectively. Group 2 solutions are not eliminated, as non-comfort solutions, because they could be feasible when the mechanical cooling option (Table 6) is added. The RES (e.g., photovoltaic) could improve the economical feasibility of the mechanical cooling solutions by covering a portion of their electricity demands. The evaluations show that investing in ESMs (Tables 1–3 and 5) has a potential to reduce the space-heating demand from about 50 to 25 $\mathrm{kWh/m^2a}$. The influence of the ESMs and shading options (Table 4) on the summer overheating level – presented by the DH_{27} – is shown in Fig. 8. With the lowest-cost shading option (internal-blind shading, option 4), acceptable overheating levels ($\mathrm{DH}_{27} \leq 150\,^{\circ}\mathrm{C\,h}$) cannot be achieved. External or outer panes shading (options 1 and 2) can achieve the comfort levels. However, they reduce the passive heating opportunity. From a thermal-comfort point-of-view, a blind between the inner panes (option 3) is a suitable shading option, if extreme building tightness

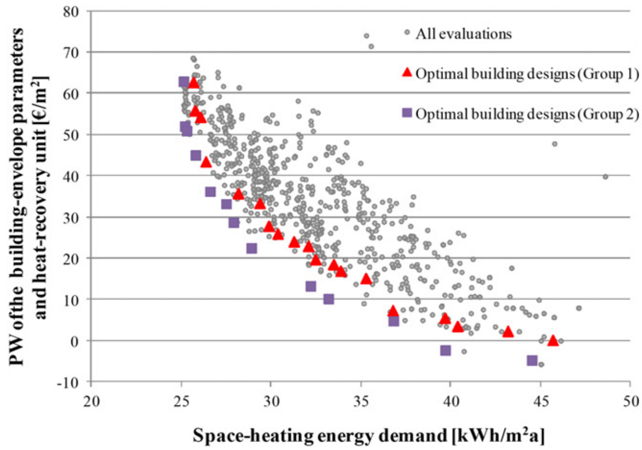

Fig. 7. Stage 1 optimization evaluation: the annual space-heating energy demands versus the present worth (PW) of different combinations of building-envelope parameters (Tables 1–4) and heat-recovery unit (Table 5).

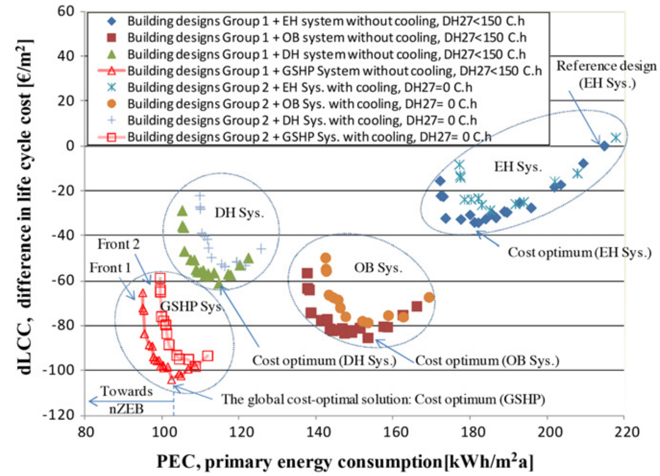

Fig. 9. Financial and environmental viability of the optimal building and HVAC designs before and after the RES improvements (Stage-3).

and/or insulation levels are not used. The cost-optimal building designs Group 1 and 2 have shading option 3 and 4, respectively.

3.2. Combining the heating/cooling systems with optimal building designs (Stage-2)

Stage 2 assesses the financial and environmental viability of Stage 1 cost-optimal building designs (Group 1 and 2; Fig. 7), addressing the offered primary heating systems (Table 7). The supplementary systems (e.g., solar systems) are out of the scope for the current stage. The stage implements mechanical cooling (Table 8) only for the overheated building designs (Group 2). Short simulation (three-month simulation) is employed to calculate the cooling demands during the summer season for only 13 building solutions (members of Group 2). The heating demands are taken from the pre-simulated results (Stage-1). Fig. 9 shows the assessment results, classifying them according to the implemented heating/cooling systems and building group. The results show that although Group 2 solutions have lower space-heating energy demands than Group 1 ones (Fig. 7), they are not economically feasible due to their need for mechanical cooling, which increases not only the investment cost but also the operating one.

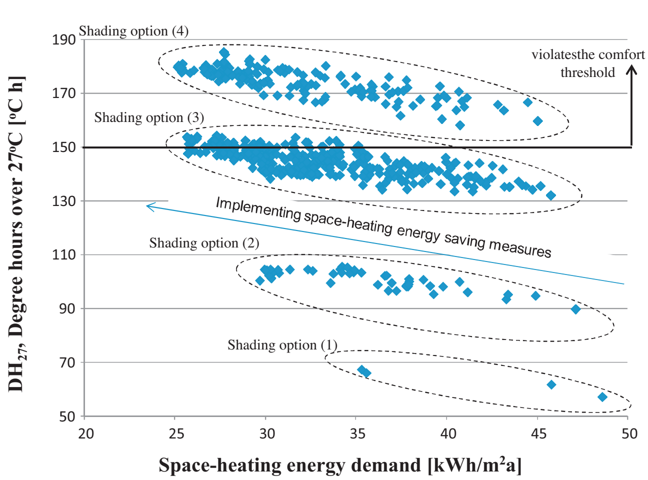

Fig. 8. Degree hours (DH_{27}) and space-heating demands of all the evaluated solutions. Shading options are described in Table 4.

The results also show that the financial and the environmental aims do not necessarily contradict each other. The highest capital cost heating system (GSHP) is the cost-optimal one in term of LCC. Annual fees, service expenses, and energy costs reduce, respectively, the economic feasibility of the other heating options: district heating (DH), oil boiler (OB), and electrical heating (EH). The global cost-optimal building design requires more ESM implementations than the reference one. The cost-optimal and the reference ones have a space-heating demand of 36.8 and 46 kWh/m^{2}a, respectively. Table 9 presents the cost-optimal combinations of building-envelope parameters and heat-recovery unit for each heating system. The combinations show that the cost-optimal implementations of space-heating ESMs (e.g., additional insulation) depend on the installed heating system. For economical operation, the highest operating-cost heating system (EH) requires more ESMs than the lower operating-cost ones: OB, DH, and GSHP.

From the environmental point of view, using a highly energy-efficient heating system reduces the potential of the ESM implementations. Generally speaking, it seems that investing in an energy-efficient heating system has a better financial and environmental viability than investing in extremely high insulation, efficient window, and/or tight envelopes. An efficient heating system reduces not only the space-heating environmental burden but also the DHW ones. Further environmental assessments of the embodied energies show that the heating systems cause marginal impacts compared with the entire house in the pre-operating phase [70]. A life-cycle assessment (LCA) of GSHP systems in Europe showed that in most countries, particularly in countries with an energy-efficient electrical grid, CO_2 savings can be achieved with the application of shallow geothermal systems. For instance, using a GSHP system only for heating achieved an average of 18% savings in comparison to gas-furnace heating and 35% in comparison to oil-fired boilers [71]. Using GSHP as a heating option for single-family houses tends to increase the costs, according to the Finnish market statistics (Fig. 3). Our current results encourage this trend. Seeking for higher economical and/or environmental building-integrated-system designs, the next stage continues the exploration, offering RES options (Table 8) as supplementary systems.

3.3. Optimal building-integrated RES-system designs: nZEB solutions (Stage-3)

This stage seeks to improve the financial and/or environmental viability of Stage-2 building-envelope and HVAC-system designs. The stage investigates the viability of implementing RES options as

Table 9
The reference design and the cost-optimal solutions for each heating system, presented in Fig. 9.

Heating system option (Table 7)	PEC (kWh/m²a)	dLCC (€/m²)	Space heating (kWh/m²a)	U-value (W/m² K)			Window type option (Table 2)	Heat recovery option (Table 3)	Building tightness option (Table 4)
				Wall	Roof	Floor			
Ref. design	215	0	46	0.170	0.090	0.170	1	1	1
EH	178	−33	28	0.095	0.080	0.157	2	3	2
OB	149	−83	34	0.131	0.087	0.171	1	2	2
DH	112	−57	35	0.154	0.090	0.157	1	2	2
GSHP	103	−104	37	0.142	0.083	0.157	1	2	1

supplementary systems for heating and/or electricity production. Since Stage-2 solutions (Fig. 9) have different potential for improvement via the RES options (Table 8), the integrated designs have a probability to compete with each other. The integrated designs are combinations of 128 ($19 \times 4 + 13 \times 4$) Stage-2 designs and 2201 (31×71) RES options. The integration composes 281,728 solutions. In order to reduce the optimization effort, pre-investigation is performed to reduce the solution space by eliminating the unpromising solutions. The pre-investigation assessed the viability of adding the largest size (70 sq m) of PV panels to all Stage-2 solutions. The assessment showed that it is not possible to improve the financial and/or the environmental viabilities of the direct electricity (EH), oil boiler (OB), and district heating (DH) solutions further than the GSHP ones. The GSHP is an indirect electrical heating system. Therefore its solutions have a higher potential for improvement by the PV electricity production than the OB and DH solutions. Solutions with direct electricity heating system (EH) have a higher RES improvement potential than the ones with a GSHP. However, due to the efficiency of the GSHP, the EH cannot compete with it. Similarly, the solar thermal system shows higher economical feasibility in integrating with the electricity-based heating systems than the fuel-based ones (OB or DH). Based on the pre-investigation results, the OB, DH, and EH solutions are eliminated from the solution space of Stage-3 exploration.

The solution space is reduced further by eliminating the GSHP-dominated solutions. The pre-investigation (adding the smallest size 1 sq m of the thermal and photovoltaic systems, sequentially, to all the GSHP solutions) shows that expensive RES options cannot improve the economic performance of the GSHP-dominated solutions when compared with the cost-optimal non-dominated ones. Eliminating the dominated solutions, with and without a separate cooling option, lets the investigation focus on very energy-efficient building designs. Inefficient energy designs are not preferable even if they are economically feasible [72]. The explored solutions (non-dominated solutions), with and without a cooling option (fronts 2 and 1, Fig. 9), are shown in Table 10 and Table 11, respectively.

Tables 8 and 9 show that the optimal solutions with mechanical cooling could compete with the optimal solutions without cooling in both aspects: economical and environmental. For instance, although solutions without cooling (e.g., solution 8; Table 11) dominate the optimality of the solutions with cooling (e.g., solution 3; Table 10), the latter have a higher potential for improvement by RES (e.g., PV). Solution 3 (Table 10) consumes more electricity–for cooling–and less space-heating than solution 8 (Table 11). Since a portion of solution 3 electricity is for cooling during summer day mornings, the electricity demand has a high potential to be reduced by PV implementation. Consequently, solution 3 might compete with the optimality of solution 8 if the same PV size were implemented for both and there were no electricity export to the grid.

In order to investigate the improvement of the cost-optimal building and HVAC designs (fronts 1 and 2, Fig. 9), optimization is performed while considering the building and HVAC design as well as the size of the thermal and photovoltaic solar systems (Table 8) as design variables. Various options are taken for each design variables: (1) eighteen options (Table 10 and Table 11 solutions) for building and HVAC designs, (2) 31 collector areas (from 0 to 30 sq m) for a solar thermal system, and (3) 71 module areas (from 0 to 70 sq m) for the photovoltaic system. The total number of the three design variable combinations is 39, 618 ($18 \times 31 \times 71$). Instead of evaluating all the 39,618 combinations, the optimization performs two times 1200 evaluations to find the cost-optimal integrated solutions with and without the cooling implementation, respectively. Linear constraint function is used to avoid solar systems (thermal and PV collectors) implementation larger than the house's roof area (70 sq m). The optimization is performed by the modified multi-criteria optimization algorithm (*PR_GA*) introduced in Section 3.1. In the preparation phase (PR), a single-objective deterministic algorithm (Fmincon, from MATLAB 2008b Toolbox) is used to minimize the first objective (PEC), considering the second objective (dLCC) = 0, −50, and −100 as constraint via three sequential optimization runs. The evaluations of the deterministic algorithm are kept in the archive then sorted by the non-dominated sorting code in MATLAB m-file. The non-dominated solutions are used as an initial population for the genetic algorithm phase (*GA*). Stage-3 explored the 39,618 offered solutions by only 2400 evaluations (6% of the offered solutions). This is a significant reduction in computational effort particularly when time-consuming simulation is used (i.e., the simulation of the integrated design solutions consumes time in considering the matching between energy production and consumption). Further reduction was applicable. However, high quality results were desired. Fig. 10 presents the financial and environmental viabilities of the optimal building and HVAC designs (packages) before and after the RES improvements. The optimization history and the Pareto optimal sets are shown in Fig. 11a.

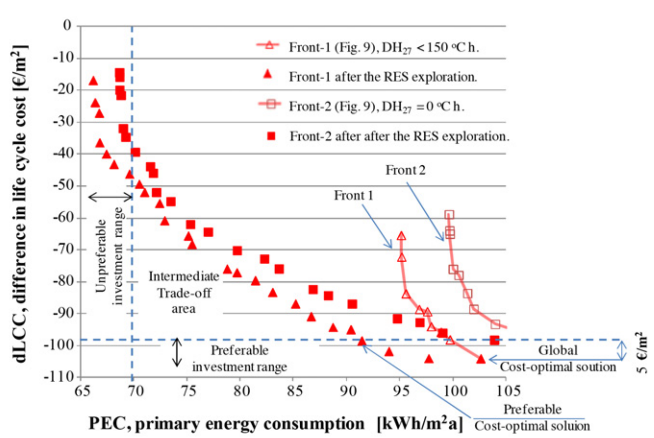

Fig. 10. Towards nearly zero energy house: the optimisation results (a), the optimal combinations of ESMs and RES (b). The ESMs implementation is presented by its space-heating energy saving potential as a percent of the reference design (46 kWh/m²a).

Table 10
Optimal solutions with mechanical cooling (Front 2, Fig. 9), heated by GSHP.

Index	NPE (kWh/m²a)	dLCC (€/m²)	Space heating (kWh/m²a)	U-value (W/m² K)			Window type option (Table 2)	Heat recovery option (Table 3)	Building tightness option (Table 4)
				Wall	Roof	Floor			
1	99.6	−58.9	26	0.069	0.070	0.092	2	3	3
2	99.7	−64.0	26.1	0.082	0.073	0.092	2	3	3
3	99.7	−65.0	26.2	0.078	0.075	0.103	2	3	3
4	100.0	−76.0	26.7	0.101	0.073	0.157	2	3	3
5	100.5	−77.9	27.5	0.114	0.087	0.144	2	3	3
6	101.4	−83.6	28.8	0.131	0.080	0.109	2	3	2
7	102.0	−88.5	29.9	0.142	0.073	0.171	2	3	2
8	104.0	−93.2	33	0.131	0.083	0.144	1	2	2
9	108.8	−98.2	40.8	0.169	0.087	0.171	1	2	1

Table 11
Optimal solutions without mechanical cooling (Front 1, Fig. 9), heated by GSHP.

Index	NPE (kWh/m²a)	dLCC (€/m²)	Space heating (kWh/m²a)	DH_{27} (°Ch)	U-value (W/m² K)			Window type option (Table 2)	Heat recovery option (Table 3)	Building tightness option (Table 4)
					Wall	Roof	Floor			
1	95.1	−65.4	25.7	148	0.069	0.073	0.092	2	3	3
2	95.2	−72.2	25.8	150	0.082	0.073	0.103	2	3	3
3	95.6	−83.6	26.4	148	0.122	0.073	0.133	2	3	3
4	96.8	−88.5	28.2	145	0.095	0.080	0.157	2	3	2
5	97.6	−89.2	29.4	147	0.101	0.080	0.133	2	2	2
6	98.0	−93.9	29.9	146	0.154	0.083	0.144	2	3	2
7	98.9	−95.6	31.3	143	0.154	0.080	0.157	2	2	2
8	99.7	−98.0	32.5	140	0.122	0.080	0.157	1	2	2
9	102.6	−104	36.8	139	0.142	0.083	0.157	1	2	1

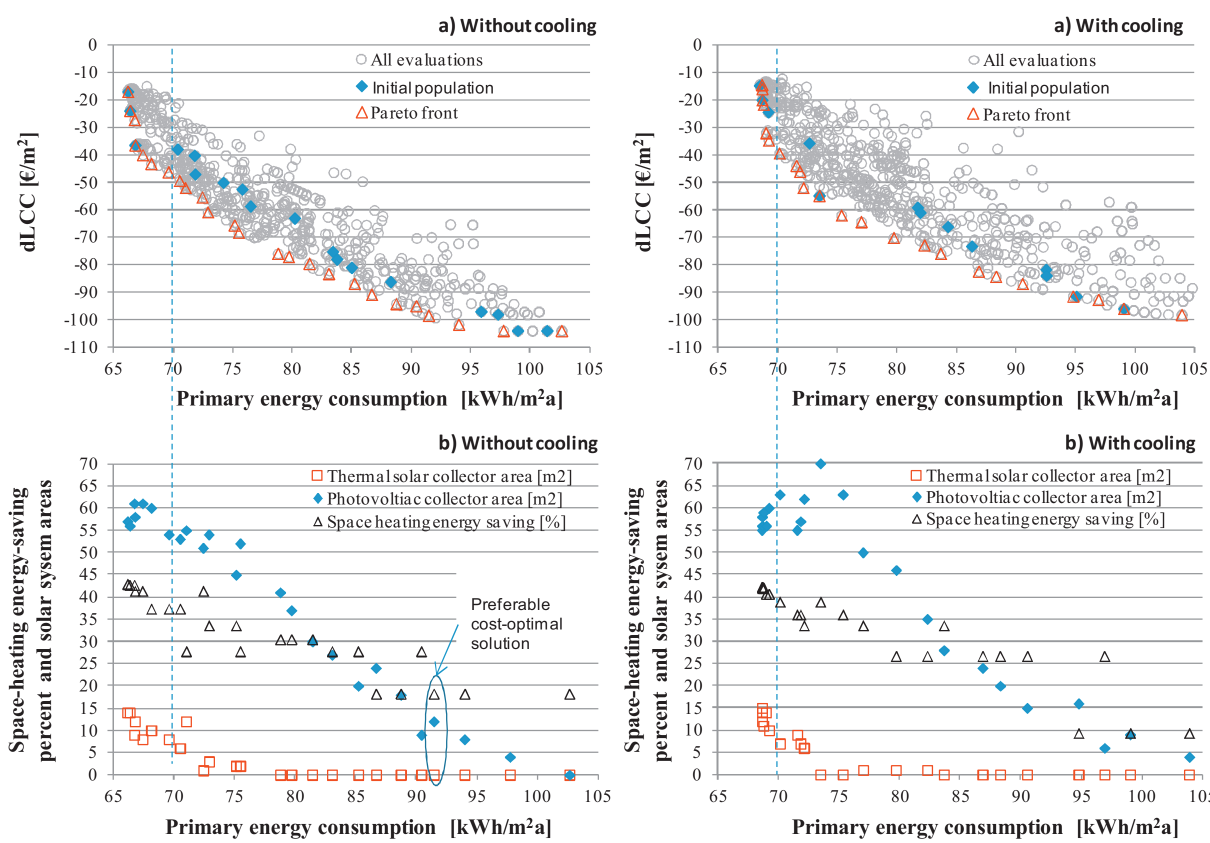

Fig. 11. Preferable cost-optimal integrations of ESMs and RES options at different energy price escalation rates. The ESMs implementation is presented by its space-heating energy-saving impact as a percent of the reference design (46 kWh/m²a). All solutions use GSHP for heating. No cooling is implemented.

Fig. 11b shows the design-variable combinations of the improved optimal solutions. The building and HVAC design is presented by its space-heating energy saving percentage (i.e., a building and HVAC design with higher energy-saving measures has lower space-heating demand than the reference design). The other design variables (thermal and PV solar systems) are presented by their areas.

According to the Directive 2010/31/EU, the minimum LCC solution (global cost-optimal solution) determines the minimum energy performance requirements. However, a slightly higher LCC solution could be preferable if it reduces the PEC significantly. Fig. 10 shows the global and preferable cost-optimal designs assuming $r = 3\%$ and $e = 2\%$. The difference between the LCC of the cost-optimal solutions is 5 €/m^2. Based on the resulted global and preferable cost-optimal solutions, the minimum energy performance level should be 103 or 92 kWh/m^{2}a of primary energy, respectively. The cost-optimal levels are respectively 40% and 47% lower than the 172 kWh/m^{2}a ($372 - 1.4 \times \text{Area}_{\text{house}}$) level, which has come in force by the Finnish code D3 [45]. The gap between the cost-optimal levels and the D3 one is larger than the EPBD gap threshold (15%). In term of $CO_{2\text{-eq}}$ mission the cost-optimal energy performance level should be in-between 27.5 and 25 kg $CO_{2\text{-eq}}$/m^{2}a. These values are calculated by assuming 0.459 kg $CO_{2\text{-eq}}$ per 1 kWh electrical energy.

Fig. 11 shows that the solar systems have a significant potential to improve the financial and environmental viability of the GSHP building designs. Although the exploration assumes that there is no export to the grid, the solar thermal and photovoltaic systems reduced the primary energy of the house about 40 kWh/m^{2}a from that needed in the global cost-optimal design. Investing in a solar system not only reduced the primary energy but also improved the economic feasibility of most of the Stage-2 optimal designs (fronts 1 and 2). The results show that investing in solar systems can achieve a nearly-zero-energy building with about 70 kWh/m^{2}a primary energy consumption. However, higher investing appears not feasible from the economic point-of-view. Energy export, economic incentives, and/or cost-effective innovative measures are required for nearly-zero-energy buildings with a lower PEC. For instance if export of PV surplus energy to the grid is allowable, the nZEB level will be as low as 40 kWh/m^{2}a.

Concerning net-zero-energy buildings, recent publications [15,72] raised a question: "To what level should we decrease the energy use by means of energy-efficiency measures before implementation of renewable energy sources?". Our results (Fig. 11) show that the optimal answer is difficult to find and generalize. Optimization is required for answering. The economic viability of the ESMs and renewable systems depend on each other as well as on the installed heating/cooling system. The optimal implementation of RES systems depends on the energy consumption of the building and its HVAC design. Larger photovoltaic systems are more economically feasible for building designs with mechanical cooling than for designs with proper passive-cooling measures. Mechanical cooling increases electricity demand; however, it allows matching between energy generation and consumption. In addition, it allows extra low space-heating solutions without the overheating risk. With a large size PV (>50 sq m), the financial and the environmental viabilities of the building design with mechanical cooling system become close to the viabilities of systems with proper passive-cooling measures (Fig. 10).

Fig. 11 shows also that the financial and environmental viability of the photovoltaic (PV) panel is higher than the viability of the solar thermal system. The reason is that the PV not only reduces lighting and appliances' electrical demand but also reduces the heating requirement. All the cost-optimal building designs are heated by GSHP, which uses electricity in an indirect way. The energy-saving potential of the PV implementation increases when

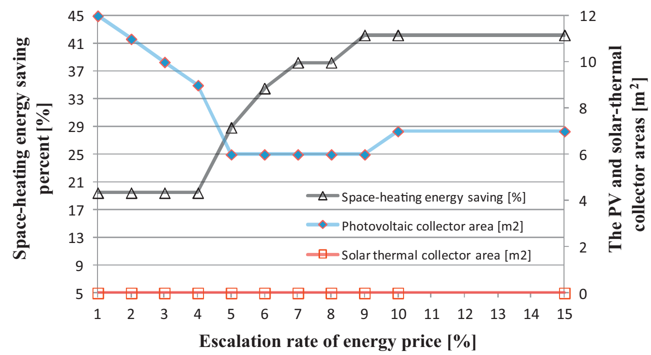

Fig. 12. Preferable cost-optimal integrations of ESMs and RES options at different energy price escalation rates. The ESMs implementation is presented by its space-heating energy-saving impact as a percent of the reference design (46 kWh/m^{2}a). All solutions use GSHP for heating. No cooling is implemented.

electrical demand increases (Fig. 5). The maximum economically feasible size of a solar thermal collector is 15 sq m, according to Fig. 11. Regarding storage capacity and temperature limit considerations, large collector sizes (>15 sq m) cannot significantly reduce domestic hot water demand (Fig. 4).

4. Sensitivity analysis

Sensitivity analysis is performed to show the impact of energy price escalation rates (e) on cost-optimal results. Seeking for a preferable cost-optimal solution, as illustrated in Fig. 10, multi-objective optimization is required. The preferable solution is not the global optimal one. Therefore, a single-objective optimization method is not suitable for finding it. The introduced multi-stage multi-objective optimization method is used to find the preferable cost-optimal solution, at the range of e: from 2 to 15% and with 3% real interest rate (r). To reduce the computational effort, mechanical cooling is not considered as an option. The above calculation, with $r = 3\%$ and $e = 2\%$, shows that it is not cost-optimal to use mechanical cooling to avoid summer overheating risk. Passive techniques (e.g., shading) is proper. This assumption reduced the solution space by eliminating all the building envelopes which suffer overheating from the exploration. Fig. 12 shows the preferable cost-optimal integrations of ESMs and RES options at different energy price escalation rates.

The results show that GSHP is the cost-optimal heating system at the studied range of e. The solar thermal system cannot compete as a cost-optimal solution because it increases both the investment and replacement costs. Solar thermal collectors require replacement at the half of the indicated life cycle (30 years), while no replacement is assumed for the PV. The economic viability of investing in ESMs (Tables 1–5) increases proportionally with the energy price escalation rate from 4% to 9%. Since the ESMs have a limited influence on the energy consumption, their extreme levels (e.g., passive U-values) do not appear as cost-optimal ones. The maximum ESMs implementation has a potential for 44% space-heating energy saving. At $e \geq 9\%$, lower ESMs are used as a cost-optimal solution to save 41% of the SH energy. Cost-optimal investing in RES (e.g., PV) depends on the space-heating demand and the escalation price's escalation rate (e). Investing in 11 sq m PV-panels is economically feasible when a low level of space-heating ESMs are implemented (energy saving ≤20%) and low energy-price escalation rates (≤4%) are assumed. With that level of ESMs implementation, 11 sq m of PV has a potential to reduce the heating cost supplementing the indirect heating system (GSHP) by free electricity. At high rates of escalation ($e \geq 5\%$), space-heating energy saving (>20%) is economically feasible. However, there is no potential for PV > 7 sq m to reduce the heating cost. Generally speaking, from the economic point of view, investing in ESMs and/or the RES option is feasible at higher energy-price escalation rates. The optimal integration of ESMs and RES options is mutually dependent and also depends on the economic assumption.

It is worthwhile to mention that a small number of building and HVAC design options could not reach the cost-optimum and might lead to non-preferable environmental solution. A two-objective optimization algorithm is required to find the preferable cost-optimal solution. The global cost-optimal solution can be found by a single-objective algorithm. However, it does not provide the decision maker a preferable solution with significantly better environmental burden and slightly higher investments (5% LCC).

5. Conclusions

A multi-stage simulation-based optimization method is introduced to find cost-optimal and nearly-zero-energy building solutions in line with the EPBD-recast 2010. The method significantly reduces the computational effort (compared with the exhaustive search or trial and error methods) and supports a transparent cost-optimality analysis, presenting the effect of the different design variable combinations. The method provides a wide-solution-space exploration in reasonable time.

As a case study, the method is applied to find the cost-optimal and nZEB energy performance levels for a single-family house in Finland. An enormous number of combinations (more than 3×10^9) of building-envelopes, heat-recovery units, cooling and heating options, as well as solar-thermal and photovoltaic solar systems are explored with a suitable number of iterations (less than 3400). The method speeds up the exploration, not only by reducing the number of evaluations but also by using pre-simulated results instead of running time-consuming simulations (when possible).

The introduced method explored the defined solution space in three stages. In the first stage, an efficient multi-objective genetic algorithm (a variant of NSGA-II [65]) is used to find cost-effective energy-efficient combinations of the design variants which influence the thermal performance of the house: the building-envelope (insulation thickness of external wall, roof, and floor, window type, and building tightness) and the heat-recovery unit. Then the summer overheating risk is checked and a mechanical cooling system is added to the combinations which suffer unacceptable summer overheating levels. The second stage assesses the primary-energy consumption (PEC) and the life-cycle cost (LCC) of the optimal combinations, addressing the offered primary heating options (e.g., electrical heating, oil boiler, district heating, GSHP). Then a non-dominated sorting code is used to determine the optimal trade-off between the objective functions (PEC and LCC). The third stage attempts to improve the financial and/or environmental viabilities of the optimal found building and HVAC solutions by implementing the optimal sizes of solar- thermal and photovoltaic systems.

The results show that for a single-family house in cold climate of Finland:

- The financial and the environmental aims do not necessarily contradict each other. The achieved preferable cost-optimal solutions, at different energy price escalation rates (from 2 to 15%) and a calculation period of 30 years, have primary-energy consumption around 47% lower than the D3-2012 standard value (172 kWh/m^{2}a).
- The cost-optimal implementations of ESMs and RES methods depend on the installed heating/cooling system and its energy-price escalation rate. For a cost-optimal operation, a building with a fully electrical heating system requires more ESMs (e.g., additional insulation) than a building heated by a GSHP or fuel-based heating systems (e.g., OB and DH). PV sizes up to 20 sq m and 15 sq m are preferable cost-optimal options for houses with high electrical energy demands: houses with a mechanical cooling option and a direct or indirect electrical heating system (EH and GSHP), respectively. Smaller PV sizes (up to 5 sq m) are economically feasible for houses without a mechanical cooling implementation and fuel-based heating systems. Solar-thermal system is not a cost-optimal solution, particularly for houses heated by fuel-based heating systems. The solar-thermal system has a lower economic viability than the PV system because the latter reduces the most expensive energy source (electrical energy). The solar-thermal system not only increases the investment cost but also the replacement one. The life-span of a solar-thermal collector is often shorter than that of a PV one. For nZEB solutions, a solar-thermal system with collector up to 15 sq m is economically feasible.
- The cost-optimal combinations of space-heating ESMs depend on their influence on summer overheating. Measures which significantly increase summer overheating (e.g., inefficient shading methods) are not preferable from an economic point of view because they could lead to a need for mechanical cooling.
- Mechanical cooling is not a cost-optimal option. It increases not only the investment cost but also the operating cost. Proper shading and building tightness as well as natural cooling via operable windows can eliminate the summer overheating risk. The economical feasibility of the mechanical cooling option becomes close to optimal when it is integrated with a sufficient size of PV for free electricity from solar panels.
- Higher energy-price escalation rates encourage investments in RES and/or ESMs options. This is limited by the energy-saving potential of the options. For instance, increasing insulation to "the passive house *U*-values" is not a cost-optimal option because it has a limited influence on the space-heating energy saving. A lower insulation level is the cost-optimal one.
- Currently, on-site solar systems cannot contribute as a part of a global cost-optimal solution because of their expensive capital costs. However, small PV sizes can compete with the ESMs for achieving energy performance levels higher than the global cost-optimal one, with a slight increase in the LCC.
- From the economic point of view, it is viable to achieve nZEB with primary-energy consumption up to 70 kWh/m^{2}a. Economical and environmental incentives/credits are required to improve the economic feasibility of solutions towards net-zero-energy building. For instance if export of PV surplus energy to the grid is allowable, the nZEB level will be as low as 40 kWh/m^{2}a.

Exploring a huge number of design options, which include RES technologies, HVAC systems, and commonly used/advanced energy saving measures, is extremely time-consuming and arduous to analyse. Automatic simulation-based optimization is required to find the optimal combinations when having the economical and the environmental viabilities as objective functions and the minimum acceptable thermal comfort level as a constraint. A multi-stage optimization method can reduce the exploration effort and support a fully informative and transparent analysis in line with the EPBD-recast 2010.

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